STARDUST

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Impact of the Tumbling Rate on the Performances of a CW Laser Deflection System for Asteroids

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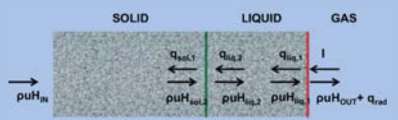
Introduction

Using a high-power laser, material can be ablated on the surface of an asteroid to remotely generate a controllable thrust without propellant. In fact, the asteroid itself becomes its own propellant. Despite this clear advantage, questions arise regarding the applicability of these methods. In particular, the rotation rate of the asteroid limits the time available to heat a given point at the surface and reach a temperature sufficient to start the ablation process. The influence of the rotation rate is included in this work on the form of a mean exposition time τ:

$$\tau = \frac{\pi}{4}\frac{\phi}{v_{rot}^{\perp}}$$

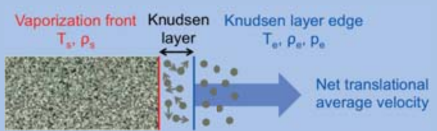
τ is a function of the beam diameter ϕ and the transverse velocity on the surface of the target $v_{rot}^{\perp}$.

Vaporization of an Asteroid



Continuity relations at the interfaces:

$$q_{liq,1} = a\Phi - q_{rad} - \rho_A u E_v$$
$$q_{liq,2} = q_{sol,1} + \rho u_m E_m$$



Conservation of mass through the passage of the interface implies a change of velocity proportional to the density decrease. This velocity is acquired by collisions at the molecular level through a thin gas-dynamic discontinuity called the Knudsen layer[1].

$$\frac{T_e}{T_s} = \left[\sqrt{1+\pi\left(\frac{\gamma-1}{\gamma+1}\frac{m}{2}\right)^2} - \sqrt{\pi}\frac{\gamma-1}{\gamma+1}\frac{m}{2}\right]^2$$

$$\frac{\rho_e}{\rho_s} = \sqrt{\frac{T_s}{T_e}}\left[(m^2+\frac{1}{2})e^{m^2}\,\mathrm{erfc}(m) - \frac{m}{\sqrt{pi}}\right] + \frac{1}{2}\frac{T_s}{T_e}\left[1-\sqrt{\pi}me^{m^2}\,\mathrm{erfc}(m)\right]$$

In vacuum, the sonic limit is reached and $m = \sqrt{\frac{\gamma}{2}}$. The recession rate $u = \frac{\rho_e}{\rho_A}\sqrt{\gamma R T_e}$ increases with the surface temperature T_s and the flux Φ.

References

[1] C. J. Knight (1979) *AIAA journal* 17(5):519.

[2] S. I. Anisimov, et al. (1995) *Instabilities in laser-matter interaction* CRC press.

[3] C. Phipps, et al. (2010) *Journal of Propulsion and Power* 26(4):609.

Steady Analytical Model

In the regime state, T_s is obtained by solving:

$$a\Phi = q_{rad} + \rho_A u(T_s)\left(E_v + E_m + c(T_s - T_\infty)\right)$$

The temperature within the asteroid is:

$$T(z>z_m) = \frac{T_S - T_m}{1-\exp\left(-\frac{u}{\alpha}z_m\right)}\exp\left(-\frac{u}{\alpha}z\right) + \frac{T_m - \exp\left(-\frac{u}{\alpha}z_m\right)T_S}{1-\exp\left(-\frac{u}{\alpha}z_m\right)}$$

$$T(z \le z_m) = (T_m - T_0)\exp\left(-\frac{u}{\alpha}(z-z_m)\right) + T_0$$

A melting front is located beneath the surface and precedes the vaporization wave:

$$z_m = \frac{\alpha}{u}\log\left(\frac{T_S - T_m}{T_m - T_0 + \frac{E_m}{c}} + 1\right)$$

An estimation of the time to reach the steady-state is given by [2]

$$\tau_{ss} \approx \frac{\alpha}{u^2} \approx \left(\frac{\Gamma}{a\Phi}\right)^2\left(\frac{E_v}{c}\right)^2 \propto \Phi^{-2}$$

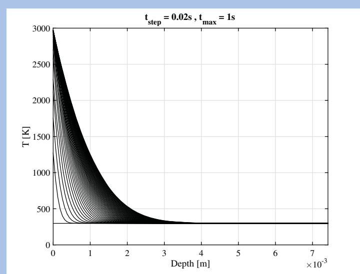
Transient Numerical Model

$$\frac{dH_i}{dt} = -\frac{q_{i+1/2} - q_{i-1/2}}{\Delta z} + u(T_1)\frac{H_{i+1} - H_i}{\Delta z}$$

The boundary conditions are then taken into account by setting:

$$q_{1-1/2} = a\Phi - q_{rad}(T_1) - \rho_A u(T_1)E_v$$
$$q_{N+1/2} = -k\frac{T_\infty - T_N}{\Delta z}$$

Temperature is recovered at each time-step and its evolution is illustrated here for $\Phi = 39MW/m^2$:

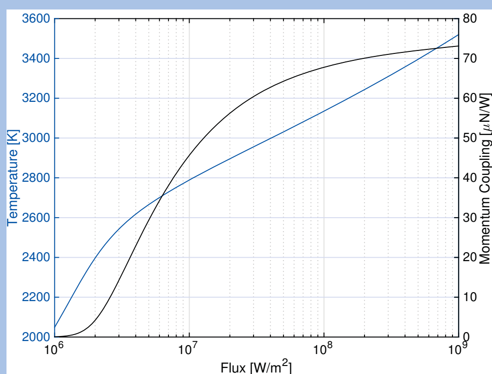


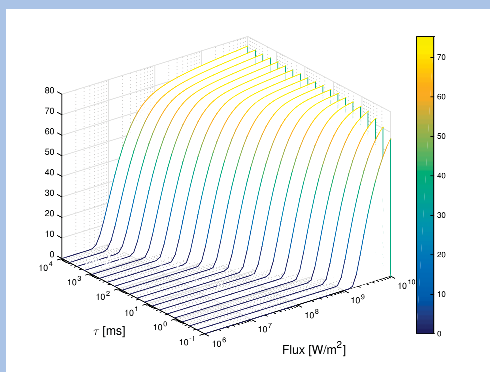
Impulse Coupling

The figure of merit is given by the impulse coupling C_m, equal to the ratio between the effective pressure p_{eff} and the laser flux:

$$C_m = \frac{p_{eff}}{\Phi} = \frac{p_e + \rho_e v_e^2}{\Phi} = \frac{(\gamma+1)p_e}{\Phi}$$

The impulse coupling is plotted in function of the flux on the left for the steady-state model and on the right for the numerical model for different values of the mean exposition time τ ($\propto (v_{rot}^{\perp})^{-1}$)





Both models predict a coupling beyond $70\mu N/W$ when transient effects are negligible. In this case, a minimum flux of 1-10MW/m^2 appears necessary to enable the ablation process at a meaningful level. Transient effects are seen to shift the region of high efficiency towards higher fluxes. Both the theory and the numerical model suggest that the impulse coupling is function of the scaling variable $\Phi\sqrt{\tau}$ only. Hence, dividing the time by a factor 2 implies to multiply the flux by a factor 4 to keep the same level of efficiency. Our result is consistent with previous studies on pulsed lasers from Phipps et al. [3].

Conclusion

- An analytical and a numerical model have been developed to study the efficiency of a CW laser deflection system on an asteroid submitted to a rotational motion
- Both models predict an impulse coupling up to $70\mu N/W$ when transient effects are negligible.
- A minimum flux in the range of 1-10MW/m^2 is necessary to enable the ablation process
- The ablation threshold and the region of maximum efficiency are shifted towards higher fluxes when the rotation rate is taken into account