Ultra-Light Solar Sail for Interstellar Travel

Phase I

Presented to:
NIAC
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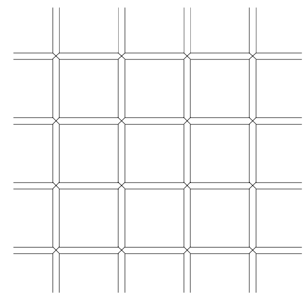
Scope of Phase I Work

- **Objective**
  - **Analyze Capabilities of an Ultralight Solar Sail Using a Nanogrid of Reflector Material without a Plastic Backing (Similar to a Nanoscale Antenna Mesh).**

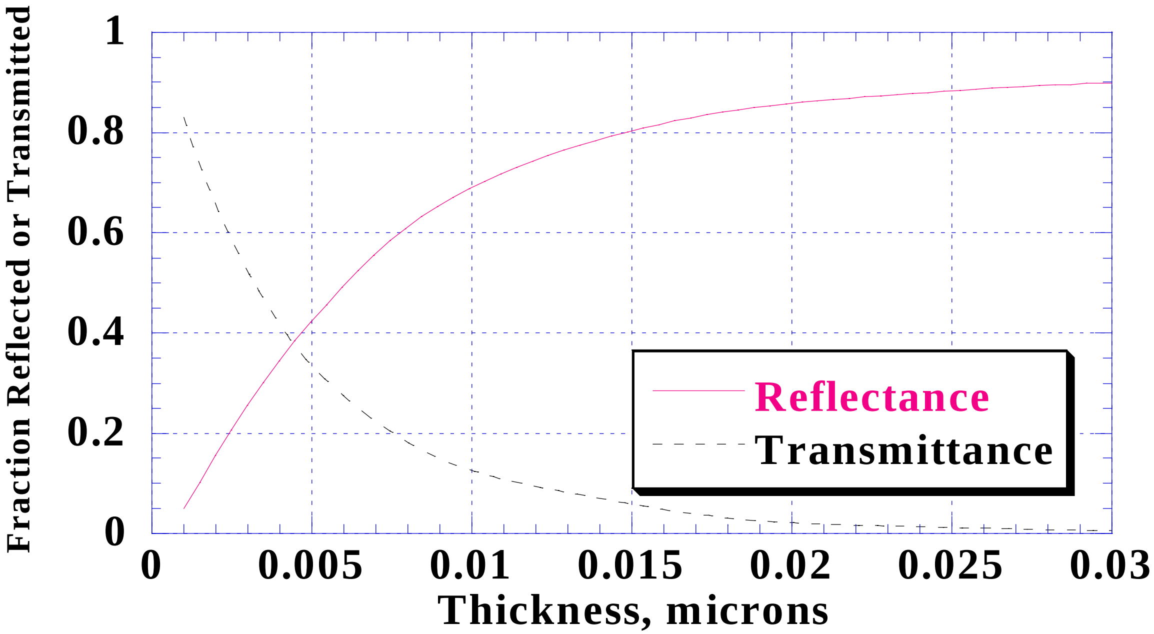


(Not drawn to scale)

- **Approach**
  - **Develop Equations for the Reflectivity of a Nanogrid of Wires.**
  - **Analyze Engineering Constraints of Dimensions and Strength.**
  - **Address Operational Issues of Deployment and Control.**
  - **Determine Manufacturing Technologies Required for Fabrication.**
  - **Develop a Phase II Plan to Demonstrate Key Fabrication Technologies and Verify Basic Concepts.**
  - **Present Briefing and Final Report.**

Physics Issues

- **Develop Equations for the Solar Reflectivity Off a Nanogrid.**
  - **Rigorous Treatment**
  - **Compare to Lower Frequency Treatments by Marcuvitz (1951) and Forward (1985), Extrapolated to Visible**
- **First, Obtain a Baseline for the Solar Reflectivity Off a Solid Sheet without a Plastic Backing.**



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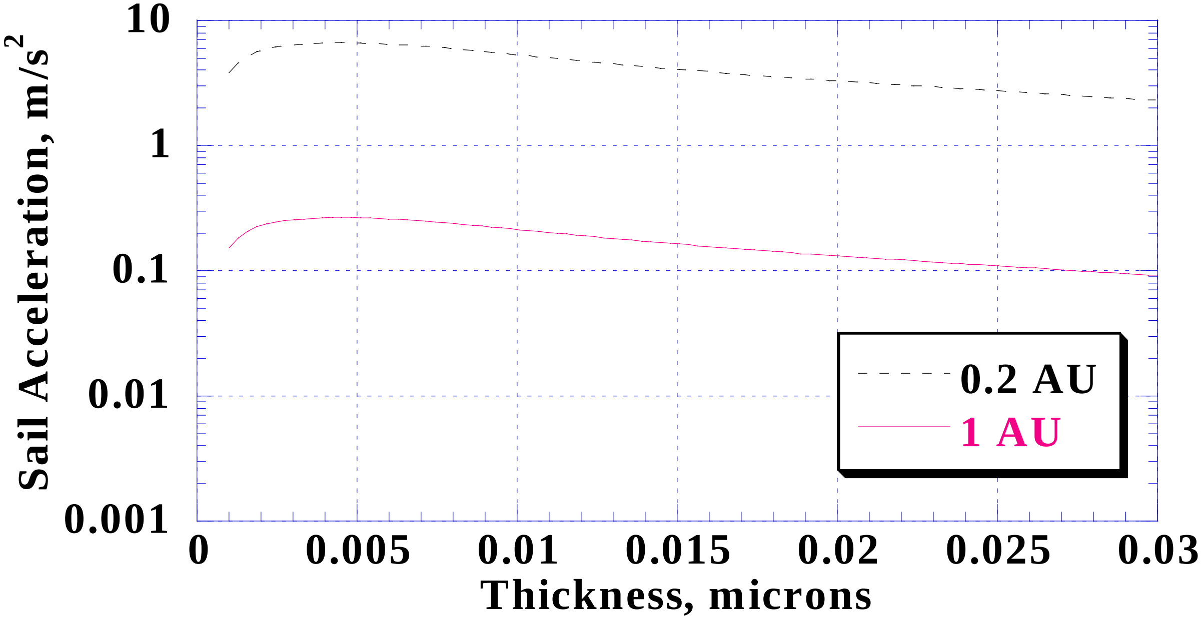
Nanoscale Aluminum Sheets Achieve a_c~0.3 m/s^2

- **Although Reflectivity Reaches a Maximum Above 30 nm Thickness, an Optimum Thrust-to-Mass Ratio (i.e., Acceleration) of ~0.3 m/s^2 Occurs at Only a Few Nanometers Thickness at 1 AU.**



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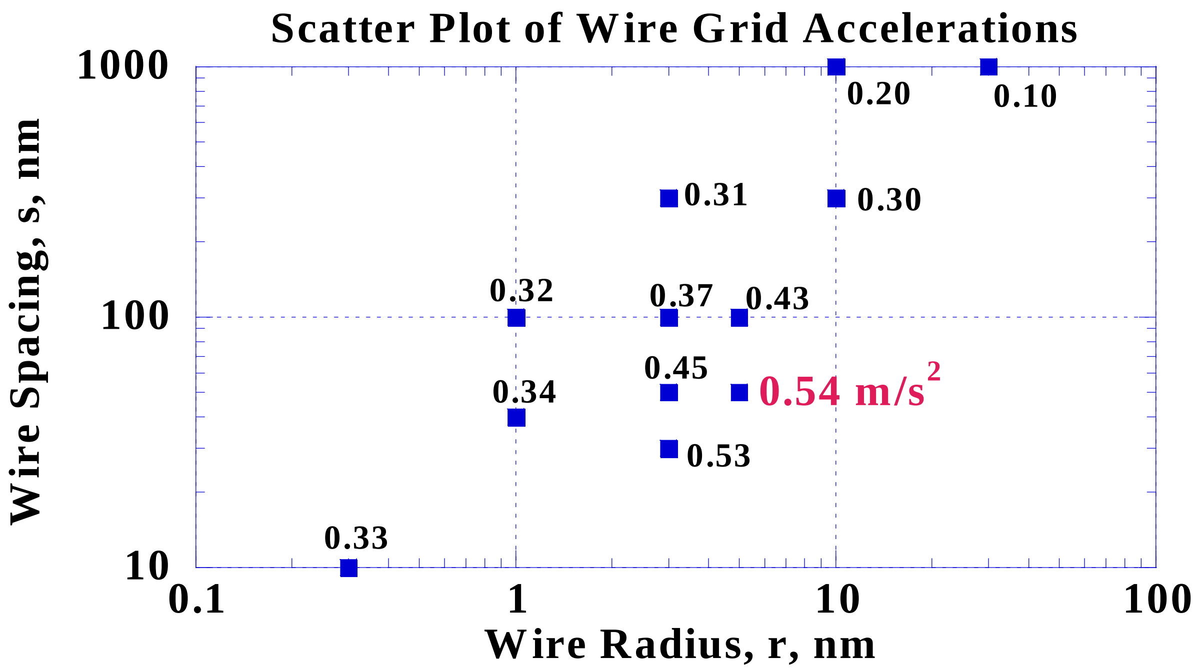
Multi-wire Analysis Results in $a_c > 0.54$ m/s^2

- **Solution of Maxwell's Equations for Reflection Off a Grid of Wires with Finite Electrical Conductivity (see Progress Report #3, October 1999).**
- **Best Acceleration: Radius = 5 nm, Interwire spacing = 50 nm**
  - **Not yet optimum, due to convergence issues at other values**



(Analysis by Dr. Cindy R. Christensen)

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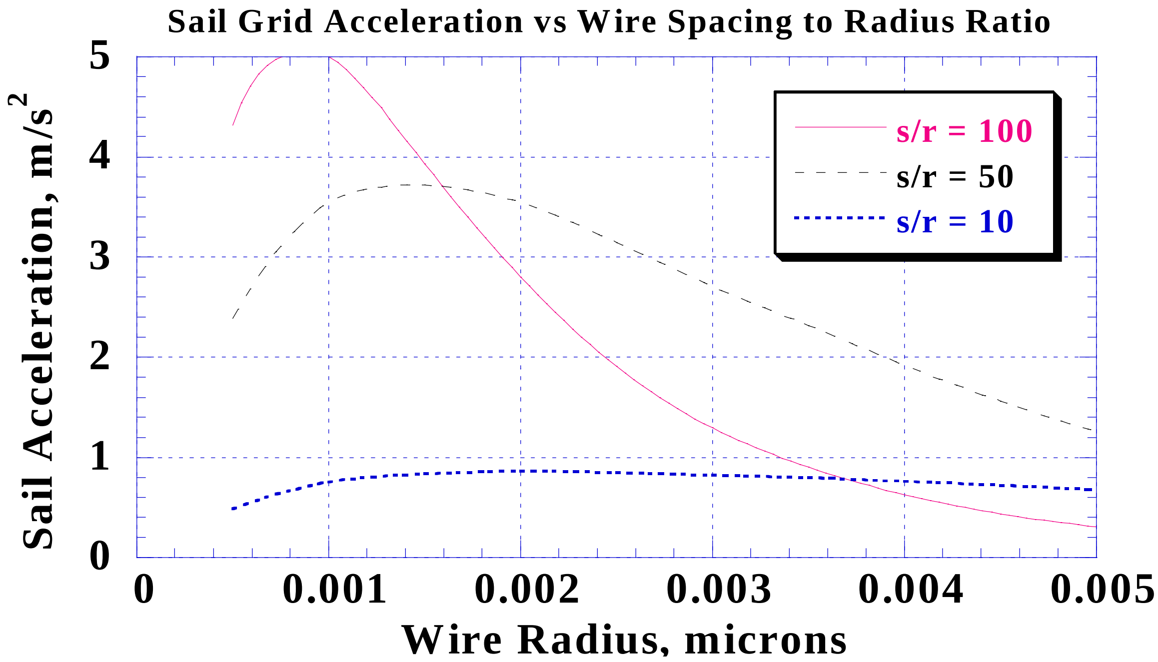
Multi-wire RF Analogy Results in a_c ~5 m/s^2

- **Extension of Marcuvitz's (1951) Equations from Microwave to Visible Frequencies, with Uncoupled Thickness Factor, see p 3.**
- **Close Agreement with Forward's (1985) Equations for s/r<20.**
- **Yet >10X Higher Than Christensen's Analysis.**
- **Resolve Discrepancies via Fab and Test in Phase II.**



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Carbon Nanotubes as "Hollow" Wires

- **Start Out Analysis with "Hollow" Wires.**
  - **For graphite, best thrust to mass is 0.18 m/s^2.**
    - » **DC conductivity of nanotubes is only half that of bulk aluminum**
- **Then Dope the Graphite Nanotubes.**
  - **With doping, conductivity is greatly enhanced, Dekker (1999).**
  - **Best Answers:** **Radius = 1.38 nm, Spacing = 100 nm**
    Thrust to mass: 18 m/s^2
- **Conductively Coated or Doped Carbon Nanostructures Show Great Promise in the Far Term, for Its Low Mass and High Temperature Characteristics.**

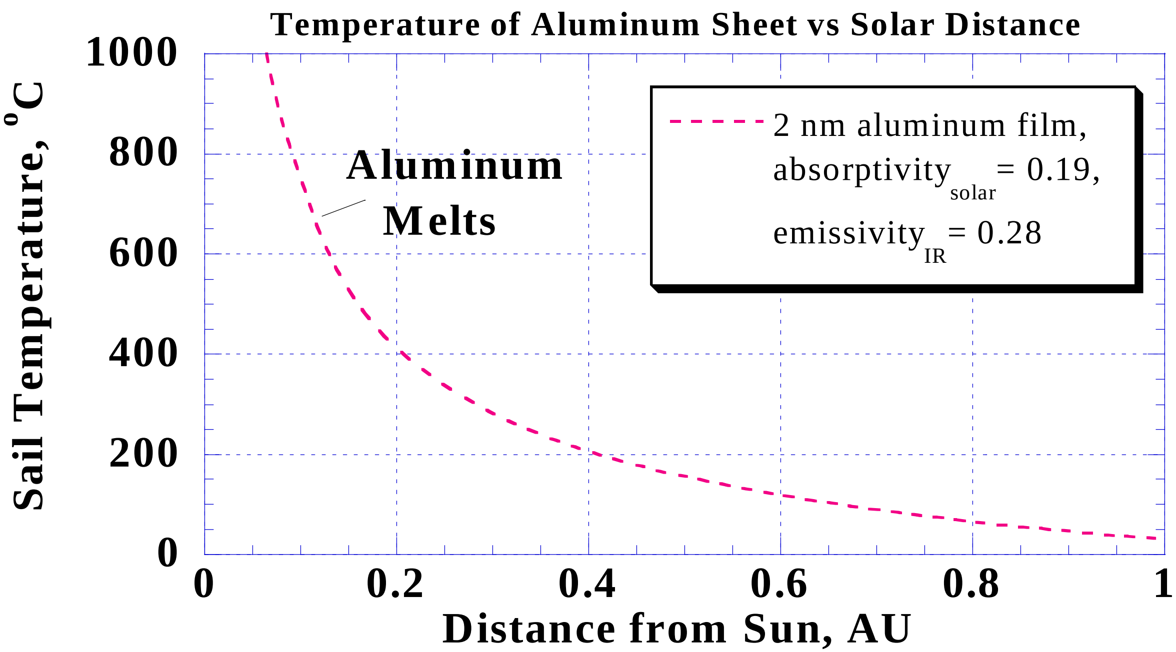
(Analysis by Dr. Cindy R. Christensen)

Engineering Considerations

- **Aluminum Foil Rips Rather Easily, and is 10,000X Thicker Than 1 to 10 nm Thick Ultrathin Solar Sails Analyzed.**
- **Can We Apply This Sheet or Mesh on a Plastic to Avoid Ripping for Handling, Storage, Launch, and Deployment, Then Allow the Plastic to Disintegrate or Outgas Once in Space?**
  - **Aluminized Mylar is Space Qualified, although with 100 nm Coating**
  - **Low E Coatings for Windows Involve nm Thick Coatings**
  - **Is There a Simpler Solution Than Using a Diamond-Like Coating Buffer Layer?**
- **Once Deployed in Interplanetary Space:**
  - **Metals are Very Stable to Radiation, Unlike Plastics**
  - **As Approach Sun, Perhaps Eventually to 0.2 AU**
    - » **Plastic Support Membrane Disappears - Must Cover Critical Payload Surfaces (Optics & Thermal Control) from Contamination**
    - » **Avoid Outgassing/ Melting of Aluminum with Solar Approach**
    - » **Watch Reduction in Tensile Strength with Temperature**

Ultrathin Aluminum Sails Can Survive Solar Approach

- **Ultrathin Sheet of Aluminum Can Survive Solar Equilibrium Temperature at 0.2 AU.**
- **Desirable α/ε Ratio for Thermal Control at a Few Nanometers Thickness. (Similar trends as for chromium, which is recommended on backside of conventional solar sail, i.e., emittance increases as approach nanometers thickness.)**



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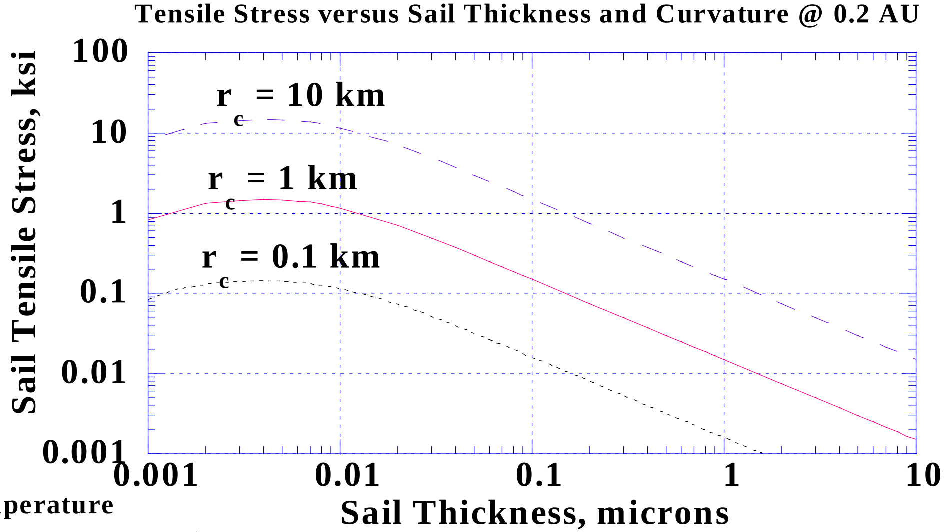
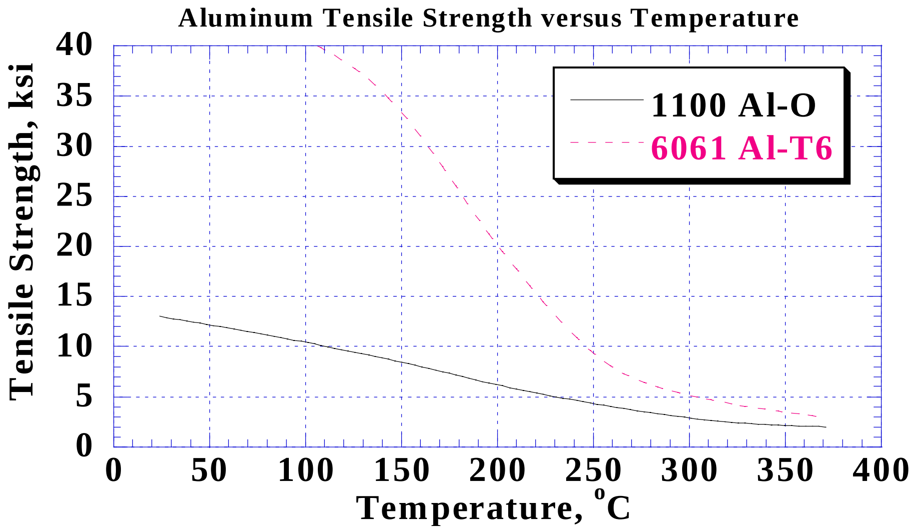
Ultrathin Aluminum Can Survive Solar Radiation Pressure

- Sail Radius of Curvature r_c Must Be < 1 km for Sheet @ 0.2 AU.
- Aluminum Grid Can Also Likely Survive Stresses.





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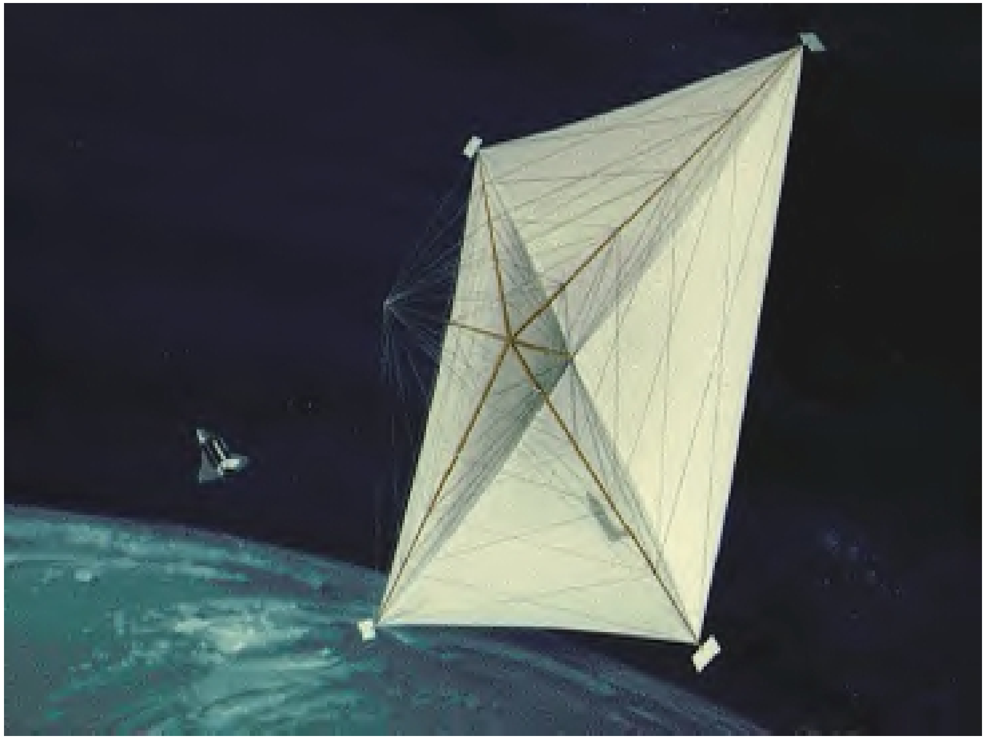
Operational Issues

- **Deployment and Control in Space**
  - **Deployment Comparable to Conventional Sail, as Strong Plastic Substrate is Intact During Deployment**
  - **Control Possibly Using Conventional Sail Technology**



Comet Halley Concept (NASA/JPL)

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Manufacturing Issues

- Manufacture in Space
  - Conceivable But Far Into the Future
  - Sail Size Can Be Much Larger than Manufactured Size on Earth
    - » Analogy to Spider Web in-situ Fabrication
- Manufacture on Earth
  - Substrate
    - » Low Temperature, Thin Plastic
  - Reinforcement
    - » Kapton Tape
    - » Embed High Temperature Netting with High Tensile Strength
  - Coating
    - » Several Nanometers of Aluminum
    - » Examples: Aluminized Mylar or Kapton, or Window Film
  - Patterning
    - » e-Beam Lithography is Now Approaching Needed Scale
    - » Laser Drilling Scale May Be Too Large

Note: Nanotubes are also Under Development

Mission Analysis

- **Near-Term (within 10 years)**
  - nm Thin Aluminized Plastics, With Sail Plastic Disintegration, Reinforced with Kapton Tape and High Strength Cord
  - Within 0.2 AU of Sun with Accelerations ~10 m/s^2 (a_c~0.3 m/s^2)
  - Several Hundred Times Better Than Conventional Solar Sails with Only 2 micron Thick Kapton
- **Mid-Term (within 20 years)**
  - Large Scale Nanopatterning of Mesh-like Grid on Plastic
  - Characteristic Accelerations a_c~ 1 m/s^2, Analysis Ongoing
- **Far-Term (beyond 20 years)**
  - Large Scale Grid of Doped Carbon Nanotubes
  - Manufacture in Space Above 1000 km (to avoid drag & atomic O)
  - Solar Approach within 4 R_s (0.019 AU) and a_c> 10 m/s^2

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Mission Times to Interstellar Space

- **In Near-Term, Could Reach Pluto in ~100 days.**
- **In Mid-Term, Can Reach JPL Goal of 35 yrs for 10,000 AU Probe**
  - **Table Below Shows 27 yrs for 1 m/s^2 from 0.1 AU to 10,000 AU**
  - **Assumes Improvements in Mesh Technology (Phase II)**
- **Far-Term Technology, Possibly Using Carbon Nanotubes, May Reach 10,000 AU in 4 Years! Or α Centauri in a Century!**

Acceleration @ 1 AU with Payload, m/s^2	Closest Solar Approach, AU	Terminal Velocity, km/s	40 AU Pluto Mission, days	10,000AU Mission, yrs
0.3	0.2	671	102	71
1.0	0.1	1,733	40	27
10	0.019 (4 Rs)	12,572 (4.2%c)	6	4

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Phase II Proposed Tasks

- **Task 1 - Nanometer Class Solar Sail Sheet**
  - Vacuum Deposit 2, ..., 10 nm Thick Films on Plastic Substrate.
  - Attempt Plastic Decomposition in Thermal-Vacuum Chamber.
  - Measure Optical & Mechanical Properties After Test, to Verify Over 100X More Acceleration Than Conventional Sail Technology.
- **Task 2 - Nanometer Grid Reflector Solar Sail**
  - Update Nanogrid Analysis for Various Geometries and Materials.
  - Pattern Grid Using e-beam Lithography or UV Lasers.
  - Measure Solar Absorptance, BRDF, Emittance versus Grid Geometry.
- **Task 3 - Fastener and Rip Stops - Integrate with Sail so It Does Not Decompose.**
- **Task 4 - Carbon Nanostructures Solar Sail Analysis.**
- **Task 5 - Final Report & Update Interstellar Mission Implications.**

Summary

- **Ultralight Aluminum Solar Sails, without a Plastic Backing, Have Orders of Magnitude Improvement Over Conventional Solar Sails with a Plastic Backing.**
- **High Characteristic Accelerations @ 1 AU**
  - **Thin Aluminum Membranes ~0.3 m/s^2 vs 0.001 m/s^2 Conventional**
  - **Aluminum Nanowires ~0.6 m/s^2, Possibly Much Higher**
  - **Doped Carbon Nanotubes >10 m/s^2**
- **Fantastic Velocities to Interstellar Space**
  - **Aluminum Membranes to ~1000 km/s – 10,000 AU within a Lifetime**
  - **Carbon Nanostructures Possibly to ~4%c, α Cen in a Century**
- **Strong Experimental Program Recommended**
  - **e-Beam Lithography of Nanoscale Reflectors**
  - **Optical Measurements of Fabricated Reflectors**
  - **Thermal-Vacuum Tests with Enhanced UV & Heat to Ascertain Clean Removal of Various Plastics**

Key References

- **N. Marcuvitz (1951), *Waveguide Handbook*, MIT Rad. Lab. Ser. , McGraw-Hill, New York, p 286.**
- **W.M. Rowe, et. Al. (1978), "Thermal Radiative Properties of Solar Sail Film Materials," AIAA Paper 78-852.**
- **Robert Forward (1984), "Roundtrip Interstellar Travel Using Laser-Pushed Lightsails," J. Spacecraft and Rockets, Vol. 21, No. 2, pp 187-195.**
- **Robert Forward (1985), "Starwisp: An Ultra-Light Interstellar Probe," J. Spacecraft and Rockets, Vol. 22, No. 3, pp 345-350.**
- **Robert Forward (1990), "Light-Levitated Geostationary Cylindrical Orbits: Correction and Expansion," J. Astronautical Sci., Vol. 38, No. 3, pp 335-353.**
- **C.R. McInnes (1999), *Solar Sailing*, Praxis Publishing, UK.**
- **Cees Dekker (1999), "Carbon Nanotubes as Molecular Quantum Wires," Physics Today, May 1999.**