Knudsen-Pump-Based Propulsion for Atmospheric and Martian Exploration

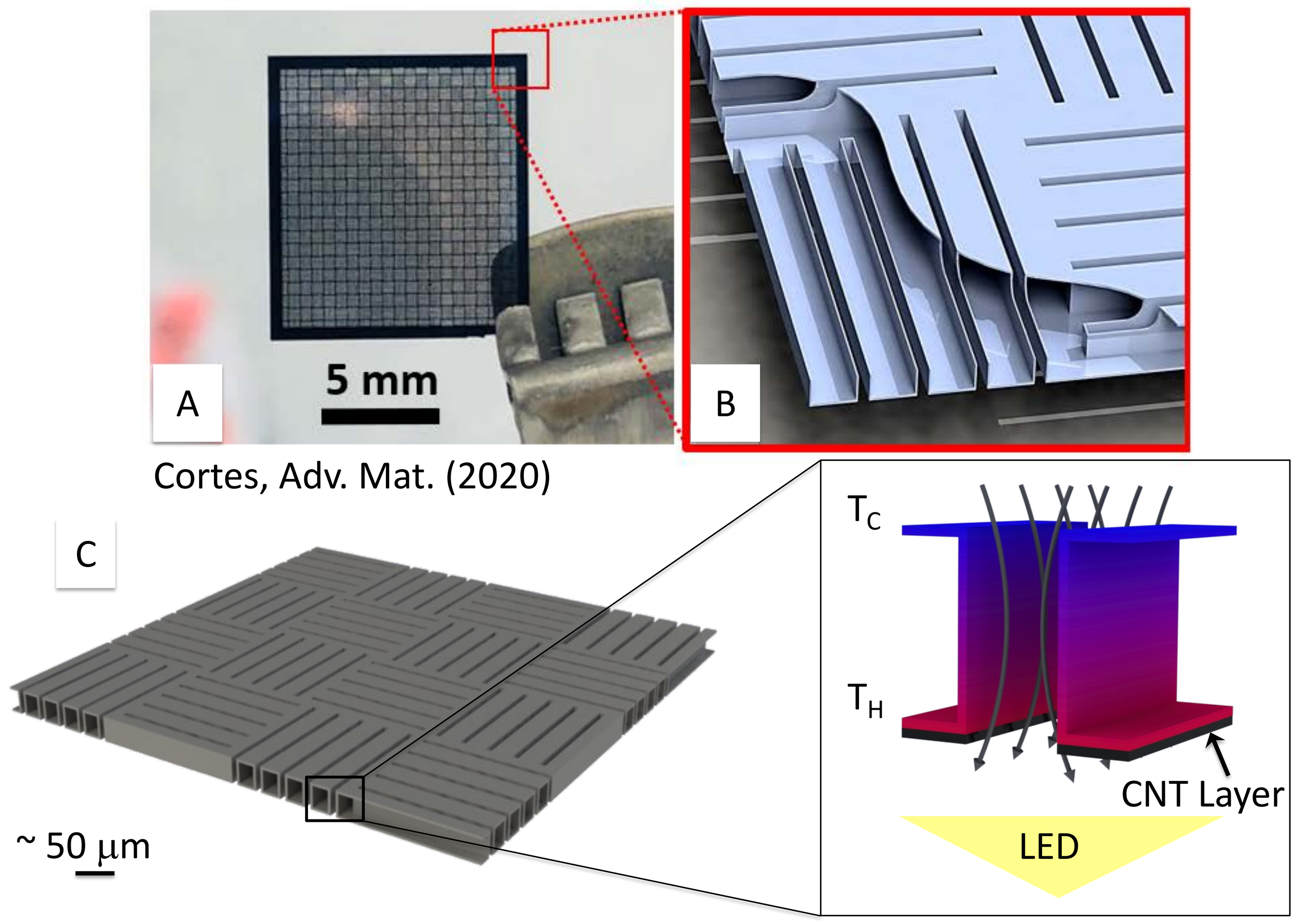
Thomas Celenza, Andy Eskenazi, Zhipeng Lu, Lorenzo Yao-Bate, Igor Bargatin

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania

Abstract

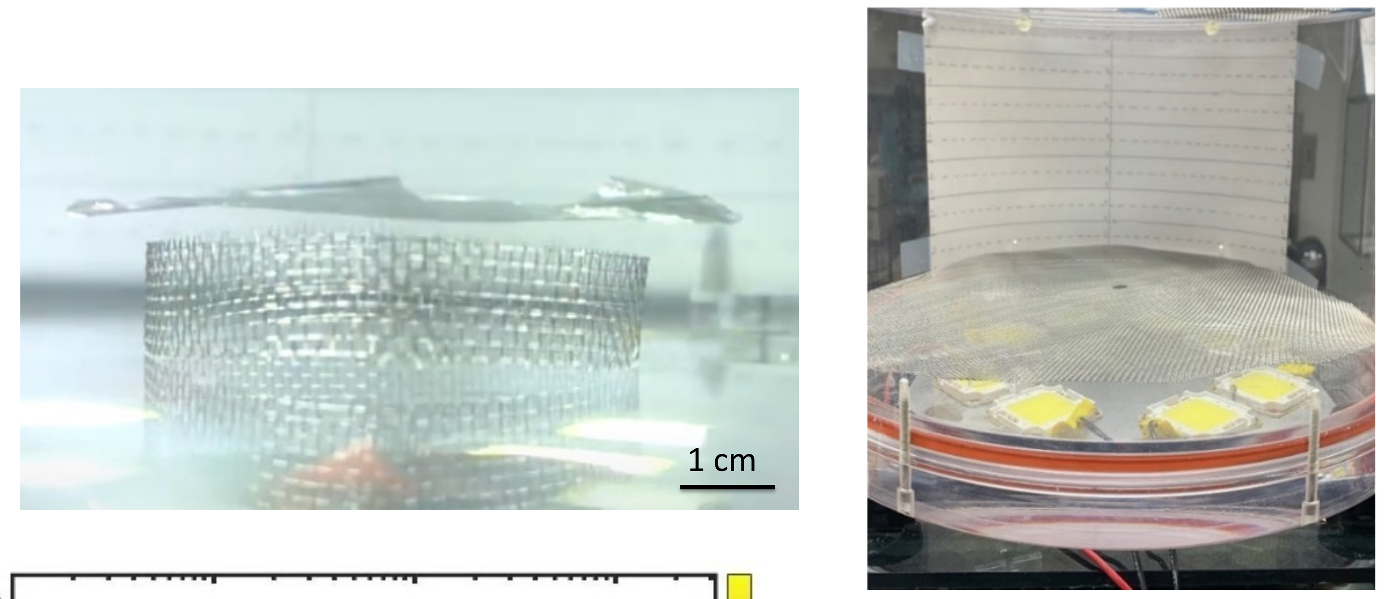
The mesosphere has air pressures too low for aerodynamic flight and too high for satellites, making in situ measurements, and therefore climate modeling, extremely difficult. We propose a flight mechanism using only light, optimal for these air pressures, that would allow for kilogram-scale payloads. The lift force is created through Knudsen pumping in meter-scale ultralight structures made of "nanocardboard." Applications include GPS tracking of winds, temperature measurements, gas species concentrations, and more.

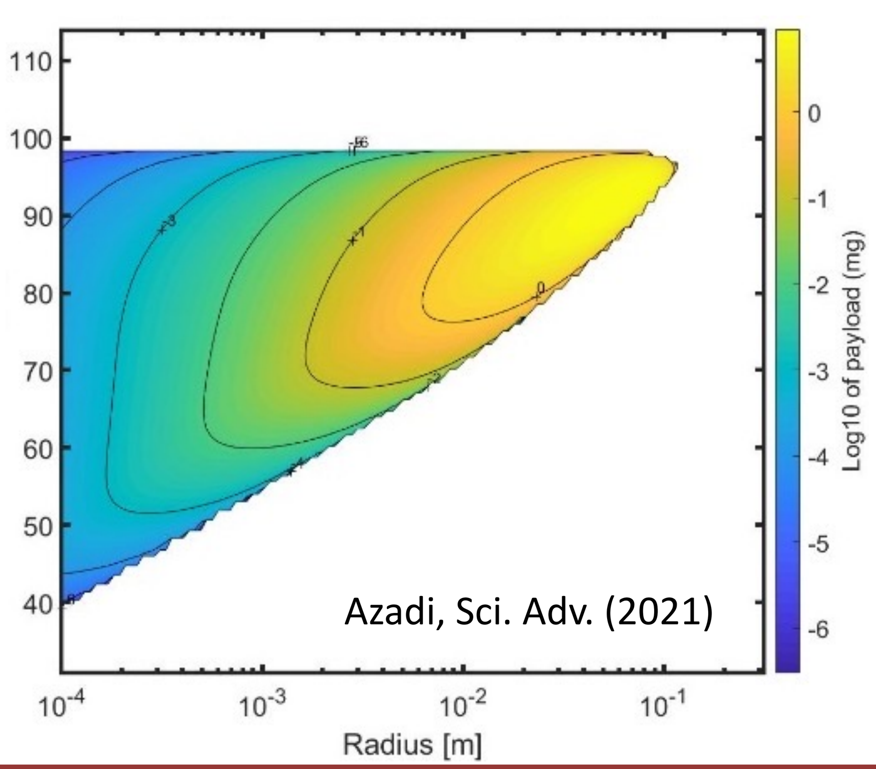
Introduction



Cortes, Adv. Mat. (2020)

Nanocardboard is a microfabricated analog of sandwich composites, made of nanoscale sheets connected by microscale channels. The channels exploit temperature difference created by carbon nanotubes on the bottom absorbing light, driving air downward and creating lift, also called the **photophoretic force.**



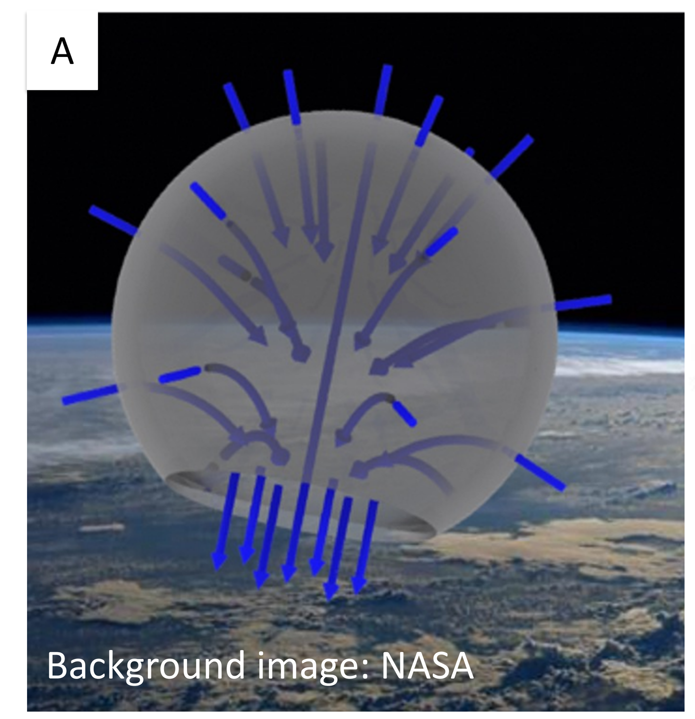


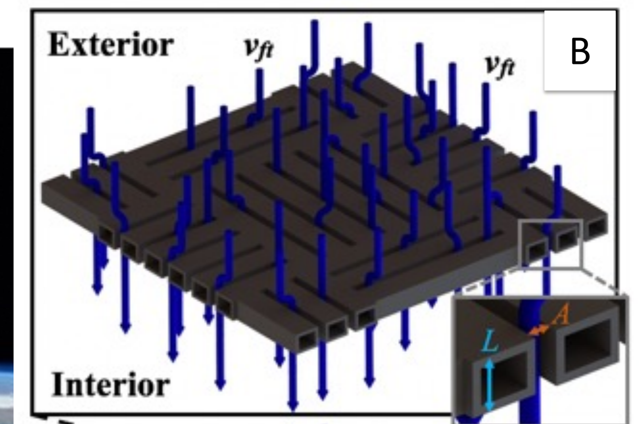
Azadi, Sci. Adv. (2021)

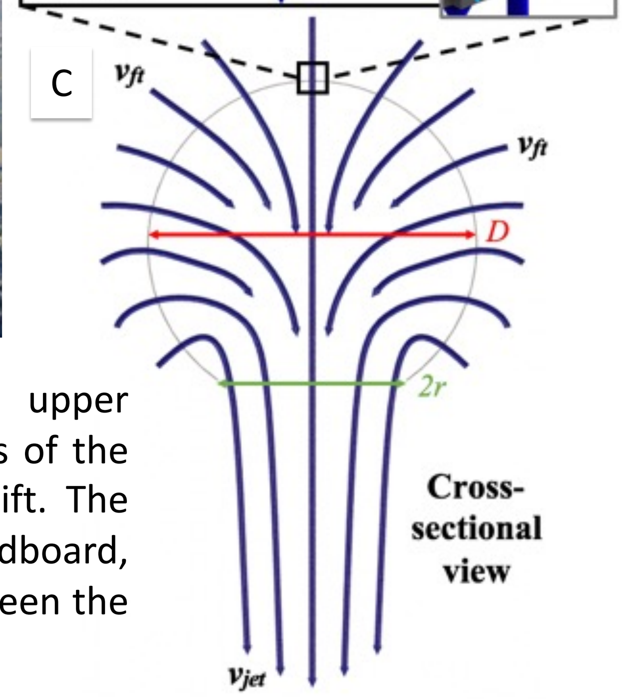
Above: Testing set up with LED array, steel mesh launch pad, and acrylic vacuum chamber for levitation tests with varying pressure and light intensity.

Left: Theoretical payload calculations for small disks on the milligram scale, which is enough for MEMS sensors, in optimal pressures of 1 – 1000 Pa.

3D Structures





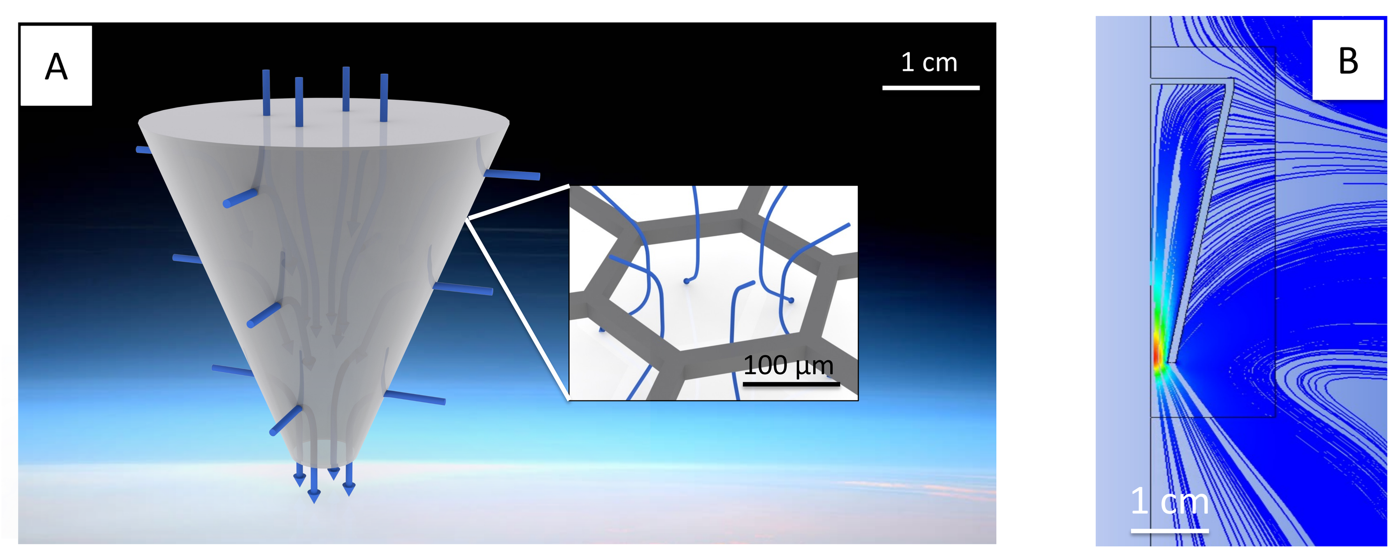


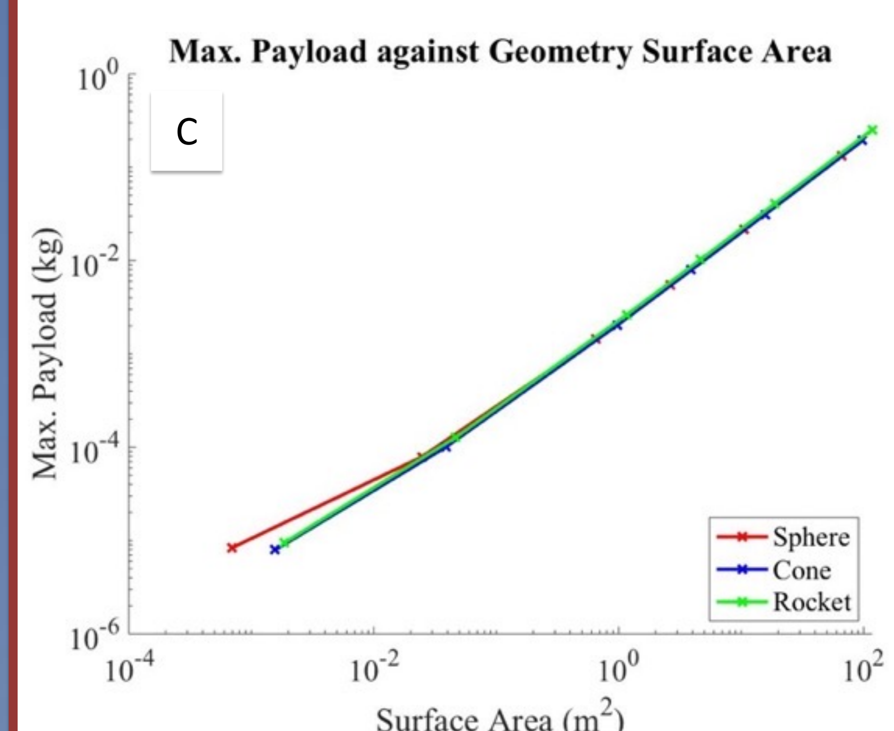
Spherical geometry rendering in the upper atmosphere, showing airflow through walls of the structure and out the exit for increased lift. The walls of the structure are made of nanocardboard, and the temperature difference exists between the outside and inner chamber.

For centimeter-scale disks, the payloads are too small to carry significant scientific instruments. However, if we transform the 2D plates and disks into 3D structures, the lift force increases by several orders of magnitude. We performed simulations and numerical analysis to confirm this at altitudes of 50 to 80 km where the Knudsen pumping mechanism is optimized. The characterizing equation is:

$$F = C_1 16 \mu R v_{in} + C_2 \rho A v_{jet}^2$$

Simulations



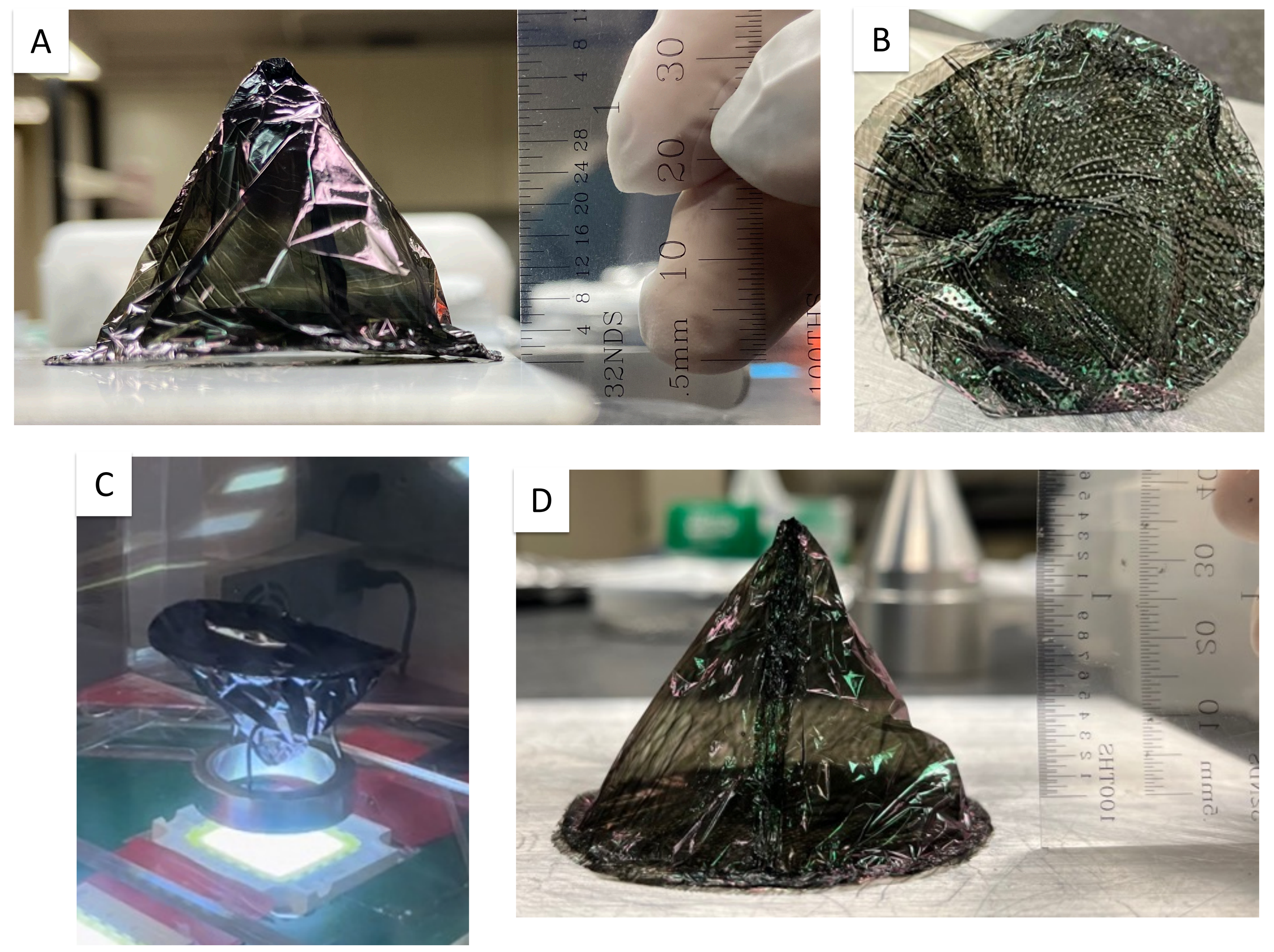


Above: Rendering and streamlines from ANSYS Fluent simulations which were used to characterize the lift by simulating various geometries with various overall dimensions.

Left: Numerical results were then used with the characteristic equation to optimize the structures for the ideal porosity parameters for different sized structures, showing kilogram-scale payloads that scale with surface area.

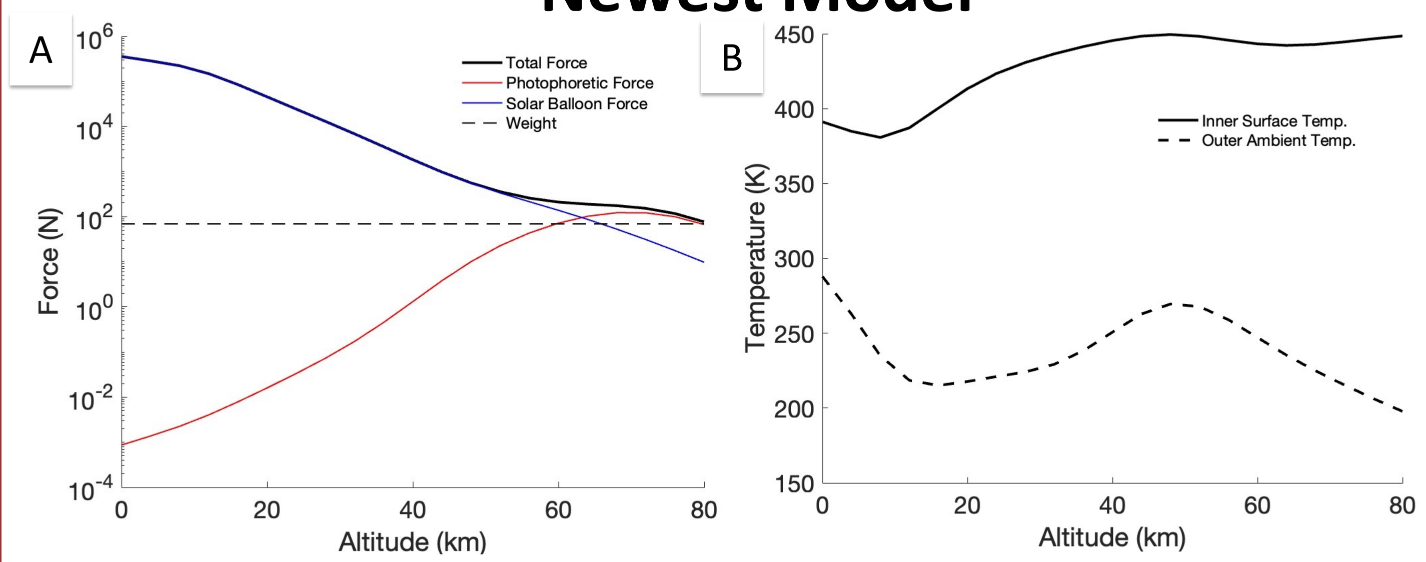
https://arxiv.org/abs/2301.04281

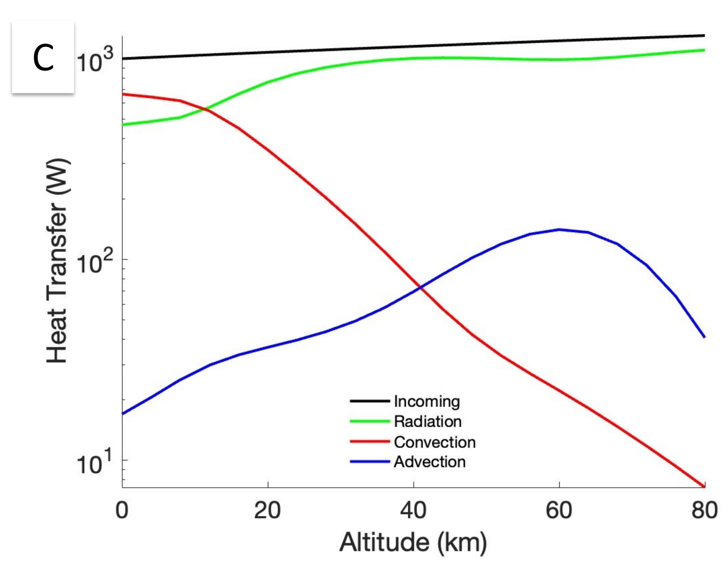
Fabrication and Experiments



Fabrication of the structures involves: (1) spin-coating a film of Mylar with carbon nanotubes, (2) depositing 50-100 nm of alumina through ALD, (3) laser-cut the desired patterns/shapes, (4) solder together 2D shapes to form 3D geometries. Image C also shows an example testing set up for atmospheric solar balloon tests.

Newest Model





Our newest model considers the structure as a solar balloon at lower altitude, where the inner decreased density from heating results in a buoyant force that increases payloads to ~10 kg. This is more than enough for atmospheric measurements from 0 to 80 km with a meter-scale structure.

A) Overall forces vs. altitude (R = 30 m)
B) Inner temperature of structure
C) Thermal model for heat transfer mechanisms leading to flight

Conclusions

The results of this work prove the possibilities for a brand-new flight mechanism from 0 to 80 km with kg-scale payloads, while remaining cheap and mass-manufacturable. By deploying several of these structures, mapping of mesosphere winds is achievable, as well as many other types of measurements that require sensors within the payload, and all that is needed for flight is sunlight.

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