

Self-Deployed Extremely Large Low Mass Space Structures

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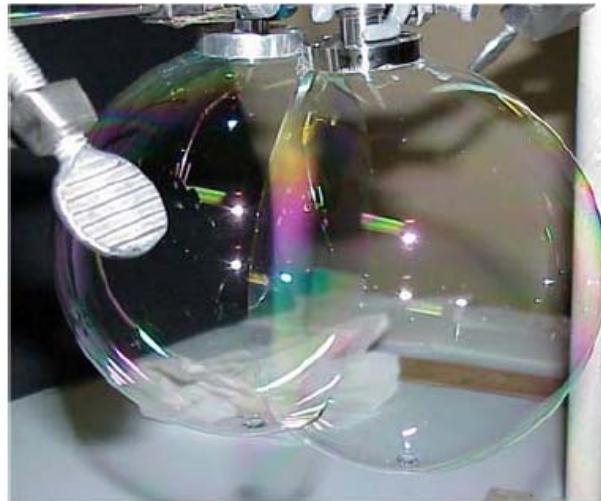
Physical Sciences, Inc.

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*With a little help from our friends W. Cash and A. Labeyrie

Low Mass Approach

- Rigid structures can be fabricated from bubbles or foams that are inflated at very low pressures ($\sim 10^{-4}$ atmospheres) before being made rigid by solar UV curing



Features

- Bubbles and foam with individual cell sizes up to 100 meters
- Structural spans could exceed 10,000 kilometers in micro-g environments
- Structural densities as low as $15 \mu\text{g/cc}$
- Areal densities under 1g/m^2
- Foam densities that tessellate volume in a structured way to maximize density in regions of stress
- Phononic crystals designed into the foam tailor the stiffness of structural members
- In-situ bubble and foam formation and rigidization allows a deployed structure volume of up to 10^8 times the spacecraft volume that deploys it

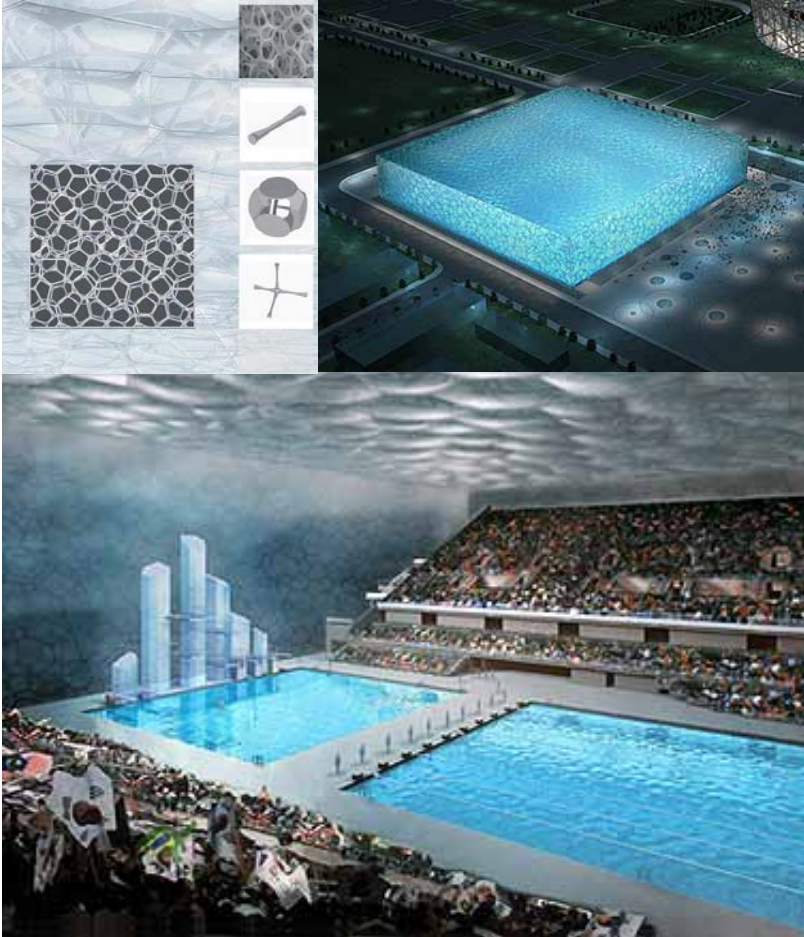
Applications

- Self-sustaining space habitats for extended duration uses
 - Space stations
 - Planetary expeditions
 - Interstellar voyages
 - Planetary surface buildings
- Astronomical telescope structures that replace formation flying requirements at very large scales
 - Interferometer arrays
 - Pinhole imagers
 - Long focal length Fresnel plate telescopes
- Large area photon sails, stellar energy collectors, or astronomical primary photon collection surfaces
 - Interstellar photon sailing
 - Solar powered propulsion
 - Laser propulsion at extreme ranges
 - Beamed power transmission
 - Photon perturbation of comet orbits for planetary protection
 - Astronomical research on the origins of the universe and on evidence of life on planets within other solar systems
 - Solar earth shade for global warming mitigation
 - Optical apertures with tailored radius of curvature up to 100 meters in diameter
 - Solar ablation of cometary surfaces to deflect NEO objects from earth-intersecting orbits for planetary defense

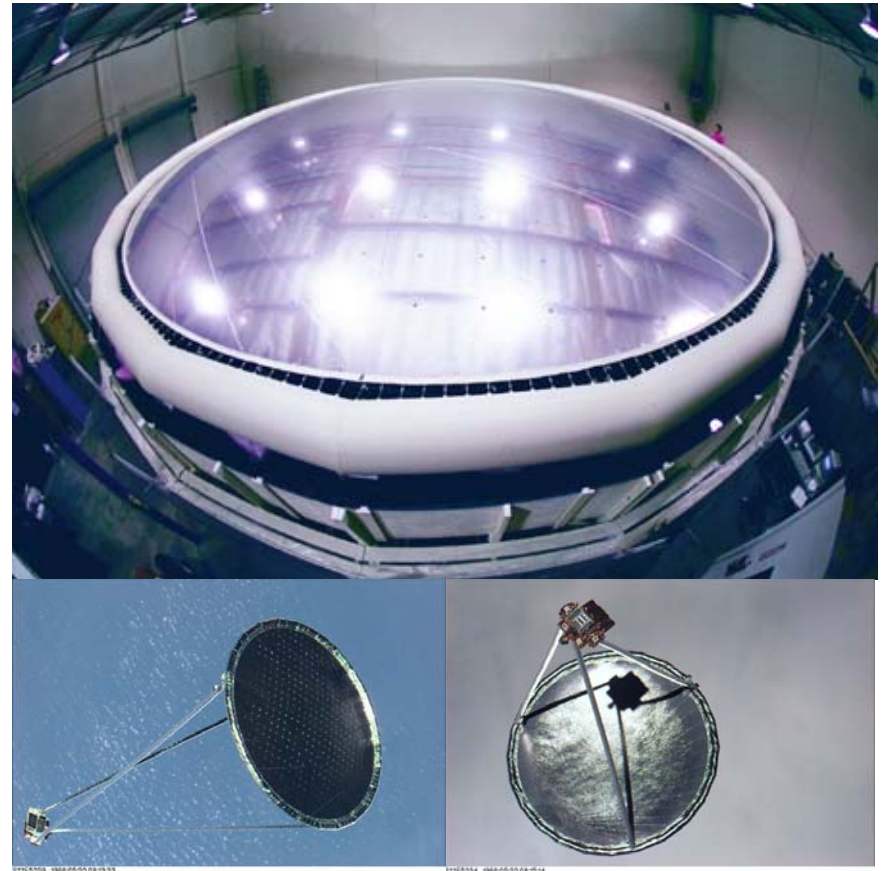
Deployed Structures

- Example Structures
 - Orbiting large spheres with multi-kilometer dimensions
 - Domes, or either cylindrical or rectangular prisms, for use as buildings on planetary surfaces
 - Long structural elements to hundreds of kilometers in size and beyond
 - Large area thin walls to tens of thousands of square kilometers and beyond
- Deployment Methods
 - Bubble inflation followed by rigidization
 - Frame member inflation followed by rigidization
 - Frame member inflation followed by suspending “soap film” analogs followed by rigidization

History of Foams and Inflated Structures



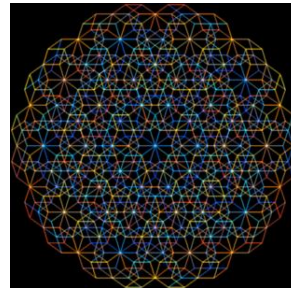
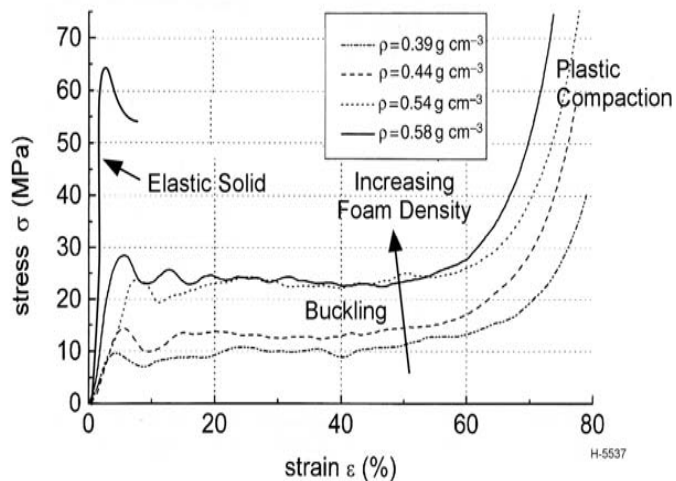
National Swimming Center Design
for the Beijing, China Olympics



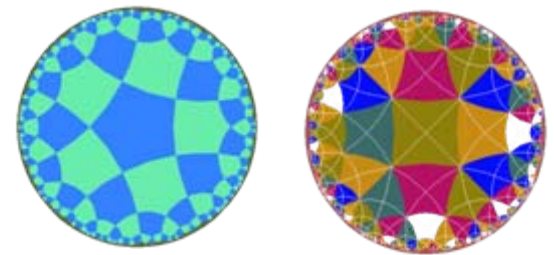
14-meter L'Garde Inflatable Antenna
Space Shuttle Experiment

Foam Structural Members

- The strength of a cellular structure (foam) is due to a combination of the aggregated rigidity of the cell boundaries and the net tensile strength of the cell walls.
- The aggregate rigidity is a function of geometry, density, and materials
- Foam structural members support or align the films that will be detailed in this presentation



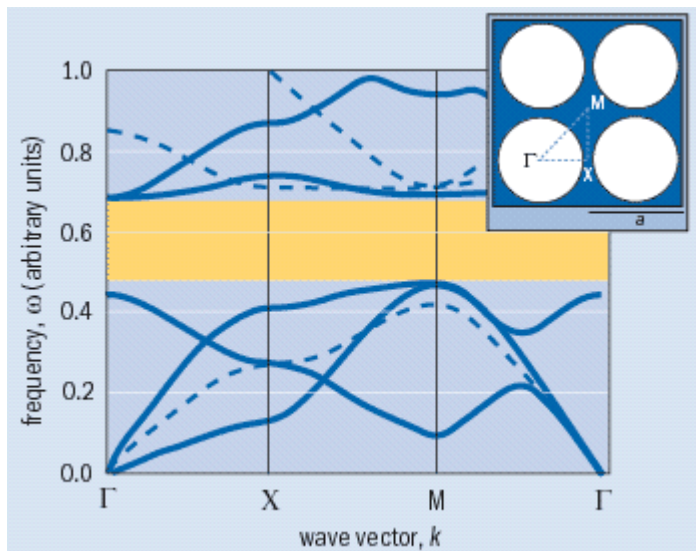
Penrose
volume
tessellation



Single and Dual
Hyperbolic Tessellations

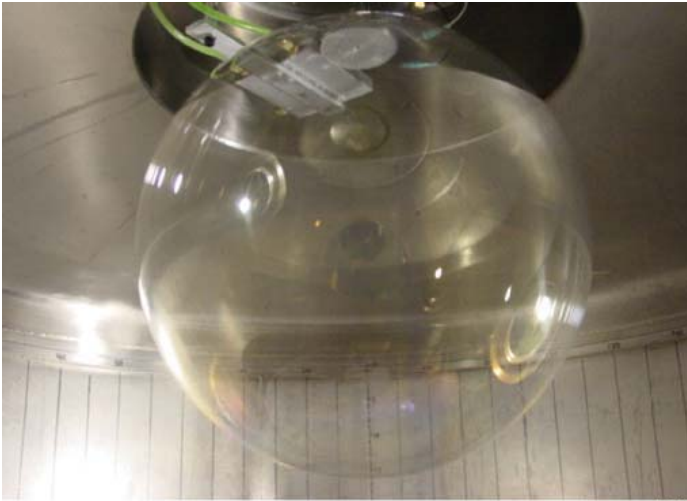
Phononic Crystals

- Of the many analogies to electronic and photonic bandgap structures available through the use of phononic crystals, we are interested here in forbidden frequency bands of mechanical vibration
- By tailoring periodic structures of holes and material, it is possible to create forbidden eigenvalue ranges for suppressing resonances and stiffening



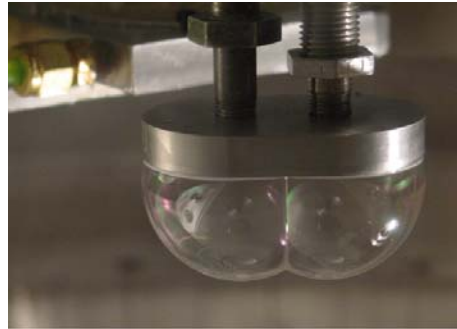
"This kinematic sculpture by Eusebio Sempere consists of a periodic array of hollow stainless-steel cylinders, each 2.9 cm in diameter, arranged on a square 10×10 cm lattice. In 1995 researchers at the Materials Science Institute of Madrid showed that the sculpture strongly attenuated sound waves at certain frequencies, thus providing the first experimental evidence for the existence of phononic band gaps in periodic structures. **

Bubble Experiments I

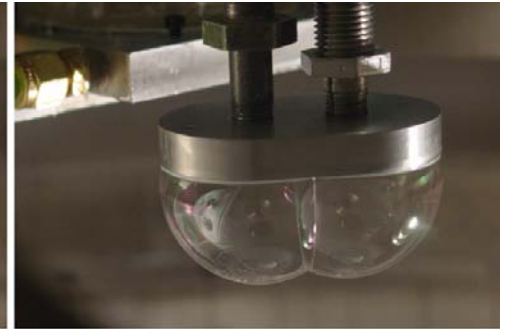


F-8241

Demonstrated 70-cm rigid bubble created in a laboratory vacuum



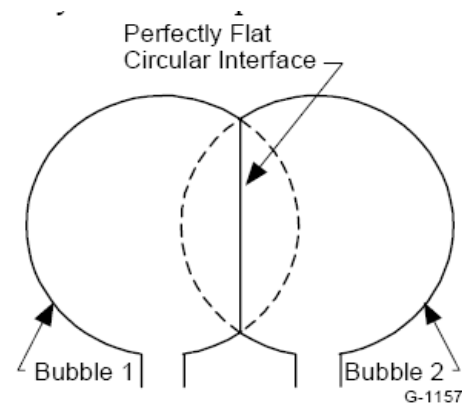
(a)



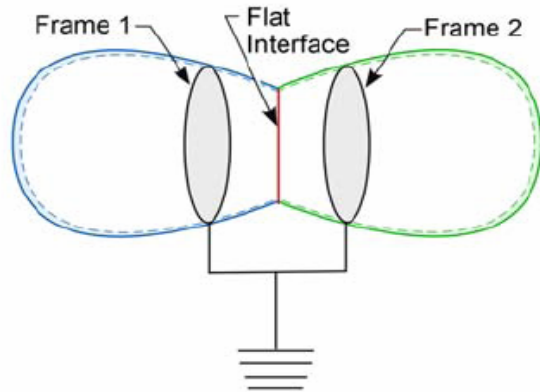
(b)

F-8261

Demonstrated spherical bubbles with either flat or tailored curved surface interfaces between bubbles in contact



Bubble Experiments II



(a) Concept Schematic



(b) Rigidized Polymer Bubbles Intersecting Within Two Wire Frames



(c) Excision of Unneeded Material

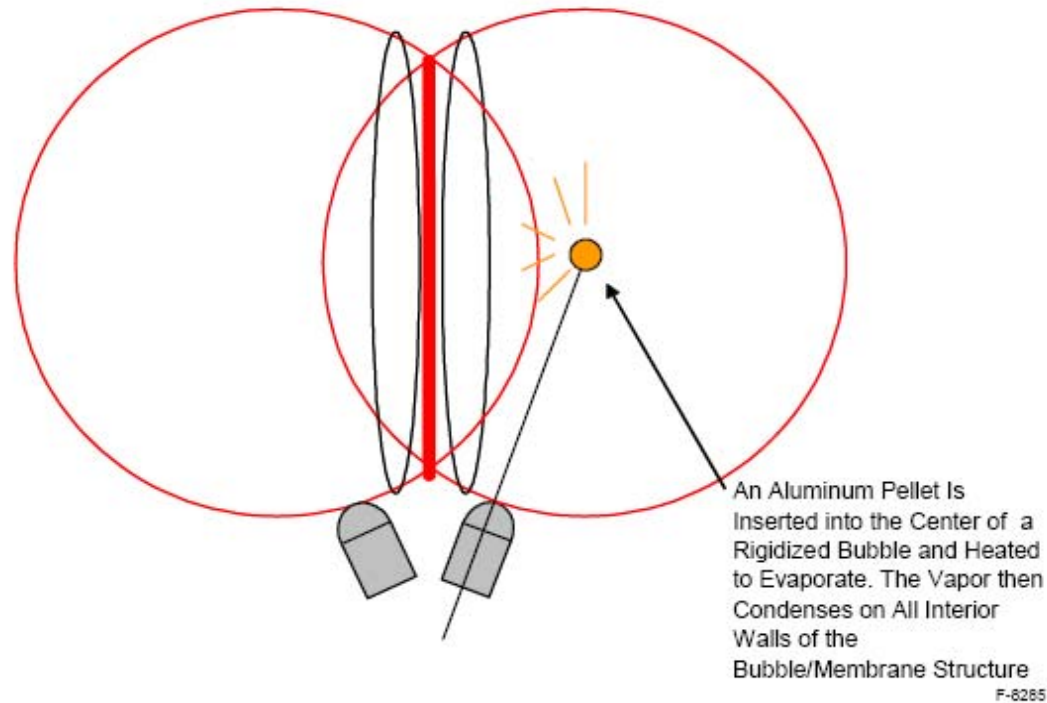


(d) Structurally Supported Rigidized Interface

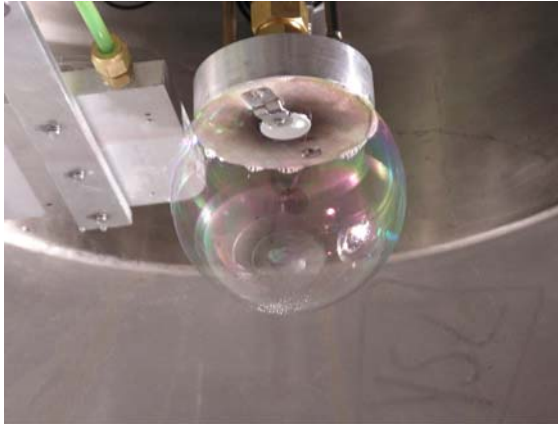
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Demonstration of the fabrication of structurally supported solar sails by intersecting and rigidizing two polymeric bubbles between wire hoops

Concept for creating a reflective solar sail by metal vapor deposition

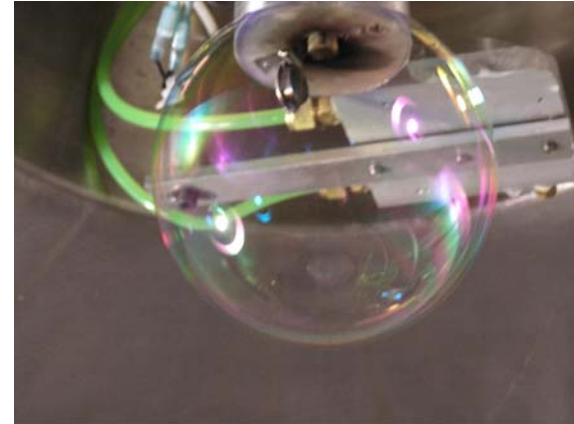


First Metallization Experiment



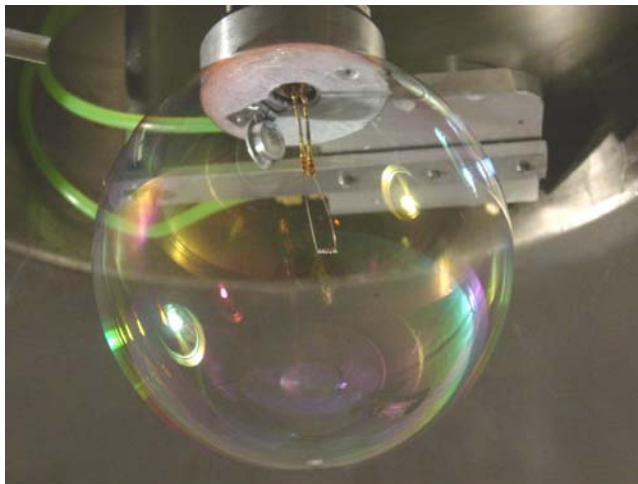
J-0054

(a) Picture of a UV-rigidized bubble in vacuum chamber prior to beginning metallization (trap door closed)



J-0055

(b) Bubble with trap door open



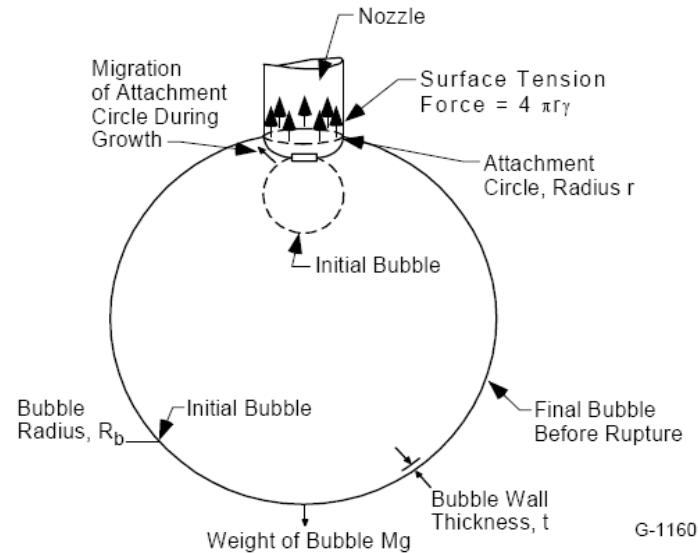
J-0057

(c) Metallization filament inserted into the bubble



(d) Bubble metallized with zinc (note reflection)

Scaling Up I

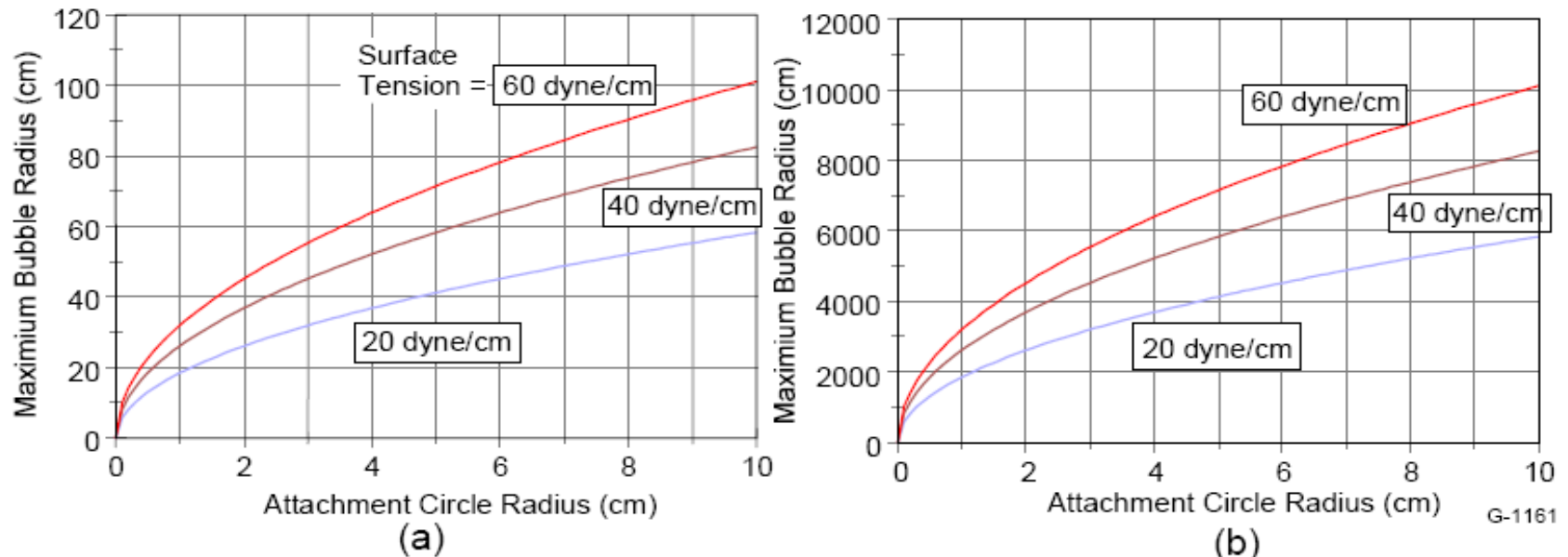


We can estimate the largest bubble radius in a gravitational field by balancing the weight of the bubble against the surface tension force along the circumference of the circle that defines the attachment of the bubble to the injection nozzle:

$$R_{b_{\max}} = \sqrt{\frac{r\gamma}{\rho g t}}$$

where r = attachment circle radius, $R_{b_{\max}}$ = maximum bubble radius before rupture, γ = surface tension of polymer liquid, ρ = liquid density, g = acceleration due to gravity, and t = bubble wall thickness.

Scaling Up II

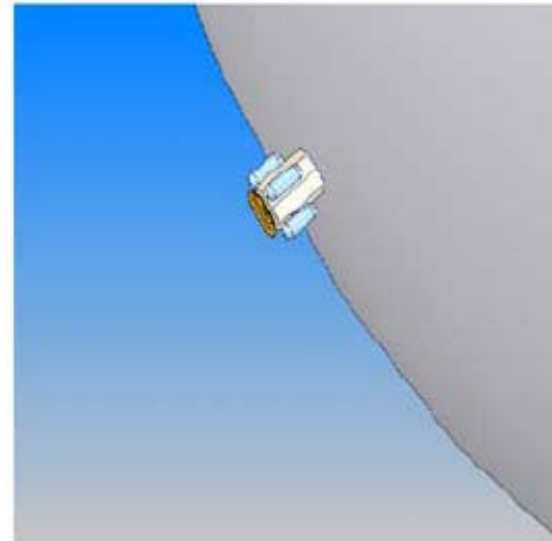
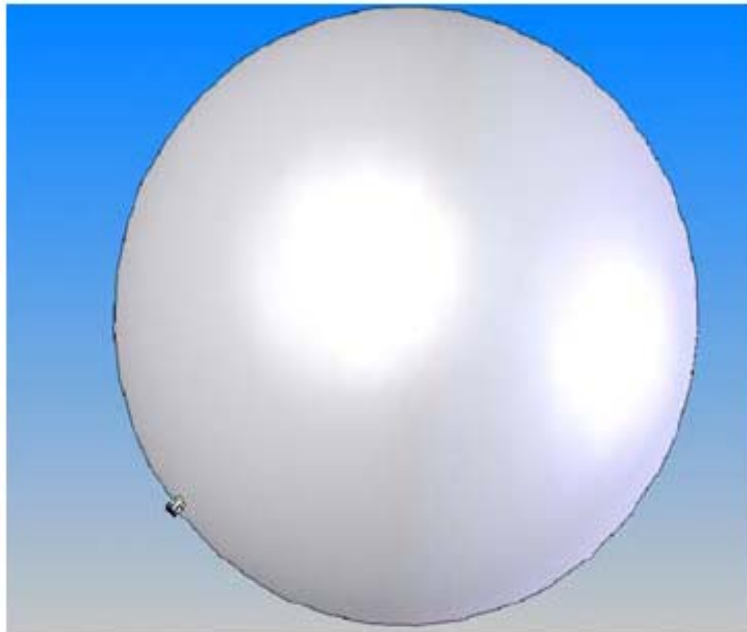


Effect of gravity on maximum bubble size before rupture.
(a) Earth gravity (1 g); (b) Low earth orbit ($10^{-4}g$)

100-m radius attachment => 100 km bubble

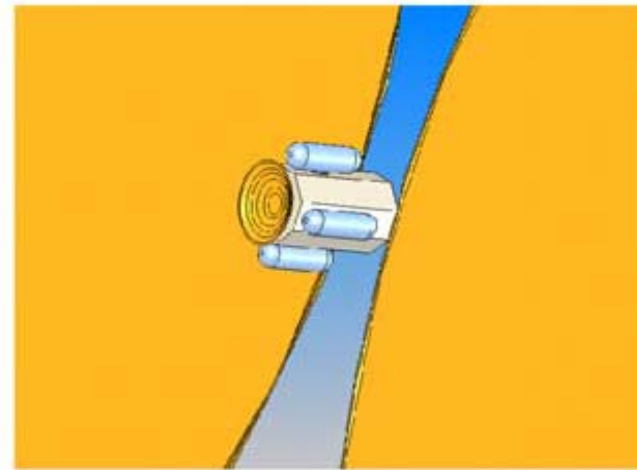
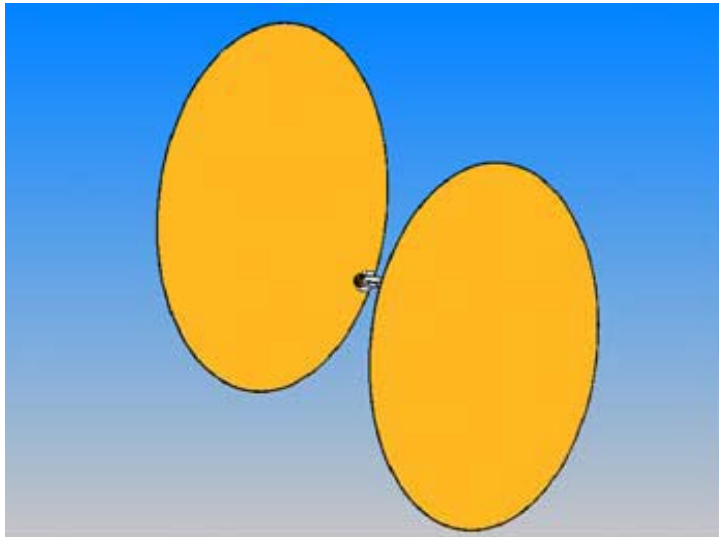
A reflective spherical bubble sail propelling a spacecraft (Bubble diameter ~ 100 m).

(The spacecraft is shown 5X larger than scale to aid visualization.)



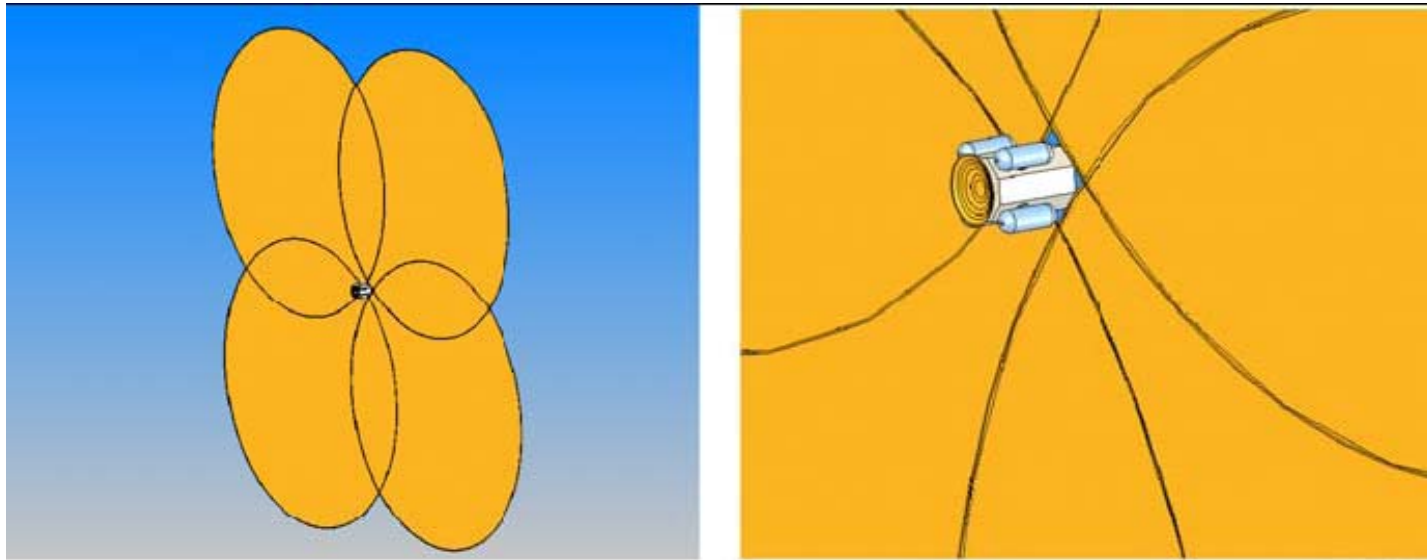
Twin flat sails (~100 m diameter each) propelling a spacecraft.

(The spacecraft is shown 5X larger than scale to aid visualization.)

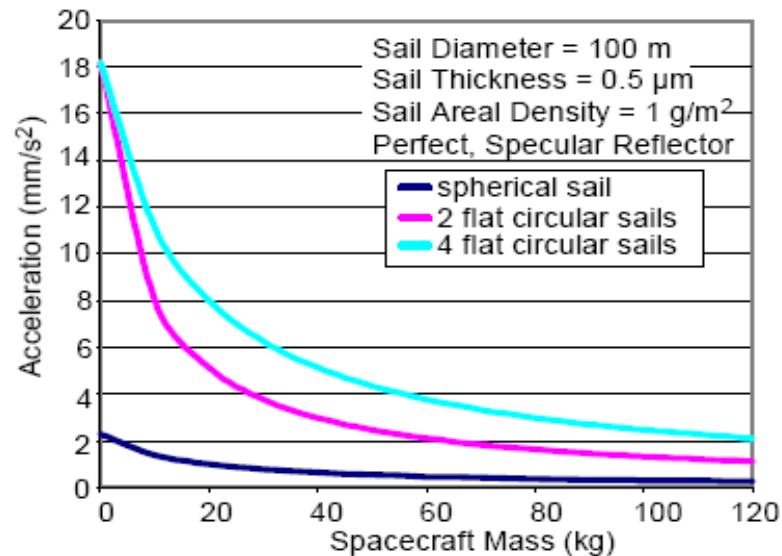


Four flat sails (~100 m diameter each) propelling a spacecraft.

(The spacecraft is shown 5X larger than scale to aid visualization.)



Sailcraft Acceleration



Sailcraft acceleration versus spacecraft weight and sail loading for various sail configurations.

Plans for NIAC Phase 2

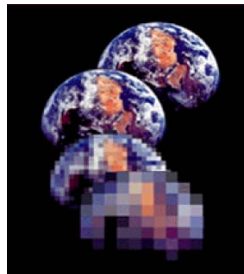
- Phase 2 is intended to combine Mission Designs with further laboratory development
- Webster Cash has agreed to join the team for Phase 2 to integrate the concept into both the New Worlds Imager and one additional mission concept to be called Maxim
- Antoine Labeyrie has contributed suggestions for large space telescope applications that include the Hypertelescope
- One Phase 2 goal is to lay the foundation for flight missions for Block 2020

More Plans for NIAC Phase 2

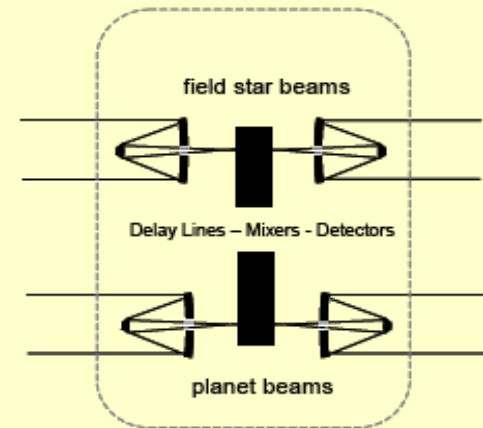
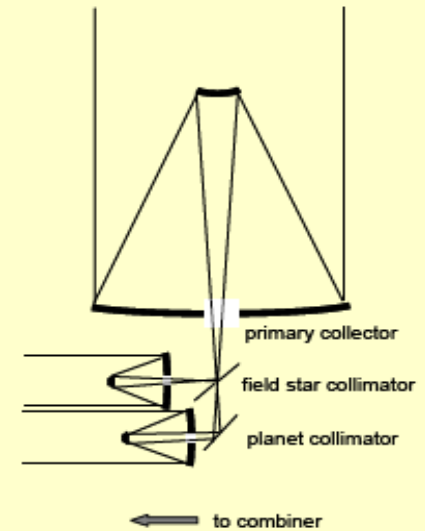
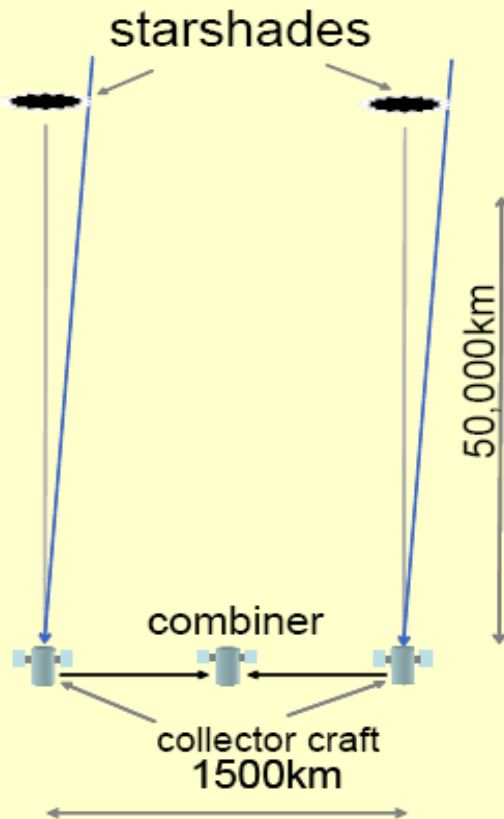
- New Worlds Imager mission planning will be examined with the goal of incorporating low mass components to gain advantages that include:
 - More star shades in one launch for increased search rate by looking in one direction while other shades are maneuvering.
 - More Star shades for spares.
 - More star shades to serve more telescopes to increase the search set.
 - A lower mass, lower cost mission alternative.
 - The technology can also make lower mass mirrors of any conical and some non-conical shapes.
- Web Cash has another mission called Maxim in the planning stages that will also be included

New Worlds Imager Application

- NWI uses star shades to allow viewing of extrasolar planets
- Formation maintenance is a major issue
- Launch mass is a major issue
 - Foam deployment of 35-meter star shades
- Foam technology addresses each of these issues
- Low mass enables a lower cost NWI or multiple NWI's for increased search rate
- Combine with the Hypertelescope concept to further address these issues

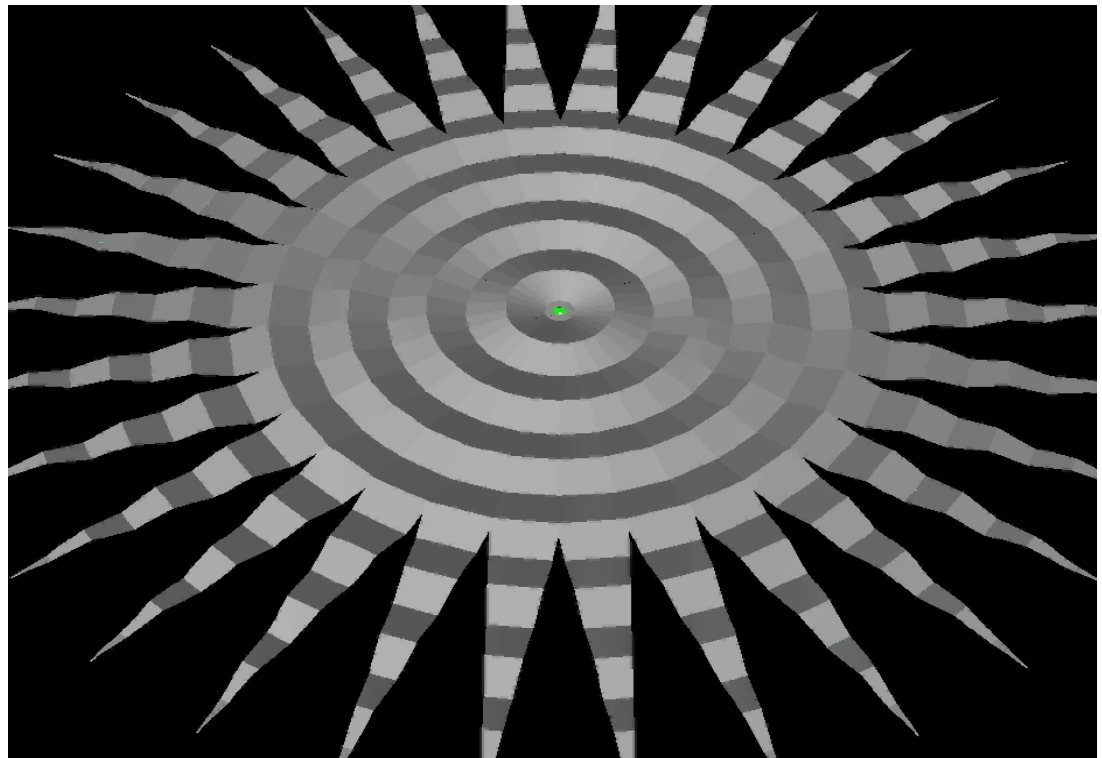
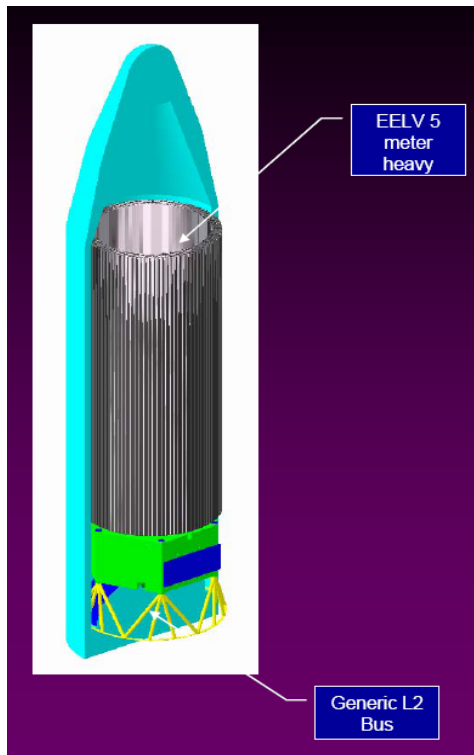


NWI Concept



Star Shade Mass Reduction

- Reduction by orders of magnitude in launch volume and launch mass

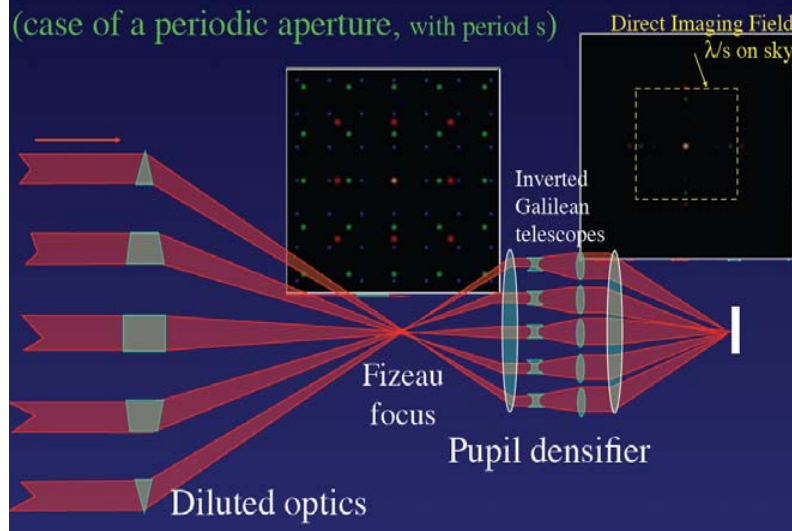


Hypertelescope Concept

- A natural application of the extremely large low mass spherical bubble fabrication technique is the Hypertelescope
- The Hypertelescope combines the low mass high resolution features of an interferometer with the image quality of a filled aperture
- Antoine Labeyrie has devised coronagraphic concepts for the application to direct extra-solar planetary imaging

Principle of hypertelescopes

(case of a periodic aperture, with period s)



The ultimate space observatory ? A static « bubble » interferometer

- Diluted mirror sphere
- Focal sphere explored with mobile beam combiners
- Central metrology unit

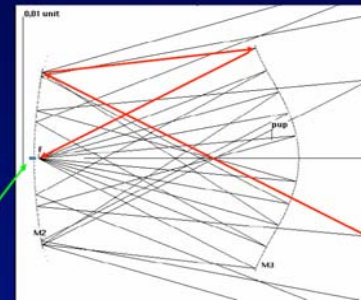


Diluted clam-shell corrector for the Exo-Earth Imager

1 km diameter for a 100 km Exo-Earth Imager

- Flotilla of 20cm mirror elements
- Corrects spherical aberration at F/1 and coma

Pupil densifier and coronagraph



Figures Courtesy of Antoine Labeyrie

Hypertelescope Application

- Bubble sphere accurately defines optical element locations
- Aluminizing the bubble itself in selected locations creates the primary optical elements
- A filled aperture is possible in principle

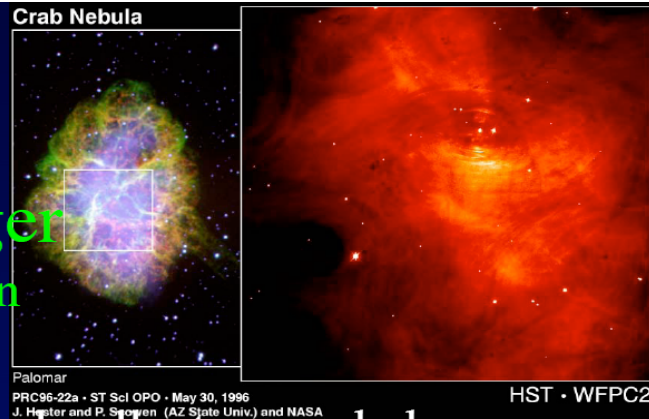
How Large is Useful?

Next step ?

100,000 km

Neutron Star Imager

nano-arcsecond resolution

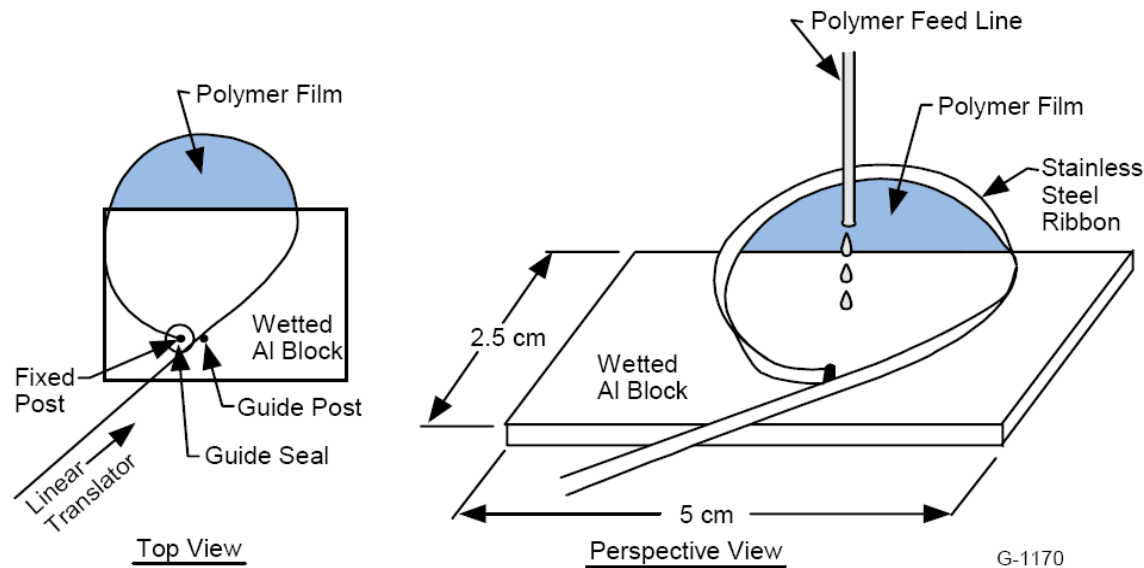


- Large apertures and focal collector needed...
- ...due to diffractive beam spreading from M1 to M2
 - Condition: $D_1 D_2 = \lambda L$
 - example: $D_1 = D_2 = 8\text{m}$ in yellow for $L = 100,000\text{ km}$
- Many photons/resel on Crab Pulsar
 - few on cooler stars

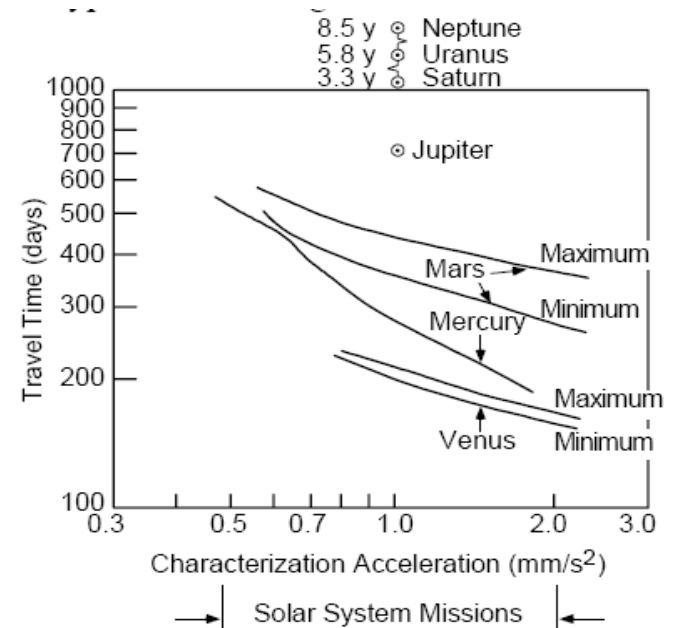
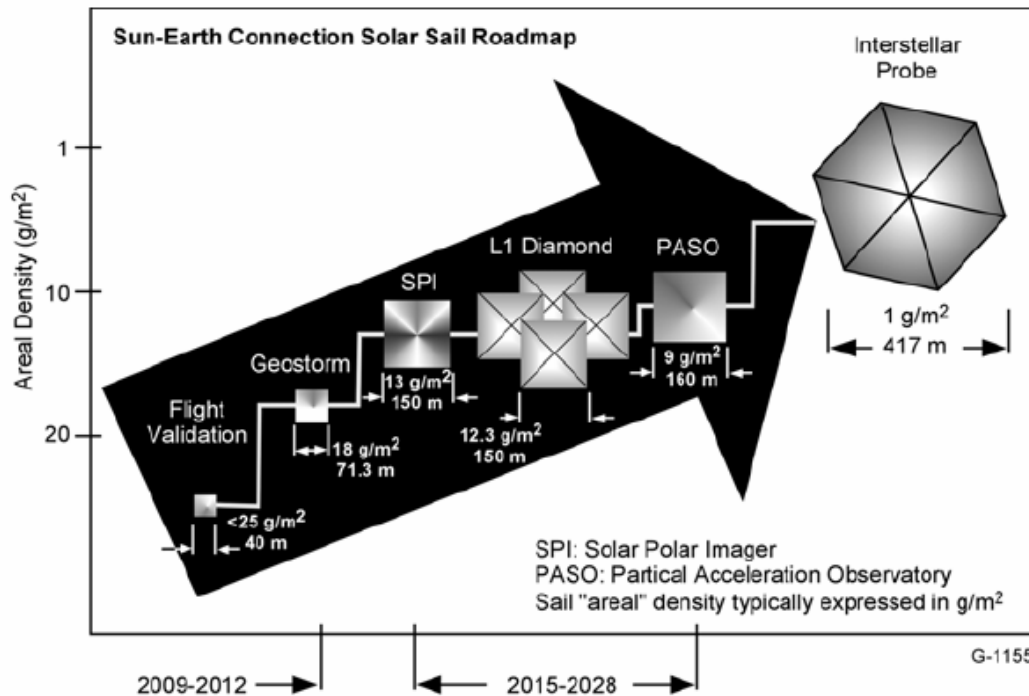
Figure Courtesy of Antoine Labeyrie

Solar Sails

- Phase 2 includes demonstration of flat surface fabrication
- Areal densities will be under the 1 gram/m² mission requirements



Solar Sail Mission Requirements



Summary

- Deployment of Rigid Bubbles has been demonstrated in the laboratory
 - Spheres
 - Flats
 - Curved surfaces
 - Theoretically Scalable to 100 km single bubble in low earth orbit
 - Theoretically Scalable to 1,000 km single bubble in deep space
 - Foam structural element span can far exceed single bubble in extent
- Suitability for selected missions has been analyzed
 - Solar sails
 - Extra solar planet imaging telescopes
- We propose to design missions in Phase 2 that could fly in the 2020 to 2030 mission planning period
 - New Worlds Imager (Web Cash)
 - Maxim (Web Cash)
 - Hypertelescope embodiments
 - Solar Sails
- We propose to demonstrate laboratory feasibility of miniature mission prototype structural elements and optical surfaces