Desorption-Assisted Sun Diver Missions*

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Abstract. Solar-driven sails which can also accelerate by "boil off" of coated materials offer new high-velocity missions. These can take advantage of high temperature characteristics of the sail by using the large solar flux at perihelion. For the near term use of beamed power, beam illumination at ~kW/cm^2 in LEO can simulate conditions any solar grazer mission will experience to within 0.01 A.U. Sublimation (or desorption) thrust from LEO into interplanetary orbit can omit the several-year orbits 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 of ~50 km/s for >40 A.U. missions. The mission begins with deployment in Low Earth Orbit by conventional rocket. Then the launch begins, driven by a microwave beam (and much smaller solar photon thrust) 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. 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. It then sails away as a conventional, reflecting solar sail, with the final Aluminum layer revealed. Its final speed is after leaving the solar potential well is ~ 10 AU/year. Within ~5 years, it sails beyond Pluto, giving high velocity mapping of the outer solar system, the heliopause and interstellar medium.

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 (Forward, 1985) led to work by James Benford. and Richard Dickinson in 1995 (Benford, 1995). Under the leadership of Henry Harris and Neville Marzwell, JPL began experiments on microwave-beam-driven sails in 2000 (Benford, 2001). 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 fast evaporation of heated absorbed molecules from the hot side of the sail on timescales short compared to that of thermal diffusion.

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 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.

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The upper temperature range of thermal desorption-driven sails promises higher specific impulse than liquid rockets, as Figure 1 shows, derived from the work of Selph and Horning (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.

The results of the work we report here suggest development of sails that fly due to loss of "paint" from their illuminated side. Microwaves do not damage sail materials as short-range 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 desorb 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.*

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.

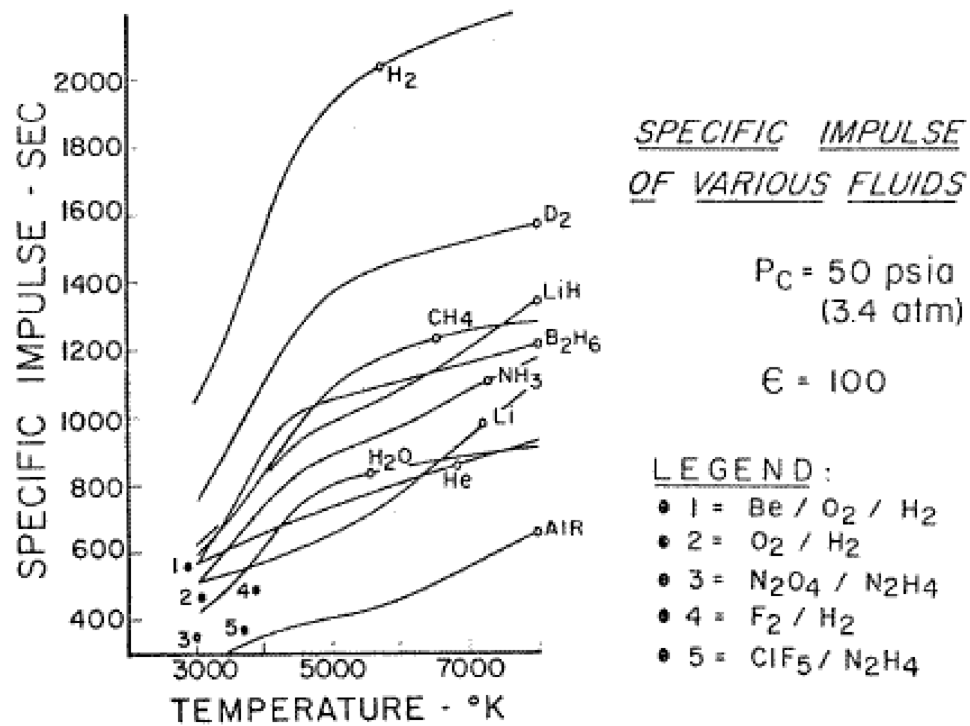

FIGURE 1 Specific Impulse Of A Range Of Fuels. Typical rocket fuels are dotted. Microwave-heated sails at T>3000K can use other compounds embedded in the sail itself or "painted" on. [Selph and Horning, 1985] Here a nozzle effect enhances I_{sp} above the thermal level; this would not be present in a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

ACCELERATION BY THERMAL DESORPTION

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 ε 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.

We briefly discuss major issues figure 1 brings up for future work. .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.* 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, imply powers of the order of 100MW(Selph&Horning,1985).

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

$$a = a_P + a_d = P(2r+\alpha)/Mc+V(dm/dt)/M \qquad (1)$$

where the first term is from pure photon reflection (r) and absorption (α), for a sail of mass M bombarded by waves 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

$$dT/dt= AP – BT – CT^4 \qquad (2)$$

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

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

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

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

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

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

Here the values of the emissivity ε and absorption α are chosen to show the effects possible in absorbing materials. P/A, the power per unit area, 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*,

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

Let us choose dm/dt=1g/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 flight experiments that observed carbon sails lifting off with accelerations several times the photonic level (Benford, 2001).*

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

$$a_d/a_P = (2/\pi g^*)\ c/V \tag{7}$$

with the thermal velocity V and g* is the number of degrees of freedom in the 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 accelerations from a beam source can exceed solar acceleraton if it illuminates the sail for more than 10^{-4} of the sail's orbit time around Earth. Such a large multiplier is the essence of the beam-driven approach to sail missions.

THERMAL DESORPTION BEAM-DRIVEN MISSIONS

To illustrate the effects of heated mass loss upon mission efficiency, Figure 2 shows a sail inserted into interplanetary space in a dozen elliptical orbits. These calculations were done by G. David Nordley using stepped-orbital system of dynamic equations, with applied power appearing solely as a delivered momentum transfer. This allows us to scale to either the pure photonic case or to a subliming/desorping case.

With heat-induced mass loss, the calculation shows that power could be lowered to ~100 MW, using attainable subliming "paints" or embedded molecules. With 10GW microwave power on the sail and a combined 10 kg for the sail and payload mass, this numerical integration shows heavier (blue) lines where the sail is lit by the source. The sail area is 1000 m^2, with beam illumination of kW/cm^2, comparable to current lab experiments on carbon sails. This case is very high power; a more realistic case would involve hundreds of orbits.

To see how sublimation (desorption) changes this, compare the ratio of accelerations, from eq. 6

$$a_D/a_P = 0.05\ (dm/dt)(g/s)\ P^{-1}(10\ GW)\ [(\alpha/0.5)(\varepsilon/0.1)^{-1}(P/A/kW/cm^2)]^{1/8} \tag{8}$$

We have taken 2r+α=2 and scaled to the above figure. By using a desorbing coat with advantageous α and ε we can increase the acceleration ratio by a factor of 22 while dropping power on sail to 10 MW. This is because a_D increases as $(P/A)^{1/8}$, so once the sail operates in the desired temperature range, a wide variation in power can yield useful accelerations. In this case, the total illumination time t*=5000 sec, so on each pass the beam is on only ~400sec.

This simple case works provided the desorbing material maintains the dm/dt rate of gm/s. Plainly, this cannot work for very low powers, but these values seem plausible. Subliming hydrogen would have an escape velocity of 7 km/s at P/A = kW/cm^2 (= 10 MW/m^2), the JPL experiments' power levels. This yields I_{sp} = 637 $(T/3000K)^{1/2}$ = 840 s.

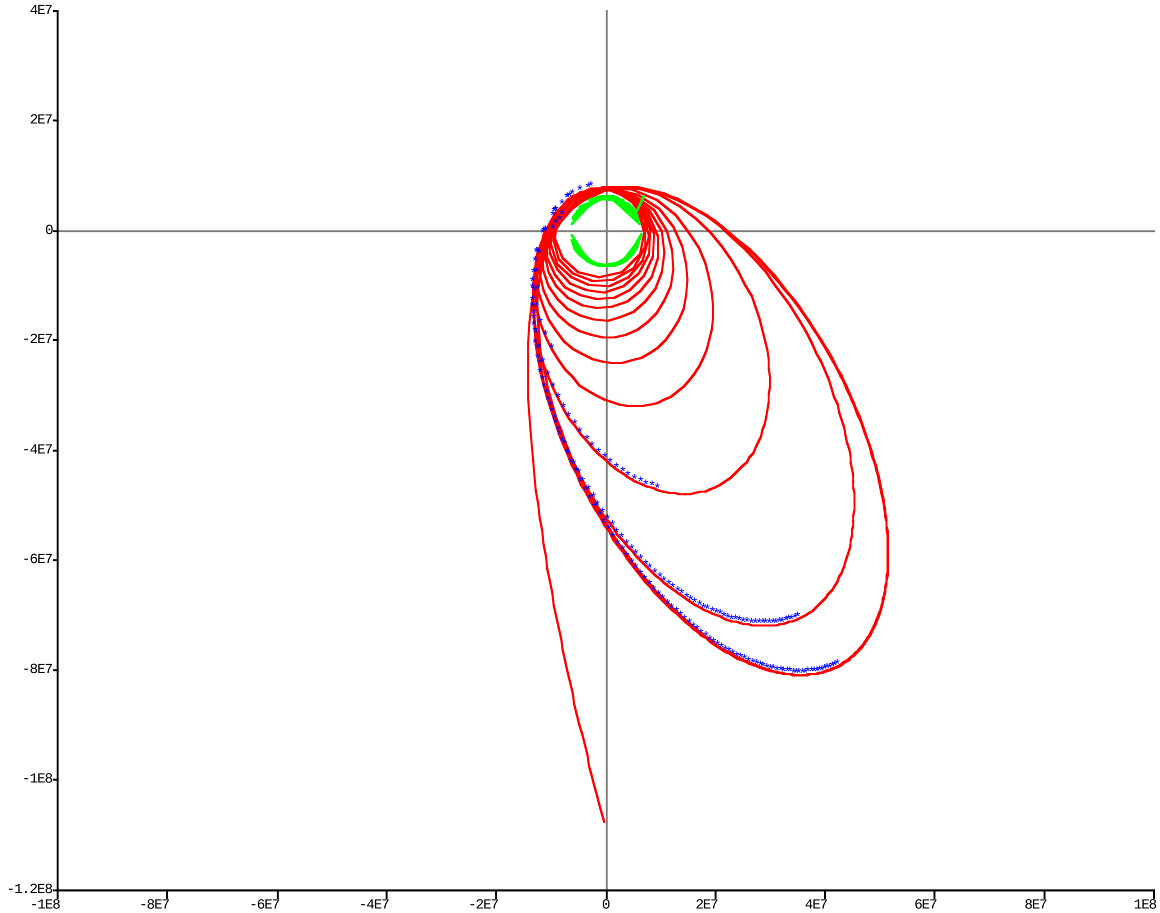

FIGURE 2 Beam-Driven Sail Orbits Around Earth On Scale Of 10^7 Km. Numerical solution of a sail illuminated with 10GW microwave power. With 10 kg payload mass, it escapes into interplanetary orbit in 12 shots from a phased array that can be either in orbit or on the ground (calculation by G. David Nordley). Heavy lines trace the illuminated portions of the orbits.

Consider the acceleration of a sail under conditions slightly modified from the above case. Here we assume payload plus adsorped material has a mass of 20 kg, while the underlying sail has 10 kg, giving the entire sail a total mass areal density of 30 g/m^2. The acceleration yields a velocity gain of 0.84 km/s for each 10,000 sec pulse that drives mass loss at a nominal 1 gm/sec. Higher mass loss rates will lower the number of pulses needed.

SUN-DIVER MISSIONS

For a schematic of the approach, see Figure 3. 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/cm^2 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. (See Sweetzer, 2001 and C. Maccone, 1996.) 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 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 such as Sweetzer's (Sweetzer, 2001), with plausible rates of mass loss gained from laboratory work, before judging the overall credibility of such a mission.

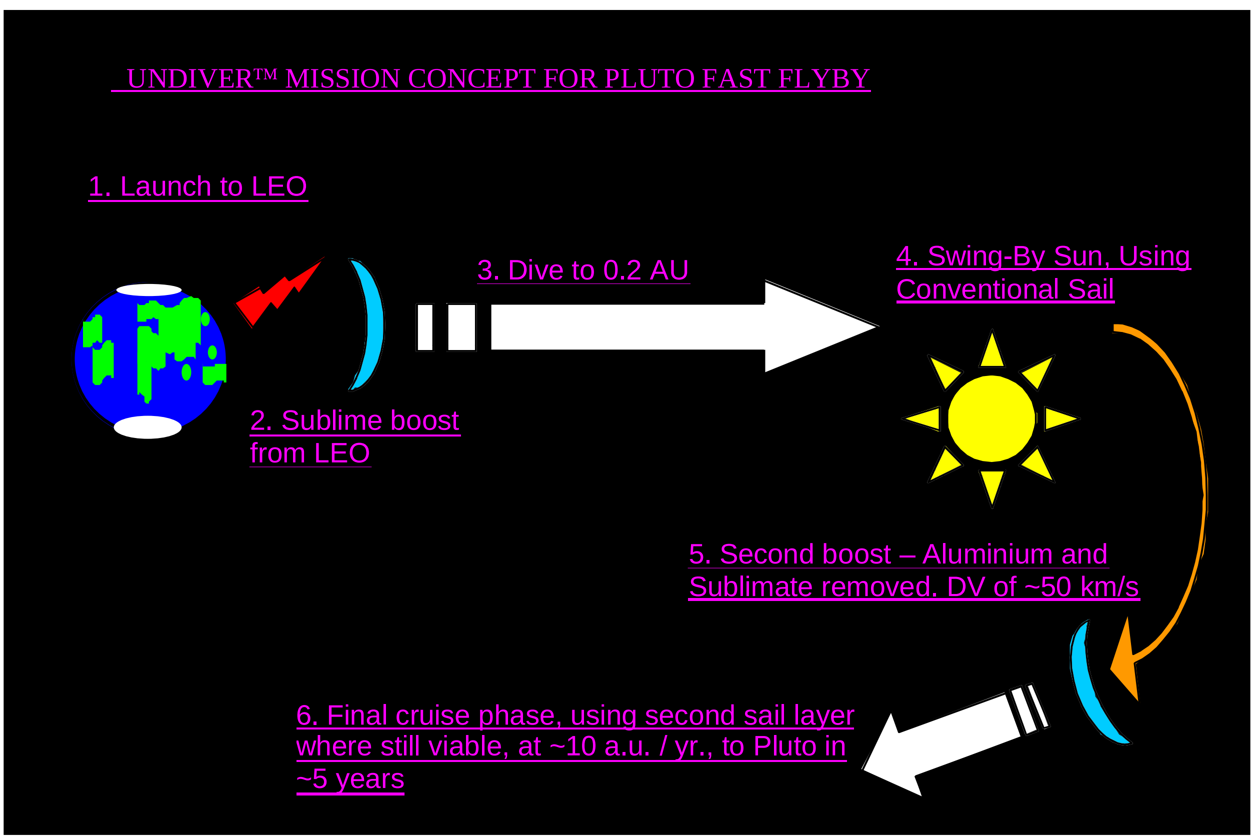

FIGURE 3. Phases of a Desorption-Assisted Sun-Diver Mission.

AN INTERSTELLAR SUNDIVER

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* (Matloff, 2000). The sail's parabolic velocity at distance R is

$$V = 1.4\ (GM/R)^{1/2} = 93\ \text{km/s}\ \ (R/0.1\ \text{AU})^{-1/2} \qquad (9)$$

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

$$T = 927\ \text{K}\ [(\alpha/0.3)(\varepsilon/0.5)^{-1}]^{1/4}\ (R/0.1\ \text{AU})^{-1/2} \qquad (10)$$

For such temperatures, a considerable $\Delta V >$ 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

$$V^F = 19.5\ \text{km/s}\ [(\Delta V/2\ \text{km/s}) + (3\sigma)^{-1}\ ]^{1/2} = 3.9\ \text{AU/year}\ (\Delta V/2\ \text{km/s})^{1/2}\ [1 + 0.33\ /(\Delta V/2\ \text{km/s})(\sigma')]^{1/2} \qquad (11)$$

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. The linear sum of ΔV and 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.

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,
- promise whole new classes of missions.

NOMENCLATURE

In some equations, the units are not SI, but are multiples of SI units, as stated in the specific equation.

a = acceleration, due to either photons, a_P, or to thermal desorption, a_d (m/s^2)
α = absorptivity

c = speed of light (m/s^2)
dm/dt = rate of desorption (kg/s)
ΔV = velocity change (m/s)
ε = emissivity
G = gravational constant ($m^3\ kg^{-1}\ s^{-2}$)
K = Stefan-Boltzman constant = W $m^{-2}\ K^{-4}$)
M = mass (kg)
P = power on sail (kW)
r = reflectivity
R = radial distance (m)
σ = sail areal mass density (100 gm/m^2)
t = time (s)
T = temperature (K)
V = velocity (m/s)

ACKNOWLEDGMENTS

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