# ACCELERATION OF SAILS BY THERMAL DESORPTION OF COATINGS

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***ABSTRACT***

Photon pressure can push light sails to low speeds in the range of 10 km/s, whether the photons come from the sun or from a beamed source. Beamed power opens a host of fresh possibilities that greatly enhance mission possibilities beyond those contemplated in traditional solar sailing.

Beam heating of a sail until its surface coat "blows off" materials, through sublimation or thermal desorption, can add far more thrust, roughly a factor of 1000. Beamed power from Earth can heat sails to temperatures >1000 K, both to drive them to high velocities and to simulate similar conditions for very near-Sun missions.

The major points in this report are:

(a) **Beamed power can drive thermal desorption from LEO sails, giving high initial velocities, using coated sail surfaces.**

(b) **This capability will open many kinds of fast-start interplanetary solar sailing missions**

(c) **Sun Diver missions, which need to have sails tested to high temperatures, can be studied in LEO, observing their response to power beamed to (or from) LEO.**

(d) **Laboratory sail flights can test acceleration & stability of carbon sails *now.***

(e) **This basic physics can apply to sails heated by lasers as well. There is a wide variety of promising possible materials for laboratory studies.**

To support these points this report has several sections:

Part I considers the tradeoffs between lasers and microwave beams.

Part II treats candidate materials for thermal desorption (termed "desorption" when molecules leave a substrate of different composition). Many promising materials could enhance capability for thrust, beyond our rough calculations of specific impulse. Much laboratory exploration/development is needed.

Part III considers possible thermal desorption-assisted missions. “Sun Diver” missions seem especially promising for subliming sails, which can make great use of the high photon flux. In particular, high velocity sails not demanding exact targeting seem ideal candidates for light probes of the > 100 AU region, requiring a velocity > 42 km/s.

Appendix A solves the acceleration equations for a microwave beamed case, finding the efficiencies and final velocities. Using a simple thermal desorption model, we consider a carbon fiber sail pushed by microwave-heated, subliming molecules to the diffraction distance of a focused beam, ~1000 km. For high fluxes ~ $MW/m^2$ a versatile sail can attain a velocity of 1.14(m/M) km/s, with m/M the ratio of desorpd mass to final sail mass.

The microwave source could be on the Earth or LEO. Sails could reach high velocities in a series of orbital passes by the sail in steepening elliptical low perigee orbits, giving many chances to “shoot” at the sail. Many design features can optimize this rough result, particularly by using sails with several tailored coats designed to maximize the benefits of thermal desorption.

Such missions could be done in less than a decade flight time. Once an antenna array of sufficient power exists, one can dispatch low-mass missions throughout the solar system at low marginal cost.

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# I. INTRODUCTION

Solar sailing is an old idea, but as yet no mission has flown. In part this comes from the difficulty in flying a sail from LEO, because the far upper atmosphere's pressure on an orbiting sail exceeds sunlight pressure. Also, solar sails are plagued in mission plans by low accelerations, which dictate long trajectory-raising times.

Only in the last few years have *beam-riding sails* fully emerged as a valuable addition to conventional solar sails. Robert Forward's prescient 1985 paper led to work by James Benford. and Richard Dickenson, in 1995. Under the leadership of Henry Harris and Neville Marzwell, JPL began experiments in beam-riding sails in 2000, as reported in J. Benford, et. al., STIAF Conference, 2001, February.

One may ask why a simple chemical rocket kick-stage could not be used, rather than a beam. Although at a seeming disadvantage to sails, (which require no overhead mass for engines, nozzle or propellants) a comparison of the relative merits of both approaches must proceed using the equivalent $I_{sp}$ of the arrangement, as well as cost. Liquid boosters are expensive and have a lower payload mass ratio. High impulse solid rockets exceed the structural strength of a deployed sail with concentrated points of thrust. Microwave powers ~ $kW/cm^2$ can give sails exhaust velocities at > 5 km/sec, competitive with chemical rockets.

## Overview

This work follows from the first laboratory flight experiments on beam-riding sails, in which UC Irvine participated. In that work, an intense microwave beam drove an ultralight carbon sail to liftoff and flight against gravity. Although there was photon pressure, it wasn't strong enough to explain the observed accelerations. The most plausible explanation for the bulk of the observed accelerations greater than gravity is evaporation of absorbed molecules from the hot side of the sail.

This suggested use of such effects in space, yielding a thrust advantage over pure photon thrust. Results from MIRO (Microwave Instrument for ROsetta, the ESA comet rendezvous mission) found that instrument that material sublimes off the surface of a comet at a velocity just under the sonic velocity in a gas at the temperature of the surface. Thrust is the sail thermal speed times the rate of mass blowoff, dm/dt.

The upper temperature range of thermal desorption-driven sails promises higher specific impulse than liquid rockets, as Figure 1 below shows, derived from the work of Selph and Horning, 1985. LOX ($0_2/H_2$; point 2) rockets have specific impulse ~500 sec, but various molecules ($CH_4$, LiH, $NH_3$, $B_2H_6$ even water) at T~4000K exceed this. Embedded in a sail lattice or as a "paint," they could out-perform existing rockets.

A major thrust of future work should be to study such embedding and the resultant loss rates of both painted materials and desorption of embedded atoms. We briefly discuss major issues Figure 1 brings up for future work.

The results of this study suggest development of sails that fly due to loss of "paint" from their illuminated side. Microwaves do not damage sail materials as lasers do, and so can heat them less destructively. This approach promises to make microwave-riding sails greatly superior to both solar sails and laser-driven sails, because it uses the best features of both. After the coats desorp away, a sail can perform as a conventional solar sail, using an aluminum coat beneath.

Solar sails are plagued in mission plans by low accelerations, which dictate long orbital times. Laser sails have problems with atmospheric distortion if the laser beam is fired from the ground, which microwave beams do not. *A natural collaboration emerges between subliming sails driven by beams in LEO, converting to greatly accelerated solar sails for the long mission.*

UC Irvine now, under JPL contracts, has a coherent program to provide an initial existence proof /demonstration of the effect known as 'beam-riding' and to *show that beam-riding is a robust phenomenon*--that it is possible, with a variety of beam profiles and sail shapes, to maintain stable flight. Propellant use can make such studies easier at lower powers.

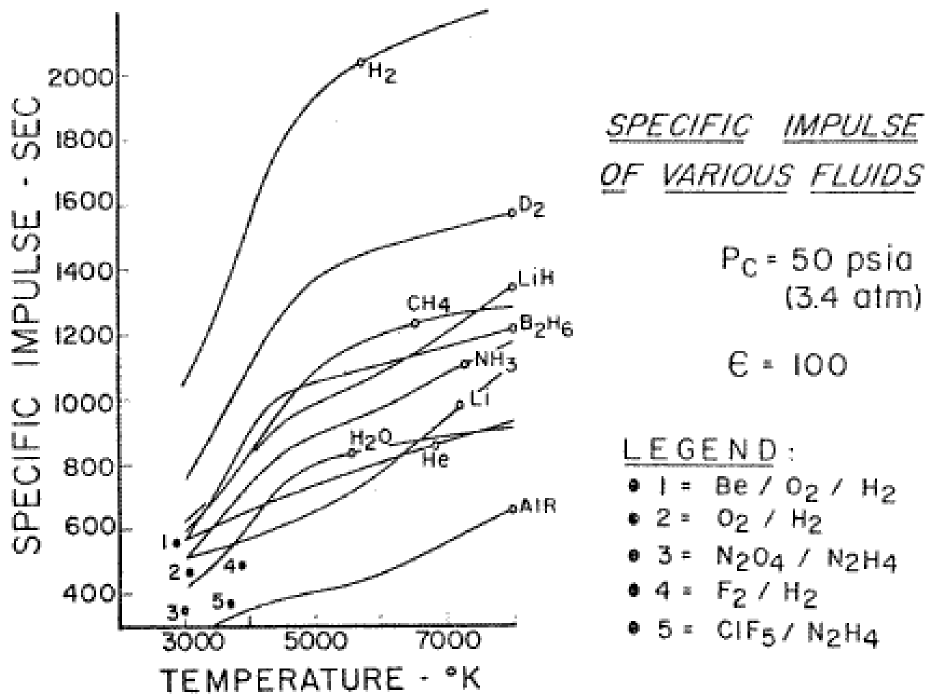



*Figure 1 Specific impulse of a range of fuels. Typical rocket fuels are dotted. Microwave-heated sails at T>3000K can use other compounds embedded in the sail itself or "painted" on. [*Selph and Horning, 1985] *A nozzle effect enhances* $I_{sp}$ *above the thermal level; this would not be present in a sail.*

The best method to show this is in true sail flight against gravity. Our earlier JPL experiments showed this is possible, apparently when loss occurs from the sail under ~5 kW illumination. The next step is to show this with a variety of "paints" especially engineered to make flight under ~kW microwave beams possible. These experiments could relate directly to simulations by a University of New Mexico team funded by JPL.

## II. Propulsion Mechanisms

### 1. *Microwaves versus lasers*

Microwave transmitters have the advantage that they have been under development much longer than lasers and are currently much more efficient and much cheaper to build. They have the disadvantage that they require much larger apertures for the same diffraction distance. This is a significant disadvantage in missions that require long accelerations times with corresponding high velocities, but can be compensated by higher acceleration. Thus, creating high temperature sails with carbon-carbon is extremely important because it enables much higher acceleration and large delta-V in shorter distances, while requiring smaller apertures for the same mission. *However, materials studied can apply to laser-driven sails as well.*

In studies of laser propulsion, the energy costs to operate the laser were found to have a surprisingly minor impact, assuming an electric discharge laser operating at 30% efficiency and use of commercial power. (Here the work of Selph and Horning, 1985, seems the most recent detailed study.)

While the laser power levels to accomplish the mission are far less than those needed for earth launch, they are nevertheless impressive. Even when the thrusting periods were stretched out over 28 days, a laser power of over 100 megawatts can lift useful payloads (6000 lb.) This is due to the very short thrusting period when the vehicle is within range of the ground-based laser -- only about a minute per revolution when the perigee altitude is 100 nautical miles. The available thrusting time may be more than an order of magnitude greater for a space-based laser with a similar orbital track.

Whereas the laser power required falls to about ten megawatts, the economic motive *completely disappeared*. The cost of transporting laser reactants to orbit exceeded the propellant savings gained at the laser propelled rocket. It is probable that a space based laser using a closed cycle concept and nuclear or solar energy would overcome this problem and generate a net cost advantage. This, however, is regarded as a rather distant technological prospect and has not been examined in detail. Similar arguments may apply to a microwave beamer in orbit, though no study has been done.

Microwaves have a singular advantage of microwaves over lasers: their small wavelengths yield a weak coupling of electromagnetic angular momentum to the sail; the interaction scales as (wavelength/diameter). For mission applications that require remote turning or attitude control, microwaves offer a distinct advantage in adjusting sail spin. We have shown this effect in the laboratory at JPL**.**

## *2. Propellant Physics*

In laser or microwave propulsion the rate of beamed energy delivery is not fixed by the rate of on-board propellant consumption, or the energetics of any particular chemical propellant combination. Thus the successful insertion of externally generated energy into the propulsion fluid is not constrained within the usual bounds of chamber temperature and resulting specific impulse. We may select working fluids for optimum expansion characteristics without regard to needs for high molecular weight oxidizer. This again translates into a potential specific impulse advantage.

Figure 1 shows customary relations between specific impulse $I_{sp}$ and temperature in K, for rocketry conditions. Selph and Horning used a rather low chamber pressure of 50 psia out of concern over high heat fluxes that would exist in the higher temperature ranges covered. The high area ratio $\varepsilon$ chosen produces a low pressure at the exit to offset the low chamber pressure – and restricts the usefulness of the calculation to space, or at least upper stage application. The flame temperatures covered range from values that are low by chemical standards to values that cannot be obtained chemically. The upper temperature bounds were generously chosen with hardware limitations in mind, rather than by assumed limitations on heating. Reactants were selected primarily for low molecular weight. Of course, a sail would have no nozzle, and so would have none of these design details.

The most obvious conclusion from Fig. 1 is that the specific impulse for hydrogen considerably exceeds that of all other fuels, as expected. It reaches a specific impulse over 1000 seconds at rather modest temperatures; and specific impulse values of 1800-2000 seconds can be reached with temperatures that do not greatly exceed today's hotter chemical combinations. *Hydrogen desorping from a substrate may well share these properties.*

Interest in other substances must be based on other considerations, such as improved propellant density and storage and handling characteristics. Most of the other propellants are themselves hydrogen-bearing compounds. An important conclusion from these lower curves is that it is possible to obtain specific impulse over 1000 seconds without elemental hydrogen, and without exceeding flame temperatures that have already been successfully handled.

There is much structure and variety to the curves, including concave upwards, concave downwards, and more complex shapes. These arise primarily from changes in molecular weight with temperature, as molecules dissociate and condensed molecules vaporize. The curve for lithium is curious. Over much of the range it is lower than helium, as is expected in light of the relative atomic weights of helium and vapor lithium. Above $6200^o$ K the lithium curve is higher, which turns out to be due to ionization. There is large partial pressure of free electrons which lowers the average molecular weight. Lithium hydride shares this characteristic; and is, unexpectedly, the best performer (except for $H_2$) at the highest temperature calculated. Over a broad range from $4800^o$ - $7500^o$ methane is the highest. The generally high performance of diborane, and its space storability, make it attractive.

The effect of changes in molecular weight in magnifying the effect of changes in temperature is significant, and is most responsible for the rapid rise in specific impulse up to about $4500^o$ K. Many of the fuels have a "knee" in this vicinity which diminishes the return on higher temperatures.

Also plotted in Fig. 1 are five characteristic chemical systems. Included are the $Be/0_2/H_2$ system, with the highest known $I_{sp}$ with stable propellants $H_2F_2$,, $H_2/0_2$, and two storable systems, $N_20_4/N_2H_4$, and $CLF_5/N_2H_4$. The specific impulse is lower as a rule at any given temperature than in the selected beam - powered systems. The difficulty lies in the lack of an oxidizer element with atomic weight to match the low values of unoxidized systems.

Exhausts from chemical rockets range in power from 10 kW on small attitude control engines to teraWatts in large boosters. Within this range of high thrust, $I_{sp} < 500$. Electric systems give low thrust and high $I_{sp}$ so between these two there may well be a role for the high $I_{sp}$ and moderate thrust of subliming sails which use low molecular weight working "fluids."

Since line of sight constraints reduce the thrusting time for any beam-riding sail, delivering the largest thrust in the time allowed is crucial. Estimates of this restriction for laser systems, for example, implies powers ~100 MW. (Selph & Horning, "Laser Propulsion", 1985)

Generally, a variety of compounds not typically thought of as fuels can be "painted" on sails and, depending on which physical process occurs, be sublimed, evaporated, or desorped. We discuss desorption, as it has a rigorous experimental base in the regime of interesting temperatures.

## II.3 *Thermal Desorption As a Propellant Mechanism*

Atoms embedded in a substrate can be liberated by heating, an effect long studied in the pursuit of ultra-clean laboratory experiments. This effect is called *thermal desorption*, and dominates all other processes for mass loss above temperatures of 300-500 C. (Since sublimation is a better known term, we shall use it in discussing sail applications when atoms of the substrate itself blow off. Generally, desorption will often be the relevant physical process; see Masel, 1996.)

A molecule is *physisorbed* when it is *adsorbed* without undergoing significant change in electronic structure, and *chemisorbed* when it does. *Physisorbed binding energies (~2-10 kcal/mole) are typically much less than chemisorbed energies (~15-100 kcal mole), by as much as an order of magnitude*. This implies that two different regimes of mass liberation can be used, with physisorbed molecules coming off at lower temperatures, and hence lower thrust per mass, while chemisorbed molecules can provide higher thrust per mass. Cuneo (1998) offers this general schematic for desorption in layers from bulk substrates:

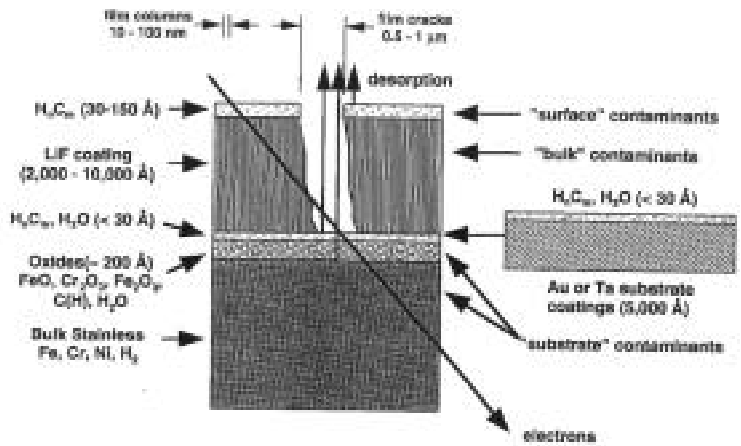



Fig. 10. Schematic representation of LiF film, stainless substrate, and substrate coatings with impurity location and type. This physical picture is consistent with small-scale experiments [45], diode experiments, and the literature. Contamination on LiF taken from XPS measurements. Contamination present on the stainless steel is taken from literature representing untreated stainless steel surfaces. Cleaning protocols can affect the surface with RF discharges and heating, but only heating and substrate coatings affect the substrate. Recontamination of the surface after cleaning is also an issue.

*Figure 2 Layers which can desorp from typical substrates. [Cuneo, 1998]*

Generally, the rate of mass loss under heating is

$$dn/dt = an\, e^{-Q/kT} \qquad \text{(II.1)}$$

where a is ~$10^{13}$ $s^{-1}$, Q is the required liberation energy (usually ~ 1 eV), and n is the area density in atoms/$m^2$, so that dn/dt is the desorbed flux under heating in atoms/$m^2$-s. (We neglect resorption, which is tiny in a space environment; Cuneo, 1998.) The exponential factor means that sublimation (or desorption) of molecules from a sail lattice will have a sudden onset as the sail warms. When temperature T varies with time, the above equation can be formally solved,

$$n(t)/n^o = \exp\{-a\int \exp[-Q/kT(t)]\, dt\} \qquad \text{(II.2)}$$

As the binding energy Q increases, the time to maximum desorption gets longer. The relationship between Q and T*, the temperature at the peak in the desorption rate dn/dt, is, for heating rate dT/dt,

$$Q/kT^{*2} = a \exp(-Q/kT^*)/(dT/dt)$$

When the peak desorption rate is reached, 63% of the mass inventory has been lost, so this is a good estimate of when the effect is largest for a given molecule of binding energy Q.

Hydrogen is often easiest to liberate, with a Q of 0.43 eV to 1.5 eV, depending on the substrate. (Little measurement is available for Al or C, alas.) Water has Q=0.61 eV. Generally, likely candidate chemisorbed compounds like hydrocarbons have Q around 1 eV (11,605 K). CO is more strongly bound and is a candidate for the most tightly held in a carbon sail lattice. Quite possibly lab sails experiencing strong, sudden-onset lift may be desorping CO at a critical temperature onset > 2300K.

Acceleration by thrust from desorped molecules seems a likely mechanism for high $I_{sp}$, since for hydrogen, the best atom to propel,

$$I_{sp} = 508 \ (T/3000K)^{1/2} \quad s \qquad \text{(II..3)}$$

so the higher the temperature required to unbound a molecule, the greater its thrust. Note that this $I_{sp}$ is higher than for *any* chemical rockets.

Sails make poor rockets because there is no nozzle. If molecules leave the surface at random angles the thrust velocity is $2V/\pi$ with V the thermal velocity for the species of mass $\mu m$. However, *some materials tend to concentrate sublimed or desorped matter toward the normal to the surface.* For simplicity I shall take V as the exhaust velocity, though this is material-dependent and the true thrust may well be somewhat lower, though never by more than $2/\pi$.

Acceleration of a subliming sail in a photon beam can be written

$$a = a_P + a_D = P(2r+\alpha)/Mc + V(dm/dt)/M \qquad \text{(II.4)}$$

where the first term is from pure photon reflection (r) and absorption ($\alpha$), for a sail of mass M bombarded by photons of power P. The second term is the thrust from sublimation or desorption at rate dm/dt at thermal velocity V.

Sail heating has two dynamically interesting regions: convection dominated at low T (and power, P) and radiation dominated at high T. The equation is

$$dT/dt = AP - BT - CT^4$$

with A, B and C constants. Only if the mass loss is constant is B=(dm/dt)/m constant, permitting a simple analysis. Mass loss carrying away energy dominates up to a temperature

$$T^* = 2{,}640\ \mathrm{K}\quad [f(d/100)/Zt]^{1/3}$$

Where f is the fraction of sail mass in propellant, t the duration of the propellant acceleration (i.e., total beam driving time) , and d the total sail areal density in units of 100 gm/cm$^2$ . This result is for molecular hydrogen, for which the mass number Z has been taken as 2. To reach this temperature T*, where radiation loss equals convection loss, demands a power

$$P = \quad 5.5\ \mathrm{MW} \quad [(f/10)/(t/1000\mathrm{sec})]^{4/3}\ [M/1000\ \mathrm{kg})(d/100)^{1/3}/Z^{1/3}]$$

Above this power, efficiency drops from very nearly 100% to much less, as radiation dominates. Note that by increasing (f/t) one reaches a higher T* because the power applied can be higher, while still remaining in the highly efficient region for T<T*. The power required scales slightly faster, $(f/t)^{4/3}$ A ready way to compare the superiority of mass loss over pure photonic thrust is to take the ratio of these accelerations for illumination of a sail for *constant dm/dt*,

$$a_d/a_P = (dm/dt)(g/s)\ P^{-1}(GW)\ (2r+\alpha)^{-1}[(\alpha/0.5)(\varepsilon/0.1)^{-1}(P/A/kW/cm^2)]^{1/4} \quad (3)$$

Let us choose dm/dt=1 g/s as a nominal rate of mass loss. Then for powers below 1 GW, desorption exceeds photonic acceleration. Note that this ratio is sensitive to P but not to P/A. *For foreseeable powers << GW, desorption dominates over photonic propulsion, just as seen in current laboratory conditions. This probably explains the JPL flight experiments that observed carbon sails lifting off with accelerations several times the photonic level.*

Probably the most interesting regime of operation occurs at high efficiencies, when desorption dominates radiation in regulating T. Then the ratio of accelerations is

$$a_d/a_P = (2/\pi g^*)c/V$$

with the thermal velocity V, and g* the degrees of freedom of the exhaust gas. This means the amplification $a_d/a_P >> 1$ for plausible temperatures. For example, for molecular hydrogen, $a_d/a_P = 4.5 \times 10^4$ for T=1000 K. This means that a beam source can exceed the solar accelerations if it illuminates the sail for ~ $10^{-4}$ of the sail's orbit time around the Earth. Such a large multiplier is the essence of the beam-driven method.

We can relate the sail temperature T to the power by the Stefan-Boltzman radiation rate, finding

$$T = 5320 \text{ K } [(\alpha/0.5)(\varepsilon/0.1)^{-1}(P/A/kW/cm^2)]^{1/4} \qquad (II.5)$$

Here the values of the emissivity ε and absorption α are chosen to show the effects possible in absorbing materials. P/A, the power/area factor, is available in the lab in the range of $kW/cm^2$. A ready way to compare the superiority of mass loss over pure photonic thrust is to take the ratio of these accelerations for illumination of a sail for *constant dm/dt*,

$$a_D/a_P = (dm/dt)(g/s)\, P^{-1}(GW)\, (2r+\alpha)^{-1}[(\alpha/0.5)(\varepsilon/0.1)^{-1}(P/A/kW/cm^2)]^{1/8} \qquad (II.6)$$

Let us choose dm/dt=1 g/s as a nominal rate of mass loss. Then for powers below 1 GW, desorption exceeds photonic acceleration. Note that this ratio is sensitive to P but not to P/A. *For foreseeable powers << GW, desorption dominates over photonic propulsion, just as seen in current laboratory conditions. This probably explains the JPL flight experiments that observed carbon sails lifting off with accelerations several times the photonic level.*

A sail with 10 kg of molecules included in the lattice, then desorped away, can be accelerated for 10,000 sec, about the time needed to lift it from Low Earth Orbit into an interplanetary trajectory. For example, consider transit from LEO to geosynchronous orbit, which demands a delta-V of 2500 m/s. If the sail is kept in range during the entire flight, so the desorption can occur continuously over a time t*=m/(dm/dt). Then 2500 m/s = $a_D$ t* = $(t^*dm/dt)10^4 (\mu T)^{1/2}/M$ m/s. Then for this mission a 10 kg sublimed (desorped) mass m, must satisfy roughly

$$m/M\, (T/\mu)^{1/2} \sim 1/4$$

where M is the sail plus payload mass without the desorped mass m, T is in eV (~1/2 for 5400 K) and μ is the mass of the desorped molecules in units of the proton mass. Thus m/M ~1 is plausible, so sails need not be greatly loaded to achieve high velocities in short times (a few hours) of illumination.

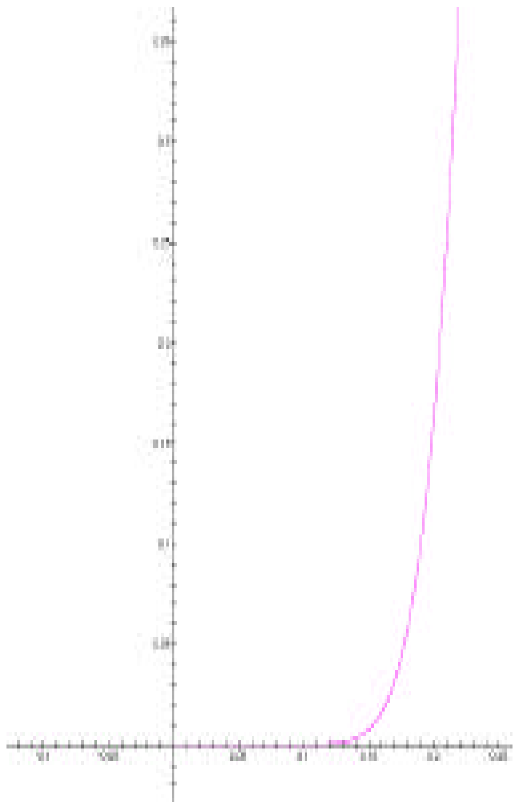
A carbon sail of 1000 $m^2$ would have 10 kg mass at an areal density of 10 $g/m^2$, and would require a power input of P=10 GW to drive it. This is a very high P, so the best solution would be to go to lower powers (and thus lower T), or smaller sails, or longer illumination times.

This in turn places a restriction upon the distance over which a beam can be focused on the sail, which is best met by illuminating the sail only when it is near perihelion of an increasingly elliptical orbit. Raising a sail orbit by repeated near-encounter shots of a ground-based (or LEO) beam seems a good method for making best use of a beam of limited power. In Appendix A we consider accelerations in a single, long shot.

We can use eq. (II.4) to calculate the acceleration of a sail of payload mass M and subliming mass m(t). Laboratory measurement shows that substrates can have areal density of N* monolayers, leading to a total desorped mass of m* when all N layers are exhausted. Then the acceleration gained of a sail is a function of temperature T(eV), given by eq. (II.1) in terms of applied microwave power P and areal density $\sigma(g/m^2)$:

$$a_D = 1.66 \times 10^{-3}\ N^* (\mu T)^{1/2}\ e^{-Q/kT} / [\sigma(g/m^2)\,(1+m^*/M)] \quad m/s^2 \qquad \text{(II.7)}$$

a $(m/s^2)$



T(eV)

*Figure 3*
*Fit of eq (II.7) for acceleration of a carbon sail in an experiment at JPL. Acceleration is in m/s$^2$ vs. T in eV. The carbon sail weighed 7.17 mg, with areal density 7 g/m$^2$, and accelerated at 2.3 gravities at T(eV)=0.18. This curve is a rough fit for CO as the adsorbed molecule, Q=1.75 eV, and N* the areal density of adsorbed CO molecules of $10^{15}$/cm$^2$. The steep curve means a fit is only qualitative. The total expended mass to achieve this acceleration was only ~$10^{-6}$ gm.*

### *II. 4    Fitting to the JPL Experiments*

In 2000 a team attempted photonic liftoff experiments at the Jet Propulsion Lab using carbon fiber sails. For 10 kW power, temperatures ~ 3000 K should occur. Sail liftoff was observed at 5 kW (versus the predicted 10 kW), implying sublimation or desorption of molecules embedded in the carbon from the sail underside, adding lift. (See J. Benford *et al*, 2001.)

The exp(Q/T) dependence in Eq. (II.7) strongly suggests the sudden liftoff observed. However, it is equally illuminating to analyze those experiments, and scale to possible missions, by replacing the adsorption loss rate of (II.1) with a simpler mass loss rate, for average N* over time t*

$$dN/dt=N^* (A/t^*)\ 10^{15}/cm^2 \qquad \text{(II.8)}$$

where N* is the number of *monolayers* lost in an area A, with the rate $10^{15}$/cm$^2$ *taken directly from an overview of many laboratory experiments in desorption.* This allows us to import the wisdom gained by experience in a distant field (Cuneo, 1998). A monolayer is a region several hundred Angstroms thick from which adsorped molecules escape under heating. A wide range of observations show that under short pulses (~seconds) several hundred monolayers can be ejected at close to the thermal speed.

| Acceleration/g | T(eV) | N*, CO monolayers lost |
|---|---|---|
| 2.0 | 0.13 | 63 |
| 2.47 | 0.14 | 75 |
| 2.3 | 0.175 | 62 |

*Fit to eq. (II.8) for JPL lab experiments in carbon sail liftoff. We assume CO adsorbed atoms are ejected for thrust at the observed temperatures T(eV) and calculate the number of monolayers lost, N,, which appears to be nearly constant ~ 70. The number of ejected atoms is ~$10^{17}$.*

We analyzed the JPL experiments using (II.8) to find the table above, suggesting that only ~$10^{17}$ atoms ejected can explain the observed sudden accelerations. As microwave power rose, the steep curve in Figure 3 suggests that abrupt ejection of CO atoms may have caused the strong accelerations in ~0.1 sec. (See III for applications of this work to a simple beam-driven mission.)

Of course we do not know that CO comprised the ejected monolayers. *This should be closely monitored in future experiments.* Another bound state such as Chlorine would give similar results. The fit will work for any strongly bound (Q~ 1 eV) atoms with mass number ~28. The narrow range of N~70 suggests that the picture developed by Cuneo et al applies.

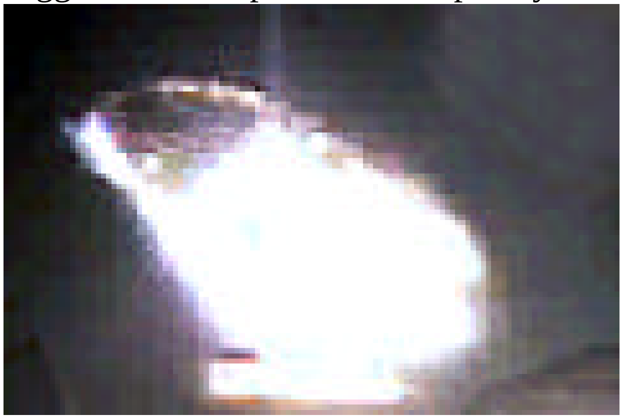


*Figure 5*
*Carbon sail lifting against gravity under 5 kW microwave beam illumination. Experiments done at JPL in 2000 with ~ 6 mg sail and observed T~2500 K. Blur is due to movement at >2g after 60 ms*

### *2.5 Promising Candidate Materials*

Many compounds may satisfy mission needs, i.e., a film that is
(a) easy to apply to a candidate sail surface;
(b) does not sublime in high vacuum at room temperatures, and
(c) readily sublimes when heated by microwaves.

Hydrogen, with the highest specific impulse per unit mass, is the best (desorbed) embedded element or painted-on subliming agent. . With this in mind, we have found potential "paint" candidates: $BH_2$, $BLiH_4$ and several $NH_4$-based compounds. One can dissolve these in ether, in varying concentrations, and let the ether evaporate to yield a paint. Other candidates known to make paints are nitrocellulose ("colodium" when dissolved), which evaporates at a few 100 C and can be loaded with added hydrogen. Magnesium dihydride breaks up into Mg + $H_2$ at 600-700 K and might be useful, as *the Mg left behind could coat a carbon fiber substrate to make it reflective of solar photons.*

*Further trials of a wide range of candidate compounds are needed. Measurements of both rate (dm/dt) and angular dependence of mass loss can determine utility of such materials under direct microwave heating. Very little is known in this area, particularly at temperatures > 1000 K.*

### *2.6 Beam Radiation Pattern*

Real microwave beams have a characteristic falloff in fluence with angle, as shown in the Figure for a laboratory beam emitted from an open waveguide. The measured power follows a pattern $\cos^m x \cos^n y$ where (x,y) are the two transverse axes and (m,n) lie in the range $2<(m,n)<3$.

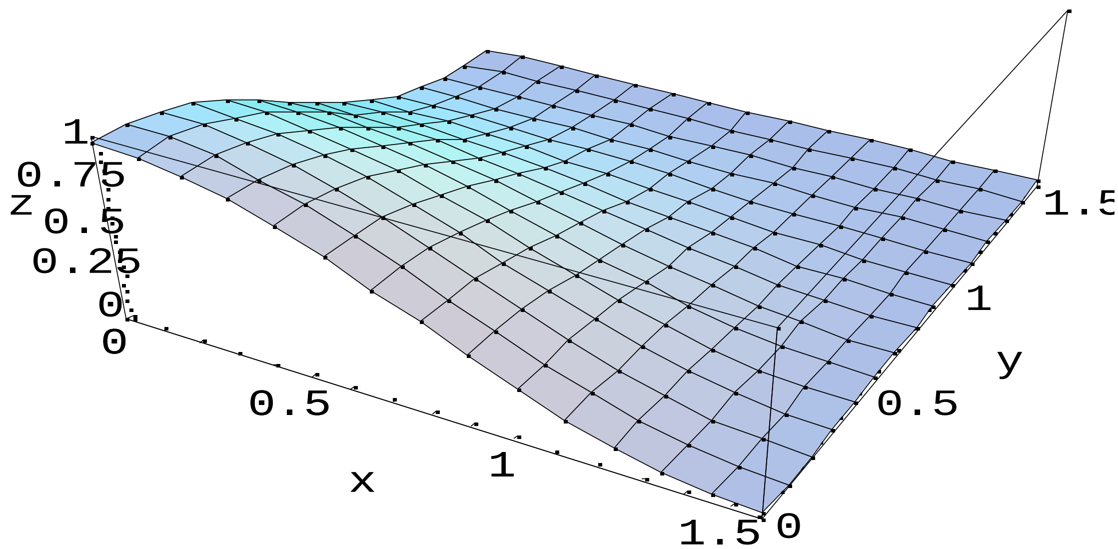



*Figure 4*
*Radiation Pattern of a microwave beam from a waveguide in the x-y plane for m=2, n=2.5.*

Plainly, unless sophisticated means are used to shape beam radial profiles, energy will be deposited preferentially toward the sail center. Spinning a sail will average heating, but the radial gradient will be significant if most of the beam energy is to be used on the sail.

*Study of the stability implications of this is needed.* Sails could be loaded with “paint” more thickly toward the center, so the paint is removed evenly in time, and the sail is cleared of paint simultaneously at all radii. *Further engineering study could optimize sail performance using this freedom.*

***Possible experiments with mass loss-driven sails***

JPL lab experience and theory imply that sails designed to fly in space can have their efficiency greatly enhanced by actively subliming material from their surfaces. This is particularly so for beam-riding sails propelled by microwave fluxes from either the ground or from a low orbital platform.

Momentum conveyed by subliming molecules can exceed by three or four orders of magnitude that of the photons striking the sail.

Using this enhancement requires coating the present lightest sails (particularly Carbon-Carbon sails, with area densities $\sigma \sim 5$ gm/m$^2$). Desorption of this coat will convey a thrust of V(dm/dt) with V the thermal speed of the illuminated sail and dm/dt the desorption rate.

*I recommend studying coating and flight of subliming sails in a high vacuum, high microwave power laboratory vessel.* One could study coating materials, measuring the desorption rates, and finally flying a sail in the laboratory, under microwave lift thrust using desorption momentum.

The ultimate aim would be to fly sails in the lab under lower microwave powers--and thus lower temperatures, which generally will damage sails less. This will greatly lessen the design constraints on available and projected spacecraft sails. Sails will begin subliming when their temperature T exceeds a critical desorption level, T*> 500 K. The illuminated sail "paint" temperature will follow a slightly recast form for the Stefan-Boltzmann thermal emission rate,

$$T = 5320\text{ K }[(\alpha/0.5)(\varepsilon/0.1)^{-1}(P/A)]^{1/4}$$

Here the emissivity $\varepsilon$ and absorption $\alpha$ are typical of advanced carbon sails, and the power/area, P/A is in units of kW/cm$^2$. To lower the needed operating temperature, desorption materials must be found which will give T* for liftoff : $V(dm/dt) > (m + M)g$. Here M is the carbon sail mass and *m* the subliming mass, with V the desorption (thermal) velocity.

*Desorption allows lower, less destructive power levels, P< 1 kW.*

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