FLIGHT AND SPIN OF MICROWAVE-DRIVEN SAILS: FIRST EXPERIMENTS

James Benford*
Microwave Sciences Inc., 1041 Los Arabis Lane, Lafayette, CA 94549

Abstract

Microwave-driven acceleration by photon reflection has been suggested for propelling probes to very high speeds for science missions to the outer solar system and the nearby stars. Beam-driven probes have the advantage that energy is expended to accelerate only the sail and payload, not the propelling beam generator. We are using an intense microwave beam driving ultralight carbon sails to conduct initial experiments of key aspects of this concept: liftoff and flight against gravity, spinning of sails by coupling electromagnetic angular momentum from the beam and initial studies of beam/sail stability, known as 'beam-riding'. We send a 10 kW, 7.16 GHz beam into a microTorr vacuum chamber onto sails of mass density 5-10 g/m^2 at microwave power densities of ~kW/cm^2. We observe flight of ultralight sails of carbon-carbon microtruss material at several gees acceleration. Sails so accelerated reach >2000 K from microwave absorption. Photon reflection can account for 3 to 30% of the observed acceleration, so another cause must be present. The most plausible explanation is evaporation of absorbed molecules from the hot side of the sail. This effect must be understood and anticipated in future sail experiments and missions, including solar sails. To spin sails of aluminum and carbon, we converted the beam to circular polarization and tethered the sail with a carbon fiber above the circular horn. The sail angular speed increases with power and reverses with polarization reversal. We explored a variety of sail shapes, such as disk, pyramid, and cone. Remotely controlling a sail's rotation with a beam increases its stability in flight. Combined, this work demonstrates the basics of microwave-beam-propulsion by showing beam driving of both the longitudinal and the azimuthal energies of the sail

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I. MICROWAVE–DRIVEN SAIL FUNDAMENTALS

Robert Forward first proposed the microwave-driven sail as an extension of his laser-driven sail concept (1). No experiments and no sail flights by any method, including laser and solar photon pressure have been done previously. The essential reason for this is the lack of a material which could allow liftoff under one earth gravity. The invention of strong and light carbon material has made sail flight possible, because carbon sublimes instead of melting, so can operate at very high temperature. This is because acceleration is strongly temperature limited. The *acceleration from photon momentum* produced by a power P on a thin film of mass m and area A is

$$a = [\eta+1]\ P/MA\ c \qquad (1)$$

where η is the reflectivity of the film of absorbtivity α, M is the mass per unit area (m=MA) and c is the speed of light. (The carbon fiber sail material we use has ~1% transmissivity.) Of the power incident on the film, a fraction αP will be absorbed. In steady state, [which will be achieved in ~3 ms for 1 mm thickness sail] this must be radiated away from both sides of the film (which may be of different temperatures) which we describe with an average temperature T and emissivity ε by the Stefan-Boltzmann law

$$\alpha P = 2A\ \varepsilon\ \sigma\ T^4 \qquad (2)$$

where σ is the Stefan-Boltzmann constant. Eliminating P and A, the sail acceleration is

$$a = [2\ \sigma/c]\ \{\ \varepsilon\ (\eta+1)\ /\alpha\ \}\ (T^4/M)$$
$$= 2.27\ x10^{-15}\ [\varepsilon\ (\eta+1)/\alpha]\ T^4/M \qquad (3)$$

where we have grouped constants and material radiative properties separately. *Clearly, the acceleration is strongly temperature limited.* This fact means that all materials considered previously in the literature (Al, Be, Nb, etc.) cannot be used for liftoff on earth, which requires acceleration greater than one gravity.

Another mechanism is *acceleration from sublimation pressure* due to mass ejected from the material downward to force the sail upward:

$$F = v_T \, dm/dt \qquad (4)$$

where v_T is the thermal speed of the evaporated carbon. The magnitude of this effect can vastly exceed the microwave photon pressure if the temperature is high enough. The essential factor is that this force must be *asymmetric*, i. e., if the sail is isothermal there is no net thrust. Thermal analysis shows that the skin effect produces a substantial temperature difference between front and back of our sails. Of course, for such thin material thermal conduction reduces such differences greatly.

II. SAIL MATERIAL—MICROTRUSS CARBON

Our carbon sails microtruss fabric 3-D architecture resembles a truss structure made of short discontinuous discrete carbon fibers with facings of long discontinuous discrete carbon fiber. Bonding the points where two fibers touch ("nodes") rigidizes the sail. The resulting sail material is stiff and lightweight, strong, conductive and creep-resistant. Most important, it is capable of high temperatures well above 2000 K, meaning sails of C-C could fly at high acceleration.

We measured the microwave properties of the C-C microtruss in a waveguide, so that the sail intercepted the wave completely. We measured the power transmitted through and reflected from the material and deduced the power absorbed. The result is very good: near-total 90% reflection, very low transmission (<1%), ~10% absorption. From ESLI observations the sheet resistance of sail material to DC is ~ 10 ohms. From the model of EM wave interaction with thin films of Cravey[3] et. al., the microwave properties vary with sheet resistance [2]. It predicts 90% reflection, 10% absorption for 10 ohms. So our experimental measurement of ~90% reflectivity at ~10 ohms fits this model very well.

III. EXPERIMENTAL APPARATUS

The experiment uses an existing 25 kW X-band (7.1675 GHz) transmitter, using a Varian model VA-876 klystron, is connected by a waveguide to a water-cooled, stainless steel vacuum chamber with an internal diameter of 1.2 m and a length of 2.1 m. The chamber is pumped by a cryogenic-pump (10-inch) and a turbo-molecular pump (12-inch) backed up by Roots, Stokes and mechanical pumps in series. Heaters attached to the interior walls of the chamber bake out the chamber prior to the sail tests. The base pressure for the chamber is 2 x 10^{-7} Torr. The tube operates continuously, but for these experiments typically were pulsed for 0.2 sec. Safety requirements meant we had to place screens on all windows to avoid microwave leakage. Overhead silicon carbide absorbers reduce microwave reflections.

The waveguide (WR-137 transitioning to WR-112) makes several turns and ends oriented vertically on the centerline of the chamber. We did not flare the waveguide into a horn because that would reduce the power density. The launcher geometry was a sail suspended over the waveguide. The sail had a grommet on axis which allowed it to slide on the support rod made of either carbon or alumina tube. This launcher geometry can been seen in some of the camera frames in Figure 3.

The pattern of the microwave beam was that of an open-ended waveguide. The angular distribution is given by $\cos^m\vartheta$, with m varying between 1 and 2.5 in the plane perpendicular to the vertical axis. We measured the profile by suspending Kapton sheet above the waveguide and heating it with microwaves. The overhead IR pyrometer/camera gave an image of the beam with ~1mm resolution, which showed that it was smooth and azimuthally symmetric. A line scan across the beam profile also showed the expected and predicted shape.

FLIGHT OF SAILS

The most interesting aspect of the experiment is that the microwave beam lifted and flew sails in the chamber. The figure shows four frames at 30 frames/sec; the data are given in [3,4). We saw the sail fly rapidly upward and strike the top of the chamber (55 cm). The video shows: Frame 1: quiescent sail, frame 2: sail lights up from microwave heating, frame 3: sail tilts, moves vertically 0.2 cm, velocity is 0.06 m/s (from framing interval), frame 4: sail has left the frame by moving at least 3 cm. Minimum velocity is 3 cm x 30 frames/sec=0.9 m/s, minimum acceleration a=0.9 x 30 frames/sec = 0.29 m/s^2. From the minimum height of 0.55 m, kinematics gives v=[2gh]$^{1/2}$= 3.28 m/s, and from the framing interval a = 98.5 m/s^2.

To summarize the flights, we see velocities from 0.3 m/s to 4.08 m/s, total accelerations from 10.9 m/s^2 to 132.3 m/s^2, or 1.1 gees to 13.5 gees. Many of these are lower bounds established by the framing interval of the camera. Temperature of the sails varies from 1700 K to 2300 K.

IV. INTREPRETATION OF PROPULSION MECHANISMS

We have analyzed two potential causes of the flights in detail and analyzed several others briefly. We conclude that both microwave photon pressure and asymmetric carbon sublimation pressure are viable mechanisms for explaining the data. But both fall short in explaining the data quantitatively. We have also concluded that neither asymmetric out-gassing nor electrostatics are credible mechanisms.

Photon pressure must of course be occurring. However, to fit the observations, it must be enhanced by a factor of 3 to 30. Additional lift could come from wave energy reflected by the sail and again by the microwave waveguide. To test for such resonance amplification of microwave power density in the sail region, we measured the effective cavity Q between the sail and the waveguide, and found it essentially unity. In the experiments, two disks of Al and strong microwave absorber were alternately positioned over the waveguide end. With 200 W emitted from the waveguide, we measured the power passing through a 3 mm hole at each disk center. We compared the effective number of "bounces" a photon made between disk and waveguide in the two configurations. An absorber should prevent reflection, while a metal plate would maximize it. Yet, the fluxes were the same. This means there was no amplification of the photonic flux in the geometry of the flight experiments.

The most plausible remaining explanation for accelerations greater than gravity is some sublimation of carbon atoms from the sails. However, we do not measure sail temperatures at which such carbon sublimation should occur: Analysis shows the sublimation rates at these temperatures don't give thrusts sufficient to explain the observed acceleration. There are hot spots visible in the carbon sails, seen by eye and videotape. We have speculated that there is a portion of the fibers, which have locally high resistivity, perhaps at the joins of fibers, which increases dissipation of the microwave–driven currents flowing through them. The

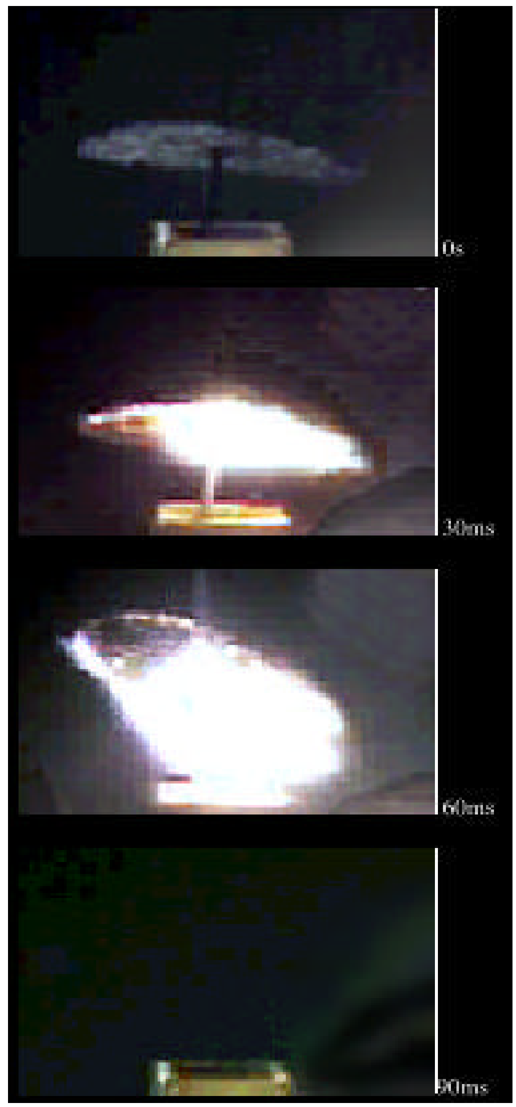

Figure: Liftoff of C-C Sail Under 10 kW Microwave Power.

mass fraction of these resistive fiber joins is small, but they will be hotter on the front face than the back face and will sublimate faster. Comparing this model to our flight data shows that the fraction must be both small

(<1% of fiber mass) and at very high temperature, approaching 3000 K. Compare to the observed temperatures about 500 K lower. A constraint on this model is that the sails show no melting effects from the flights. One would expect that the nodes where the excess heating occurs to have a changed appearance, such as singeing and blackening. However, no such signs are evident from the microphotography of the sails. We conclude that carbon sublimation pressure is the mechanism only if such very hot regions exist in sufficient numbers. If sublimation is the explanation, we need a new generation of carbon sails without hotspots.

Possibly, there is yet another unsuspected mechanism at work. The most plausible explanation is evaporation of absorbed molecules. This serious candidate is evaporation of physisorbed water vapor, chemisorbed hydrocarbons (C_n, H_m) and chemisorbed hydrogen. Although we used a bakeout procedure which heats the sail to ~1000 K for 100 seconds, this may not be enough. Our sails are driven to very high temperatures, exceeding 2000K, where evolution of absorbed molecules is greatly enhanced. Elevating the sail temperature for longer periods, to drive off water and hydrocarbons and to suppress subsequent adsorption rates, should reduce such contaminants. In principle, this can be accomplished through either an extended bake-out of the entire apparatus, or by heating the sail alone. The two essential conditions for this latter approach are that

- sufficient time at high temperature must be allowed to effect an initial decontamination. The more tightly bound chemisorbed hydrocarbons and hydrogen molecules require sail temperatures exceeding 400°C to be driven out.
- the microwave beam must be generated while the sail is too hot to allow re-condensation.

The most plausible explanation for the observed accelerations greater than gravity is evaporation of absorbed molecules (water, hydrocarbons and hydrogen) that are very difficult to remove entirely. The implication is <u>that this effect will always occur in real sails and must be understood and anticipated in future sail experiments and missions</u>. This includes not only microwave-driven sails, but also laser-driven and solar sails. Those planning sail demonstrations in orbit should be aware that the sun striking a sail could evolve molecules from the surface as well as impart photon momentum. This may be a serious source of error in all sail thrust experiments.

V. SPIN OF SAILS

It is not widely recognized that a cylindrically polarized electromagnetic wave impinging upon a sail from below can *spin* as well as lift it [see J. D. Jackson, *Classical Electrodynamics*, 1st edition, 1962, pg. 201]. The wave angular momentum L acts to produce a torque through an effective moment arm of a wavelength, so

$$L_\theta = N \hbar k \lambda$$

with N the photon number. The wave energy is $E = N \hbar \omega$. So the ratio of L_θ imparted by a wave to its energy E is

$$L_\theta / E = 1/\omega$$

Therefore, longer wavelengths are more efficient in producing spin, which rules out lasers.

Spin stabilizes the sail against the drift and yaw, which can cause loss of beam-riding. If the sail gets off center of the beam, it can be stabilized against lateral movement by a concave shape on the beam side. Adding spin can generally stabilize such a concave sail to pitch and yaw. Some concave shapes are stable, though most are not. Steep slopes are harder to keep stable. Solar sails don't face this because the sunlight they ride on is everywhere.

Our experiments show the effect is efficient and occurs at practical microwave powers. We used 100 Watts of microwave power to spin a light aluminum sail of diameter 3.5-cm. We found that an absorbing carbon sail will always spin. Carbon Sails absorb ~10%, so all shapes spin, with 10% angular momentum coupling efficiency. However, we found that spinning sails by reflection, when the sail is from conductors like aluminum, requires special sail geometry: This happens because the incoming microwave beam which produces a reflected wave of reversed polarization, with the result that the sail gets no net angular momentum. To get it to spin, you have to make a radial cut in the metal to divert the surface currents caused by the microwaves. An aluminum sail will spin only with such cuts. Cutting a slot is cut in them interrupts surface currents and allows spin, also achieving 10% angular momentum coupling efficiency.

VI. CONCLUSIONS

An intense microwave beam has driven an ultralight carbon sail to liftoff and flight against gravity. Photon pressure, while certainly present, is insufficient to account for the observed effect. The acceleration calculated from sublimation at sail observed temperatures does not give thrusts sufficient to explain the observed acceleration unless there are very small hot spots in sufficient numbers. Other mechanisms have also been discounted.

Our on-going experiments will explore this new experimental regime further with emphasis on quantifying microwave-induced thrust and then the critical issue of sail stability during powered flight.

Beam-driven spin of sails has been demonstrated; understanding the effect of sail shape is an exciting research area.

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