
This version is available at https://strathprints.strath.ac.uk/44166/

Strathprints is designed to allow users to access the research output of the University of Strathclyde. Unless otherwise explicitly stated on the manuscript, Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Please check the manuscript for details of any other licences that may have been applied. You may not engage in further distribution of the material for any profitmaking activities or any commercial gain. You may freely distribute both the url (https://strathprints.strath.ac.uk/) and the content of this paper for research or private study, educational, or not-for-profit purposes without prior permission or charge.

Any correspondence concerning this service should be sent to the Strathprints administrator: strathprints@strath.ac.uk
LASER BEES
A Concept for Asteroid Deflection & Hazard Mitigation

Alison Gibbings, Advanced Space Concepts Laboratory, University of Strathclyde
Dr Massimiliano Vasile, Advanced Space Concepts Laboratory, University of Strathclyde
Dr John-Mark Hopkin, Institute of Photonics, University of Strathclyde
Dr David Burns, Institute of Photonics, University of Strathclyde
Dr Ian Watson, Systems, Power and Energy, School of Engineering, University of Glasgow
CONTENTS

Asteroids Risk
Laser Ablation
Modelling Technique
Experiment
Results & Conclusion
ASTEROIDS

- Asteroid 99942 Apophis, non-negligible impact risk, 2039
- Asteroid YU55 passes in-between the Earth's-Moon orbit, 2011
- Asteroid 2002 MN missed the Earth by only 120000 km, 2002
- Ground Impact, New Guinea, 1994
- Ground Impact, Grand Teton Park, USA, 1972
- Ground Impact, Pribram, Czechoslovakia, 1959
- Ground Impact, Sikhote-Alin, Russia, 1947
- Ground Impact, Curaca Crater, Brazil 1930
- Air Impact, Tunguska, Russia 1908
- Ground impact, Arizona, Barringer Meteorite Crater, 50000 years ago
Methods of asteroid mitigation and deflection have therefore been addressed by numerous authors [Melosh, 1994; Conway 2001, Gritznes & Kahle 2004 Sanchez, Vasile et al, 2009; Yeomans, Bhaskaran et al 2009; Love 2005; Scheeres & Schweickart, 2004]

DEFLECTION METHODS

Impulsive Methods
- Kinematic Impactor(s)
- Nuclear Blast
- Nuclear Blast

Low Thrust Methods
- Mass Drivers
- Surface Ablation
- Low Thrust propulsion
- Gravity Tractor(s)

Passive Methods
- Paint & the Yarkovsky Effect

The overall performance depends on how the deflection method interacts with the asteroid, the response time, the mission complexity and the technology readiness
WHY SURFACE ABLATION?

Analysis from a multi-criteria quantitative comparison [Sanchez et al, 2009]

Compared kinematic impactor, nuclear detonation, mass drivers, low thrust tug, ablation and the gravity tractor

Relative to the miss distance at Earth, the warning time, the total mass into orbit and the technology readiness levels

Ablation was shown to be, theoretically, a promising technique

No fragmentation of the asteroid
No need to physically attach and/or land on the surface
Energy source is freely available and external from the Sun
Ablated material is the asteroid itself

A high rate of controllable deflection can be achieved.
Both with a relatively low mass into space and a short warning time
ABLATION

Ablation is achieved by irradiating the surface by light – direct solar radiation or laser – source. The resulting heat sublimes the surface, transforming it directly from a solid to a gas.

An ejecta cloud of the ablated material forms. This acts against the asteroid, providing a continually controlled low thrust.
ABLATION, PREVIOUS WORK


A large, single mirror – solar concentrator - mounted onto a single spacecraft
To collect, direct and concentrate solar light onto a small area of the asteroid

Technique requires a 1~10 km diameter mirror; Significant space structure
Becomes susceptible to the deposition of ejecta
Operates in close proximity to the asteroid, under an irregular gravity field
ABLATION, PREVIOUS WORK

2. Campbell, Phipps et al, 1992, 1997; Park & Mazanek, 2005

Sublimate the asteroid with a high power, mega watt, laser
Powered by a nuclear reactor

Develop a large nuclear reactor for space applications

Significant legal ramifications of operating a nuclear reactor in space

Difficulties of manoeuvring and operating large structure
ABLATION, PREVIOUS WORK

ALTERNATIVE METHOD: [Vasile & Maddock, 2009, 2010; Sanchez, 2009]

- Fractionate the monolithic spacecraft into a number of identical units
- Swarm of small scale spacecraft, flying in formation about the asteroid
- Each equipped with a small solar concentrator [known as Mirror Bees]

Each spacecraft simultaneously collects and focuses solar radiation directly onto the asteroid’s surface

By superimposing their light beams the required surface power density can be achieved, successfully ablating a small portion of the asteroid’s surface

Swarm configuration is taken to be:
- A lighter, more adaptable concept
- Increased redundancy by design
- Scaleable
However each MIRROR BEE spacecraft still needs to be placed in close proximity to the asteroid. Technique is highly susceptible to the deposition and contamination of the ablated ejecta.

To increase the distance between the asteroid and spacecraft (~1 to 4 km):

- Use a swarm of spacecraft
- Each equipped with a small solar collector and a laser
- A collimated laser beam can propagate over extended distance, without the loss of energy
LASER BEES

Equip each spacecraft with a identical kilo-watt laser
Pumped directly or in-directly from the Sun (via solar concentrators)

However, within the vicinity of the ejecta plume, any exposed surface(s) will be subjected to the contaminating effects of the condensing ejecta

M_d – Steering Mirror
LASER BEES, OPEN QUESTION

• Physical formation and evolution of the ejecta plume
  1. Is it similar to the formation of the rocket exhaust in rocket propulsion?
  2. Is there uniform dispersion of the ejecta over the given hemisphere?
  3. Is a constrained plume of ejecta more plausible?
  4. What particles are contained within the ejecta?
     A. Only hot gas? Any solid particles?

• Ablation response for different material
  1. What is the difference between dense and porous material?

• Sensitivity of contamination and degradation of the ejecta
  1. What is the actual degradation rates of the exposed surface? $f(r, \theta)$
  2. What are the physical properties of the condensed material?
  3. Does all the ejected material immediately stick?
  4. Is there any attenuation of the laser beam?

Can we ensure the maximum survivability of the system to maximise the achievable deflection of the technique?
ABLATION EXPERIMENTS

A series of laser ablation experiments using a 90 W continuous-wave laser has been performed. Investigate the development of the ejecta plume – mass flow rate, velocity and divergence – and the potential for contamination.

Calibrate and validate the development of numerical models and existing theory.

[Vasile & Maddock, 2010; Sanchez et al, 2009]
MODELLING TECHNIQUE

Current assumptions in the numerical method must be verified

Ejecta depends on the available energy & efficiency of the ablation process

[Vasile & Maddock, 2010; Phipps 2010; Sanchez, 2009; Kahle 2006]

Plume profile is similar to a rocket exhaust

Standard methods of rocket propulsion
Uniformly expanded gas of ejecta; No solid particles
No ionization of the gas; Constant scatter factor

Assumed a spherical, dense, homogenous body

Forsterite (Mg2Si04) is typically used
Asteroid has an infinite heat sink
Constant internal temperature during sublimation

Ejected particles will immediately condense and stick
Assumptions on the degradation and attenuation
MODELLING TECHNIQUE

The sublimation process is modelled on the energy balance equations [Vasile & Maddock, 2009, 2010; Sanchez, 2009]

Combines the absorption of the laser beam $P_{IN}$, the heat losses of conduction $Q_{COND}$ and radiation $Q_{RAD}$ respectively and the sublimation enthalpy of the target material $E_v$

$$\frac{dm}{dt} = \frac{1}{E_v} (P_{IN} - Q_{RAD} - Q_{COND})$$

$$Q_{RAD} = \sigma_{SB} \varepsilon A_{SPOT} \left( T_{SUB}^4 - T_{amb}^4 \right)$$

Assumes a black body

$$Q_{COND} = \left( T_{SUB} - T_0 \right) A_{SPOT} \sqrt{\frac{c_A \rho_A \kappa}{\pi t}}$$

Assumes an infinite heat sink
MODELLING TECHNIQUE

Average velocity of the gaseous ejecta is calculated from Maxwell’s distribution
Assuming the behaviour of an ideal gas

\[
\bar{v} = \sqrt{\frac{8kT_{sub}}{\pi M_a}}
\]

Force and acceleration acting on the asteroid:

\[
F_{SUB} = \lambda
\]

\[
a = \frac{F_{SUB}}{M_A}
\]

Assumes a constant scatter factor
Account for the dispersion of the ejecta plume
Considered to distribute uniformly over a half sphere
Conservative assumption
Density of the ejecta plume

Function of distance, $r$, from the spot and angle, $\theta$, from the centre line

$$\rho(r, \theta) = \rho^* A_P \frac{d_{SPOT}^2}{(2r + d_{SPOT}^2)^2} \left[ \cos \left( \frac{\pi \theta}{2\theta_{MAX}} \right) \right]^{\frac{2}{k-1}}$$

**MODELLING TECHNIQUE**

[Kahle et al, 2006]

**Density at the nozzle:**

$$\rho^* = \frac{m_{\text{exp}}}{A_{SPOT} v}$$
MODELLING TECHNIQUE

Contamination and degradation

[Kahle et al, 2006]

Will occur to any exposed surface located within the ejecta volume
Assumed that all particles – gas – will re-condense and stick

Variation in ejecta thickness – surface growth - is given by:

\[
\frac{dh}{dt} = \frac{2v\rho}{\rho_{layer}} \cos(\psi_{vf})
\]

\(\psi_{vf}\) is the view angle
\(\rho\) – Density of the ejecta
\(\rho_{layer}\) - Layer density. This is assumed to be 1000 kg/m\(^3\)
\(\eta\) - Absorption coefficient (silica, at 800 nm, ~ 10\(^6\)/m)

The degradation factor, \(\tau\),

Beer-Lambert-Bougier law

\[\tau = e^{-2\eta h_{END}}\]
MISSION CASE

Asteroid diameter of 250 m and mass of $2.7 \cdot 10^{10}$ kg
(Based on Apophis)

Swarm of spacecraft
Each with a 10 m primary concentrator
In-directly pumped
Semiconductor fibre laser,
Efficiency of 60 %
Output power 22 kW
MISSION CASE

Not accounting for degradation

Under ideal conditions, achieve a maximum deflection distance of 30,000 km.

Mirror diameter $d=10\text{m}$, $C_r=5000$, laser efficiency $=0.60$, cell efficiency $=0.4$. 

Under ideal conditions, achieve a maximum deflection distance of 30,000 km.
MISSION CASE

Assuming the parameters, given in Kahle

Condensed ejecta density of 1000 kg/m$^3$

Absorbitivity of $10^6$ m$^{-1}$

Mirror diameter d=10m, $C_r$=5000, laser efficiency=0.6, cell efficiency=0.4

Reduction in performance of 85%

Almost immediate saturation of the exposed optics

Achievable miss distance reduces to 4500 km
OBJECTIVES

Performed a series of ablation experiments using a 90 W continuous-wave laser

Investigated the development of the ejecta plume – mass flow rate, velocity and divergence – and potential for contamination.

Calibrate and validate the development of numerical models and existing theory

[Vasile & Maddock, 2010; Sanchez et al, 2009]
THE LASER

A 90 W continuous wave laser (LIMO 90-F2000-DL808)
Fibre-coupled semiconductor
Operating at 808 nm

Horizontally mounted and cooled by a recirculation chiller at 15 °C
After focusing, it provided an approximate spot diameter of 0.5 mm
After losses provides 30 kW/cm², surface power density, at the focus
Initial ablation experiments first occurred under a nitrogen purge environment
- Transparent test chamber
- Reduce the occurrence of atmospheric combustion to negligible levels. Any innate material combustion still occurred.
- Tested and refined the proposed methodologies and techniques
  - Either measured, calculated or inferred quantities

Developed and integrated the vacuum chamber system
- Allowed for maximum expansion of the plume
- Eliminating particle drag caused by an atmosphere
Focusing Optics

Use a thermocouple to measure the temperature of the target material during ablation.

Laser off screen

Measure the divergence and formation of the ejecta plume.

Measure the ablation time.

Measured the mass of the target material before and after, enabling the mass flow rate of ablation to be determined.

The experiment

Ejecta is collected on microscope slides.

Measure the deposited mass of the ejecta.

Measure the affect of contamination and degradation.

High resolution cameras

High resolution cameras

Used a thermocouple to measure the temperature of the target material during ablation.

alison.gibbings@strath.ac.uk
THE EXPERIMENT

Used a spectrometer to measure the spectra – wavelength vs intensity - of the ablated spot

Temperature of the spot was then inferred from the Wein displacement law

\[ \lambda_{PEAK} T_{SUB} = 2.898 \times 10^{-3} - \frac{8kT_{sub}}{v} = \sqrt{\frac{8kT_{Sub}}{\pi M_a}} \]

Used a microscope to measure the height of the collected ejecta on the slides and the diameter of the ablated hole

Measured the depth of the ablation hole

Measured the transmittance/absorption of the ablated slides

Calculated the absorbance per unit length, \( \eta \), of the ejecta

Used a Scanning Electron Microscope to study the composition of the plume
TARGET MATERIAL

Sandstone
Represent a rocky, dense asteroid
Bulk density: 2250-2670 kg/m³

Olivine, magnesium iron silicate ($\text{MgFe}_2\text{SiO}_4$)
Represent a rocky, dense, S-type asteroid
Bulk density – 3500 kg/m³

Fabricated a composite mixture
Represent a highly porous, rubble pile asteroid
Expanded perlite, sand, fly ash and water
Bulk density ~ 400 kg/m³
Bulk porosity ~ 80 %

[Housen, 2004, Housen & Holsapple 2003]
THE EXPERIMENT
NITROGEN PURGE

Small, and extended rocket plume
Similar mass flow rate, compared to the model

Variation in cone angle and ejecta distribution
Ablation process included solid ejecta particles
Subjected to the volumetric removal of material
Resulted in the laser tunnelling into the subsurface
Technique is sensitive to the focal point of the laser

Subjected to the structure and composition of the target material

$T_0 \sim 0.5 \text{ sec}$
$T \sim 1 \text{ min 14 sec}$
At the focus
0.5 mm diameter spot size
37 kW/cm²

Widening the spot
Defocusing the laser beam

5 mm behind the initial focus
2.4 mm diameter, spot size
1.98 kW/cm²

Adaptive Optics
Collimated Beam
NITROGEN PURGE

Local depositions in and around the ablation volume
- White residual was deposited around the ablation rim
- Within the ablation volume a semi-melted glassy material is created

These depositions do not contribute to the formation of the ejecta plume

Ablation hole was larger than the spot size diameter
- Original illumination 0.5 mm (assumed constant in model)
  - Sandstone – 1.83 mm
  - Porous – 2 mm

Volumetric heating of the target material
- Leads to increased ablation for a lower energy input
- No observable attenuation of the laser beam
VACUUM

Small & extended rocket plume. Little ejecta
At 3, 7 and 10 cm away from the spot:
  Measured the deposited mass/area, $(\Delta m/A)_{\text{SLIDES}}$
  Measured the height of the ejecta, $\Delta h_{\text{EXP}}$

From this the density of the deposited material can be calculated $\rho_{\text{EXP}}(r, \theta)$
Derive the expected collection rate of ejecta on each slide

$$\rho_{l,\text{EXP}}(r, \theta) = \left( \frac{\Delta m(r, \theta)}{A} \right)_{\text{SLIDES}} \frac{\Delta h_{\text{EXP}}}{\Delta h_{\text{EXP}}}$$

$$\frac{1}{A} \frac{dm}{dt} = 2 \rho(r, \theta)v$$

Measured the transmittance of the slides

$V_{\text{EXP}} \sim 632 \text{ m/s}$

$T_{\text{sub}} \sim 4747 \text{ K}$
MASS FLOW RATE, SAMPLE

Surface illumination of either a 43 W or 62 W laser beam

<table>
<thead>
<tr>
<th>43 W</th>
<th>Theory: $2.59 \times 10^{-8}$ kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp: $2.40 \times 10^{-8}$ kg/s (-7 %)</td>
</tr>
<tr>
<td></td>
<td>Exp: $3.90 \times 10^{-8}$ kg/s (+50 %)</td>
</tr>
<tr>
<td></td>
<td>Exp: $2.12 \times 10^{-8}$ kg/s (-18 %)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>62 W</th>
<th>Theory: $3.17 \times 10^{-8}$ kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp: $4.63 \times 10^{-8}$ kg/s (+25 %)</td>
</tr>
<tr>
<td></td>
<td>Exp: $3.07 \times 10^{-8}$ kg/s (-17 %)</td>
</tr>
<tr>
<td></td>
<td>Exp: $5.65 \times 10^{-8}$ kg/s (+52 %)</td>
</tr>
<tr>
<td></td>
<td>Exp: $4.43 \times 10^{-8}$ kg/s (20 %)</td>
</tr>
<tr>
<td></td>
<td>Exp: $3.28 \times 10^{-8}$ kg/s (-12 %)</td>
</tr>
</tbody>
</table>

Variations are considered to be caused by local variations in the rock sample
DEPOSITED MASS

Accumulated mass on the slides 3 cm from the spot

Model @ 2.82E−08 kg/s
Test 1 @ 2.40E−08 kg/s
Test 2 @ 2.03E−07 kg/s
Model @ 4.07E−08 kg/s
Test 3 @ 4.63E−08 kg/s
DEPOSITED MASS

Accumulated mass on the slides
7 cm from the spot
Accumulated mass on the slides
10 cm from the spot
THICKNESS, DEPOSITED MATERIAL

$\Delta h [m]$

$\theta [\text{deg}]$

Model @ 2.59E−08 kg/s
Test 1 @ 3.90E−08 kg/s
Test 2 @ 3.07E−08 kg/s
Model @ 3.84E−08 kg/s
Test 3 @ 5.65E−08 kg/s

$r=7\text{cm}$
THICKNESS, DEPOSITED MATERIAL

$r = 10$ cm

Test 2 @ $4.43 \times 10^{-8}$ kg/s
Model @ $3.84 \times 10^{-8}$ kg/s
Test 3 @ $3.28 \times 10^{-8}$ kg/s
THICKNESS, DEPOSITED MATERIAL

Self cleaning action
The degradation factor, $\tau$, for Beer-Lambert-Bouguier law is given by:

$$\tau = e^{-2\eta h_{\text{EXP}}}$$
DEGRADATION FACTOR

Model @ 2.59E−08 kg/s
Test 1 @ 2.40E−08 kg/s
Test 2 @ 2.03E−07 kg/s
Model @ 3.84E−08 kg/s
Test 3 @ 4.63E−08 kg/s

r=3cm

T

θ [deg]
DEGRADATION FACTOR

$T_{r=7cm}$

Model @ 2.59E−08 kg/s
Test 1 @ 3.90E−08 kg/s
Test 2 @ 3.07E−08 kg/s
Model @ 3.84E−08 kg/s
Test 3 @ 5.65E−08 kg/s
COMPARISON

- Model predicts significantly greater degradation than observed
  - Expected to be higher at lower angles; plume density is larger.

- HOWEVER, instead, the experimentally measured thickness is much higher
  - BUT with equal mass per unit area

- Density of the deposited ejecta is much lower than assumed
  - Model: 1000 kg/m$^3$ with an assumed absorptivity of $10^6$ m$^{-1}$
  - Experiment:
    - At 7 and 10 cm away

Reasonable to assume that at 3 cm the plume is very focused
Expansion leads to a more distributed layer of material at 7 and 10 cm
COMPARISON

Experiment had a correlated mass flow and deposition rate

However, the model assumed:
- An incorrect growth of the deposited material
- An incorrect density of the ejected material
- An incorrect absorptivity
- That all the material bonded with the slides

Represents an inaccuracy within the modelling technique

Experiment also demonstrated
- Variation in cone angle & dispersion geometry
- Variation in distribution of ejecta
- Ablation includes the ejection of solid particles $f(\text{material})$
- Subject to the volumetric removal of material & material phase change
- Subject to the depth of focus of the laser
LASER BEES, OPEN QUESTION

- **Physical formation and evolution of the ejecta plume**
  1. Is it similar to the formation of the rocket exhaust in rocket propulsion?
  2. Is there uniform dispersion of the ejecta over the given hemisphere?
  3. Is a constrained plume of ejecta more plausible?
  4. What particles are contained within the ejecta?
    - A. Only hot gas? Any solid particles?

- **Ablation response for different material**
  1. What is the difference between dense and porous material?

- **Sensitivity of contamination and degradation of the ejecta**
  1. What is the actual degradation rates of the exposed surface? $f(r, \theta)$
  2. What are the physical properties of the condensed material?
  3. Does all the ejected material immediately stick?
  4. Is there any attenuation of the laser beam?

Can we ensure the maximum survivability of the system to maximise the achievable deflection of the technique?
MISSION CASE

Asteroid diameter of 250 m and mass of $2.7 \times 10^{10}$ kg
(Based on Apophis)

Swarm of spacecraft
Each with a 10 m primary concentrator
In-direct pumped
Semiconductor fibre laser,
Efficiency of 60 %
Output power 22 kW
MISSION CASE

Not accounting for degradation

Mirror diameter \( d = 10 \text{m} \), \( C_r = 5000 \), laser efficiency = 0.60, cell efficiency = 0.4

Under ideal conditions achieve a maximum deflection distance of 30,000 km
MISSION CASE

Assuming the parameters, given in Kahle
Condensed ejecta density of 1000 kg/m³
Absorbitivity of $10^6$ m⁻¹

Mirror diameter $d=10m$, $C_r=5000$, laser efficiency=0.6, cell efficiency=0.4

- Reduction in performance of 85%
- Almost immediate saturation of the exposed optics
- Achievable miss distance reduces to 4500 km
MISSION CASE  

Using the experimental data

OLIVINE

Deposited ejecta density of 250 kg/m$^3$ and an absorbitivity of $5 \cdot 10^4$ m$^{-1}$

Mirror diameter $d=10$m, $C_r=5000$, laser efficiency=0.6, cell efficeincy=0.4

Compared to Kahle

Over double the achievable deflection distance

There is an effect, but its affect is not as significant

Reduction of 67 % compared to the nominal case
MISSION EXTENSION

Experiment also demonstrated that laser ablation can be used for a wide range of space-based missions. Once a plume of ejecta has been formed:

- **In-situ Spectra Analysis**
- **Collection & Sample Return**
- **Resource Extraction**
- **Resource Exploitation**
- **Capture & Control**

Contactless method
- No requirement to land and attach to the asteroid
- No complex landing operations
- No fragmentation of the asteroid

Durability and diversity of a space-based laser system
However a number of questions still remain unanswered. This includes:

- Ablation experiment on a pendulum, rather than static sample
- Ablation from a highly angled laser beam
- Ablation of a pulsed laser beam, assess higher energy ablation
- Ablation of inhomogeneous, irregular rotating samples, affect of porosity
- Using a thermal and high speed camera
  - Identification of the ejecta plume and measuring the velocity of the ejecta
  - Spot, slide and target material temperature profile during ablation f(t)
  - Efficiency of the self cleaning action
- Effect of slide heating in the contamination of the deposited ejecta
- Assess the composition and distribution of the ejecta
  - AFM for global topography and SEM for composition
- Measure the deposition of ejecta *in-situ* as a function of time
- Experiments with *in-situ* measuring of the mass flow, relative to the depth of focus
- Measure the force directly imparted onto the asteroid during ablation
- Enhanced quality – reduced pressure - of the vacuum chamber
Thank you for your time & the continued support of The Planetary Society.

Questions Please
References
BACK-UP MATERIAL
SEM – TARGET MATERIAL

Re-crystallisation around ablation hole rim
SEM – DEPOSITED EJECTA

Ablated material is chemically identical to the target material
SPECTRA ANALYSIS
Ablation Spot - Alignment

Intensity

Wavelength nm

alison.gibbings@strath.ac.uk  a.gibbings.1@research.gla.ac.uk
SPECTRA ANALYSIS

Max Value of Intensity: 3343.33
Peak Wavelength (nm): 610.26
Temperature (K): 4747
Spectra bands show that ordinary Choridities have similar mineralogy to S-type asteroids.

**Bensour [LL]**
Recovered from a 2002 fall, Morocean-Algerian Negligible terrestrial alteration Low iron, olivine, magnesium silicate [foresterite] Porosity ~ 10 %

To represent a C-type a carbonaceous choridrite meteorite, **Allende**, was selected

Allende is a meteorite from a very rate, witness fall The carbonaceous choridrite is rich in carbon, and contains microscopic diamonds Approximately 46 billion years old
To represent an M-type asteroid, the meteorite Thuathe was selected

**THUATHE**
Witnessed fall July 21, 2002, Lesotho
H4/5 Ordinary Chondrite
High iron content

Each meteorite ideally needs to be sourced from a witness fall (freshly fallen stone), with limited weathering and fusion crust.

Ablation has to occur onto the meteorites surface, not the fusion crust.