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Experimental analysis of laser ablated plumes for asteroid deflection and exploitation

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ABSTRACT

It has been theoretically demonstrated that laser ablation is effective in the potential deflection and mitigation of asteroids. However, there have been few experimental studies to support this claim. The theoretical models are currently based on assumptions regarding the laser beam diameter, the power requirement, the formation of the ejecta plume, and the potential for ejecta to contaminate and otherwise degrade any exposed surface. Recent proposals suggesting the use of a solar pumped laser, in particular, can be deeply affected by the re-condensation of the ejecta. To either validate, amend and/or eliminate these assumptions a series of laser ablation experiments have been performed. Using a 90 W, continuous-wave laser operating at 808 nm, a rocky magnesium iron silica based material – olivine – has been ablated. These experiments were used to examine the validity of the theoretical model and the experienced levels of contamination. It will be shown that the current model correctly predicts the ablated mass flow rate for rocky based asteroids, but overestimates the contamination rate and the degradation of the optics.

1. Introduction

Near Earth Asteroids (NEAs) represent both an opportunity and a risk. Their pristine environment captures the early formation of the solar system; while their impact potential could result in the mass extinction of life. The Earth has been, and will continue to be, the subject of many other ground and air impacting events. Amid the observed population, there are at least between 2000 and 200,000 objects that could impact the Earth [1]. On average, an asteroid with a diameter greater than 100 m impacts the Earth once every 10,000 years. This can cause local damage, earthquakes and tsunamis. Asteroids that impact the Earth with a diameter larger than 1 km are considered to be global killers. Such an impact event is considered to catastrophically annihilate 90% of all life, resulting in a nuclear winter, with little chance of recovery within the near term [1]. This is thought to have happened, once before, approximately 65 million years ago, with the impact of a 10 km diameter asteroid at 12 km/s [23].

Therefore potential methods of asteroid mitigation and deflection have been addressed by numerous authors [2–4]. Amongst the many possibilities to deflect NEAs, ablation has been shown to be theoretically one of the most effective methods [5]. Work conducted in 2009 by

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Nomenclature

$(\Delta m/A)_{\mathrm{SLIDES}}$	Ejecta mass per unit area deposited on the microscope slides during ablation
A	Area of the microscope slide
a_b	Absorbance
A_{SPOT}	Area of the laser's surface spot
c_A	Heat capacity of the asteroid
C_m	Momentum coupling
$C_{\boldsymbol{R}}$	Concentration ratio
d_{SPOT}	Diameter of the surface spot
dh/dt	Surface layer growth
dm/dt	Mass flow rate during sublimation
E	Incoming energy during the ablation process
E_v	Sublimation enthalpy of the asteroid
F_{SUB}	Force acting on the asteroid
h_{EXP}	Height of the deposited ejecta from the experiment
k	Adiabatic index, for diatomic molecules
k_b	Boltzman's constant
K_p	Jet constant
k_t	Thermal conductivity of the asteroid
M_a	Molar mass of the target material
NEAs	Near Earth Asteroids
$P_{1\mathrm{AU}}$	Solar power at 1 Astronomical Unit
P_{IN}	Absorption of the laser beam
Q^*	Energy required to ablated each kilogram of material
Q_{COND}	Heat losses due to conduction
Q_{RAD}	Heat losses due to radiation
R	Distance from the Sun measured in Astronomical Units
r	Radius from the spot location
SEM	Scanning Electron Microscope
t	Sublimation duration
T	Transmittance
T_{amb}	Ambient temperature
T_0	Temperature at the centre of the asteroid
T_{SUB}	Sublimation temperature of the asteroid in vacuum conditions
v	Average velocity of the ejecta plume
ε	Black body emissivity of the asteroid
η	Absorptivity
η_{AB}	Efficiency of the ablation process
θ	Elevation angle, from the surface normal
θ_{MAX}	Limited expansion angle
λ	Scatter factor
ρ	Density of the ejecta plume
ρ^*	Density at the nozzle
ρ_A	Density of the asteroid
ρ_l	Layer density
σ_{SB}	Stefan–Boltzmann constant
τ	Degradation factor
ψ_{vf}	View angle
Δh_{EXP}	Measured thickness of the deposited material
Δm	Mass loss during ablation
Δt	Ablation duration
η_{sys}	Overall conversion efficiency from solar input to laser output
η_{abs}	Absorptivity of the illuminated asteroid

Sanchez et al. [5] compared the effectiveness of six different asteroid deflection techniques. Through a multi-criteria, quantitative comparison the nuclear interceptor, kinetic impactor, mass driver, low thrust tug, ablation and the gravity tractor were assessed. Assessment was made relative to the achievable miss distance at Earth, the warning time, the total mass into orbit and the current technology readiness level. With both a relatively short warning time and a low mass into space, ablation can provide significantly higher and more controllable rates of deflection. The technique is also advantageous as it avoids the catastrophic fragmentation of the asteroid. It also eliminates the need of having to physically land and/or attach a system onto the surface of the asteroid [5].

Ablation is achieved by irradiating the asteroid with a light source. This can either be collected and focussed solar radiation or with a laser light source. Within the illuminated focal point, the absorbed energy increases the temperature of the asteroid, enabling it to sublimate. This transforms the exposed material directly from a solid to a gas. The ablated material then expands to form an ejecta plume. Over an extended period of time, the resultant thrust, induced by the ejecta plume and acting on the asteroid can be used to push the asteroid away from its original threatening trajectory [2]. This increases the minimum orbit interception distance between the Earth and the asteroid, otherwise preventing the Earth impacting event [5–8].

Previous proposals for the initiation of laser ablation considered using either a ground-based or space-based facility [1,19]. For a ground-based facility an average power level of several giga-watts would be required to deflect a small, 40–80 m in diameter asteroid [19]. This was considered to be a substantial investment in infrastructure and resources. Therefore an alternative option was to mount a mega-watt laser onto a large single spacecraft. The laser would be powered by a nuclear reactor [20]. However, manoeuvring and operating such a large structure, at close proximity to the asteroid, under an irregular gravity field was considered to be very difficult. This is further coupled with developing a nuclear reactor for space-based applications, and the associated political ramifications. Therefore an alternative concept was proposed. Instead of a large single structure, a swarm of small spacecraft, each equipped with an identical kilowatt solar-pumped laser could be used [10]. This provides a much lighter and more adaptable concept. By superimposing each laser beam, the cumulative surface power density would be used to initiate the ablation process [10]. Singular or multiple ablation spots can also be used. This increases the flexibility and overall redundancy of the deflection mission. As required, more spacecraft can be added or removed from the existing configuration, eliminating the need to develop and design new spacecraft(s) [6,7,9]. The potential for deflection is therefore dependent on the number of spacecraft located within the