POWER-BEAMING CONCEPTS FOR FUTURE DEEP SPACE EXPLORATION

GREGORY BENFORD[1] AND JAMES BENFORD[2]
1. Department of Physics, University of California Irvine, Irvine, CA 92697, USA.
2. Microwave Sciences, Inc., 1041 Los Arabis Lane, Lafayette, CA 94549, USA.

We explore uses of thermal desorption of materials from prepared LEO sails, which can give additional propulsion when struck by intense microwave beams from the ground. Beam heating of a sail until its surface coat sublimes or desorps 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. 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, in a wavelength region of maximum utility. A natural collaboration emerges between subliming and/or desorping sails driven by microwave beams in LEO, becoming high velocity solar sails for the long mission. Resonant boosting from repeated shots can liberate sails in weeks into interplanetary space. Spinning sails by using polarized beams can deploy sails. A Mars Fast Track mission to speeds ~50 km/sec may be possible with an enhanced Deep Space Network. With this array one could test near-sun conditions for desorption in a Sun-Diver mission, enabling high-speed near-interstellar voyages.

Keywords:

1. INTRODUCTION

Sails are an old idea, as yet unproven [1]. This work follows from the first laboratory flight experiments on beam-riding sails in which an intense microwave beam drove an ultralight carbon sail to liftoff and flight against gravity [2]. Although there was large 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.

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.

2. THERMAL DESORPTION AS A PROPULSION MECHANISM: THEORY

Atoms embedded in a substrate can be liberated by heating, an effect long studied in the pursuit of ultra-clean laboratory experiments [2]. This effect is called *thermal desorption*, and dominates all other processes for mass loss above temperatures of 300-500 C. (Since thermal desorption is a better known term, we shall use it when atoms of the substrate itself blow off. Generally, desorption will often be the relevant physical process.

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 [see refs. in ref. 2] offers this general schematic for desorption in layers from bulk substrates:

Generally, the rate of mass loss under heating is

$$dn/dt = an\ e^{-Q/kT}$$

where a is $\sim 10^{13}\ s^{-1}$, 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 readsorption, which is tiny in a space environment.) The exponential factor means that thermal 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,

$$n(t)/n^o = \exp\{-a^* \exp[-Q/kT(t)]\ dt\}$$

As the binding energy Q increases, the time to desorb 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,

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

At the peak desorption rate, 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 may be a candidate for the most tightly held in a carbon sail lattice. Quite possibly lab sails experiencing strong, sudden-onset lift may be desorbing 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 molecule to propel,

$$I_{sp}, = 637\ (T/3000K)1/2\ s^{-1}$$

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 rocket.

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 μm. However, some materials tend to concentrate sublimed matter toward the normal to the surface. For simplicity take V as the exhaust velocity, though this is material-dependent and the true thrust may be somewhat lower, though never by more than $2/\pi$.

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

$$a = a_P + a_D = P(2r+a)/Mc + V(dm/dt)/M$$

where the first term is from pure photon reflection (r) and absorption (*a*), for a sail of mass M bombarded by photons of power P. The second term is the thrust from thermal desorption at rate dm/dt at thermal velocity V. When desorption dominates radiation in regulating T, the ratio of accelerations is

$$ad/aP = (2/\pi g^*)c/V$$

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 $\sim 10^{-4}$ of the sail's orbit time around the Earth. Such a large multiplier is the essence of the beam-driven method. A ready way to compare the superiority of thermal desorption over pure photonic thrust is to take the ratio of these accelerations for illumination of a sail for *constant dm/dt*,

$$a_D/a_P = (dm/dt)(g/s)\ P^{-1}(GW)$$
$$(2r+a)\text{-}1[(a/0.5)(e/0.1)^{-1}(P/A/kW/cm2)]^{1/8}$$

Choosing dm/dt=1 g/s as a nominal rate of mass loss, for powers below 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, as in current laboratory conditions*.

This probably explains our JPL flight experiments that observed carbon sails lifting off with accelerations several times the photonic level [2].

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 $t^*=m/(dm/dt)$, and 2500 m/s = $a_D\ t^* = (t^*dm/dt)10^4\ (\mu T)^{1/2}/M$ m/s. Then 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 illumination times (a few hours).

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 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.

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

$$T^* = 2640\ K\ [f(d/100)/Zt]^{1/3}$$

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

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

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 efficient region for T<T*. The power required scales faster, $(f/t)^{4/3}$.

In the radiative region, we can relate the sail temperature T to the power by the Stefan-Boltzman radiation rate, finding

$$T = 5320\ K\ [(á/0.5)(å/0.1)^{-1}\ (P/A\ (kW/cm2)]^{1/4}$$

Here the values of the emissivity ε and absorption α are chosen to show the effects possible in absorbing materials. P/A, the power per unit area, is available in the lab in the range of kW/cm^2.

We have described elsewhere our experiments which lead to these ideas [2].

Obviously these advantages can sent sails into interplanetary orbits in fairly short times ~ months. But what of the outer solar system, where much mystery lurks?

3. SUN-DIVER MISSIONS

For a schematic of the approach, see the fig. 1. This deployment takes advantage of high temperature characteristics of the sail to dive to within a few radii of the sun, where it achieves a high velocity by using the large solar flux at perihelion. The planned Solar Probe mission, flying to within 0.01 A.U., is an extreme example.

For the near term use of beamed power, note that *beam illumination at ~kW/cm² in LEO can* simulate conditions any solar grazer mission will experience to within 0.01 A.U.

Conventional solar sail missions lower perihelion by adding and subtracting energy from the orbit over several revolutions around the sun. Adding mass to a sail to be lost at the sun will generally lengthen this perihelion lowering time, because of lower accelerations. Sublimation (or desorption) thrust from LEO into interplanetary orbit can omit the several-year orbits that conventional solar sails need to reach ~0.1 AU. A second "burn"at perihelion, the highest available orbital velocity in the inner solar system, and thus optimum point for a delta-V, then yields high velocities for >40 A.U. missions. The mission phases are:

1. Deployment in Low Earth Orbit by conventional rocket.
2. Launch by a microwave beam from nearby in orbit. Beam heating makes a "paint" (*polymer layer #1*) desorp from the sail. Under this enhanced thrust in repeated shots at.perihelion in steepening elliptical orbits, the sail attains ~15 km/s velocity, canceling most of its solar orbital velocity, and so can fall edge-on toward the sun immediately. (This is far faster than using solar pressure to spiral down, which takes years.) It approaches the sun edge-on, to minimize radiation pressure on it in the inward fall.
3. At perihelion the spacecraft rotates to face the sun. Under intense sunlight ~20 times Earth insolation, the sail *desorps away polymer #2*, getting a ~50 km/s boost at its maximum (infall) velocity.
4. It then sails away as a conventional, reflecting solar sail, with the final Aluminum layer revealed. Its final speed is ~ 10 AU/year.
5. Passing near the Earth, the spacecraft gets an addition delta-V by a microwave transmitter in Earth orbit (quite optional).
6. Within ~5 years, it sails beyond Pluto, giving high velocity mapping of the outer solar system, the heliopause and interstellar medium.

Obviously one needs a detailed orbital integration, with plausible rates of mass loss gained from laboratory work, before judging the overall credibility of such a mission.

4. AN INTERSTELLAR SUNDIVER

Such missions could reveal much [3,4]. As a simple example, consider a sail falling sunward on a parabolic orbit. It will be accelerated by

- the ΔV imparted by desorption at perihelion
- ordinary solar sail acceleration on the outward-bound leg, once the desorped layer is gone, leaving a reflecting sail

We can find an approximate expression for the final velocity V^F with respect to the sun, following energy analysis, as in Matloff's *Deep Space Probes* [3] The sail's parabolic velocity at distance R is

$$V = 1.4\ (GM/R)^{1/2} = 93\ \text{km/s}\ (R/0.1\ \text{AU})^{-1/2}$$

At perihelion of 0.1 A.U. the sail reaches a temperature (for seemingly plausible values of absorption and emissivity)

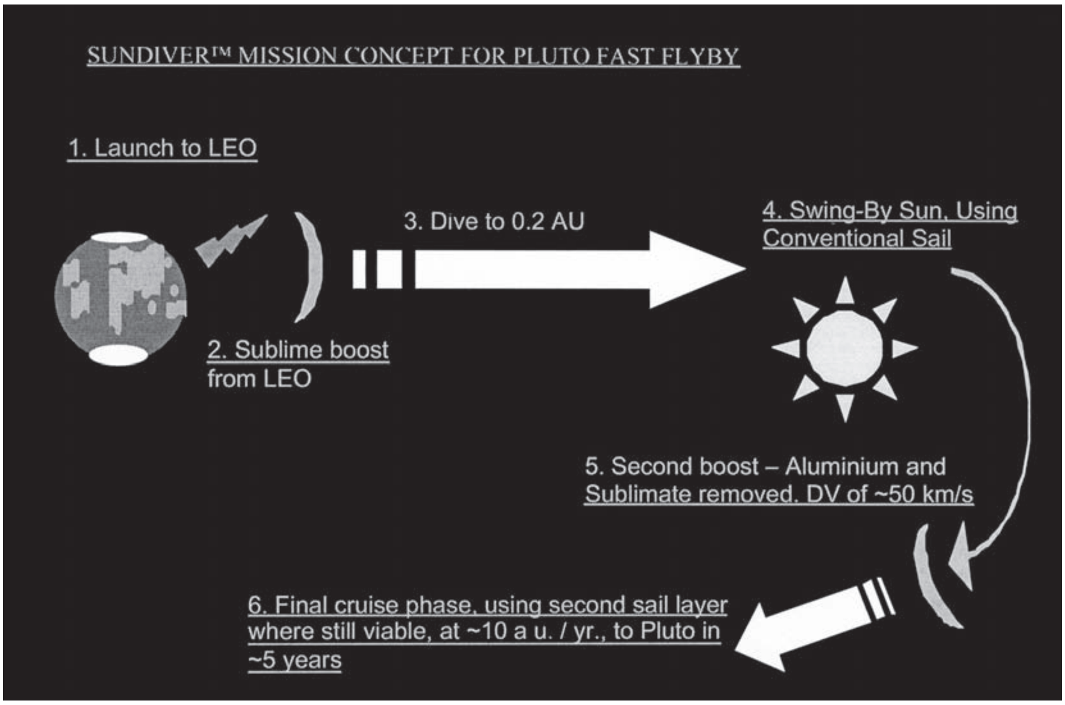

Fig. 1 Phases of a Desorption-Assisted Sun-Diver Mission.

$$T = 927\ K\ [\alpha/0.3)(\varepsilon/0.5)^{-1}]^{1/4}\ (R/0.1\ AU)^{-1/2}$$

For such temperatures, a considerable ΔV > km/s is plausible for a range of desorption materials. Losing its mass load at perihelion, the sail thereafter works as an ordinary solar sail, attaining a *final exit speed* from the solar system

$$V^F = 19.5\ km/s\ [(DV/2\ km/s) + (3\sigma)^{-1}]^{1/2} =$$
$$3.9\ AU/year\ (\Delta V/2\ km/s)^{1/2}[1 + 0.33\ /(\Delta V/2\ km/s)(\sigma')]^{1/2}$$

Here σ is the sail areal mass density in units of 100 gm/m^2. In the brackets, the first term comes from acceleration (a), the ΔV imparted by desorption at perihelion and the second from (b), ordinary solar photon acceleration on the outward-bound leg, once the desorped layer is gone, leaving a reflecting sail.

The sail's speed as it passes through the outer planets will exceed V^F. [4] The linear sum of ΔV and 70 the ordinary solar sailing momentum in the square root above means there will be a simple tradeoff in missions between the two effects, which are equal when the last term in brackets above is unity.

This is only a rough calculation, omitting many mission details, such as sail maneuvering near the sun. We assumed a perfectly reflecting sail on the outward leg, and that desorption would occur quickly at perihelion.

Still, the advantages of using desorption with huge solar fluxes are appealing.

5. MARS FAST TRACK

Recently we were asked by Barry Geltzahler at DSN to find a way to get a package to Mars quickly using beam-driven sails. As an exercise, we worked out these numbers (Table 1), also including a comparison with the familiar idea of using lasers, though they have pricey photons.

But how to slow it down? That was not asked, and we don't know.

6. CONCLUSIONS

Using mass loss for thrust is not a new idea, but it is new to apply this idea, together with a powerful microwave beam, to both heat and push a sail. It is worth pursuing because sublimation and desorption

- work well with the new carbon sail materials, which can take very high temperatures (>2000 K),
- can use promising new materials for mass loss so far not studied for thrusting applications,
- at ~kW/cm^2 in LEO, using beam illumination, can simulate conditions any solar grazer mission will experience to within 0.01 A.U.
- promise whole new classes of missions, even to the outer solar system, where ordinary solar sails can not usefully venture.

TABLE 1:

	Laser	Microwave	Microwave Desorb
Mass	10 kg	10 kg	100 kg
Flight Time	10 days	1 month	1 month
Flight Distance	1 AU	1 AU	1 AU
Transit Velocity	174 km/s	40 km/s	40 km/s
Transmitter Diameter	15 m	440 m	440 m
Sail Diameter	50 m	1 km	1 km
Frequency	300 THz	40 GHz	40 GHz
Transmitter Power	47 GW	5 GW	25 MW
Beaming time*	3.9 hrs	1.25 hrs	1.25 hrs
Diffraction Limit	310,000 km	240,000 km	240,000 km
acceleration	3.2 g	31 g	31 g
Beam coupling efficiency	3.5%	90%	90%

* time to Diffraction Limit

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