In-Space Propulsion Engine Architecture
Based on Sublimation of Planetary Resources:
From Exploration Robots to Near-Earth Object Mitigation

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Exploration Spacecraft at work

Electrical system

Thermal system

Mechanical system

Chemical system

Propulsion system
Exploration Spacecraft at work

- Electrical system
- Thermal system
- Mechanical system
- Chemical system
- Propulsion system
- Space resource ??
Exploration Spacecraft make little use of space resources

Solar illumination, vacuum, heat sink, solar winds

But same stuff is found in space as on Earth...
Ice ... everywhere
State of Knowledge
Volatile and mineral resources available on asteroids, comets, moons and planets in the solar system

Supplemental Mechanical Power for Exploration Systems
Volatile resources ➔ Mechanical power or propulsion to deep space missions?
Identify the right applications: resource, conditions, location, need.
Measure production of gas under conditions and energy input

Mitigation of Threat from Near-Earth Objects
Can volatile resources on comets and asteroids be used to deflect them?
When is it possible?
Sublimation

Phase Diagram of Water

Phase Diagram of Carbon Dioxide

Pasadena, CA
March 27-29, 2012
NIAC Symposium 2012

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Water Ice conditions in space
Carbon Dioxide Ice conditions in space

Phase Diagram of Carbon Dioxide

Mars

Halley

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### Ice types and conditions in the solar system

<table>
<thead>
<tr>
<th>Location</th>
<th>Ice Type</th>
<th>Pressure (Torr)</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>H2O</td>
<td>$10^{-14}$</td>
<td>40 - 100</td>
</tr>
<tr>
<td>Mars</td>
<td>H2O, CO2</td>
<td>4.5</td>
<td>150</td>
</tr>
<tr>
<td>Comets</td>
<td>H2O, CO2</td>
<td>$10^{-14}$</td>
<td>40</td>
</tr>
<tr>
<td>Europa</td>
<td>H2O, CH4, CO2</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Titan</td>
<td>H2O, CO2</td>
<td>1,140</td>
<td>150</td>
</tr>
</tbody>
</table>
Applications of sublimation gas in planetary missions

Pneumatic Conveying of Regolith
Soils can be excavated and/or transferred to instrumentation or chemical reactors by gas-driven conveying. 500 grams of CO$_2$ ice sublimated into gas at 10 psig would convey 5 Kg of regolith in one minute under Martian conditions.

Attitude-control thruster (Mars)
a 3.6N thruster would require 71 Kg of CO$_2$ per minute.

Surface robots mechanical power
Removal of objects, trench digging, gas powered grappling gun, small aircraft assisted launch, tumbleweed propulsion

Near Earth Asteroid deflection
Deflecting a C-type asteroid by providing a $\Delta V$ of 1m/s in one day requires ejecting 4x10^{-6} of its mass at 3m/s during that time. This means 660 Kg of material must be ejected per second for one day to deflect a 400m C-type asteroid.
Robotic hoppers acquiring ice from Martian surface to refuel attitude-control thrusters using cold gas propulsion.
Pneumatic transfer of regolith

Enthalpy of sublimation of CO$_2$ under Mars conditions: 590 kJ/kg at 155K

Earth condition transfer (760 Torr): 5-10 psig of air // 100 g/s of regolith

Mars conditions (4.5 Torr): 1-3 psig estimated
Concept for utilizing a comet’s frozen resources to provide cold propulsion and deflect it from a potential collision with Earth.
Sustained action over time may become a viable option when:

1. Political or societal pressures delay or eliminate the use of nuclear weapons
2. Disagreement among international partners on the use and availability of weapons
3. Concerns over the fate of the fragmented object.
4. Pre-positioning of propulsive deflectors is feasible ahead of decision times

Major challenges

Comets are active producers of gas through sublimation. Can we reasonably impact them by using the same principle?

Unstable environment. Operation for months to a year.

Long mission reliability
Ejected mass flow rate from a comet or asteroid to propel it on a deflected orbit with a $\Delta V$ of 1 m/s. Example assumes a gas/solid material velocity of 3 m/s, and an object of 400 m in diameter with a density of 2 g/cm$^3$. 
At perihelion, $0.25 \times 10^{27}$ molecules/s is ejected $\sim 416$ moles/s

If of water only, $416$ moles/s $\sim 7.5$ kg/s.

\[ \Delta H_s (H_2O) \sim 2.75 \text{ MJ/kg} \]

1. Controlled Mass ejection by sublimation may be effective at several AU of perihelion
2. Energy required is of the order of 2.7 MJ/kg of ice … i.e. 3 MW power source!

**Comet helps**: Phase transition of amorphous ice to crystallization is exothermic and triggers sublimation of trapped gases (1.6 kJ/mol)
Comet deflection by Water sublimation

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Concept: Trigger phase change by heat piping and propel released gases
Sublimation of silicates from asteroids at pressure $10^{-7}$ torr

Large energy required: 12 MJ/kg (i.e. 4.7 kWh/kg)

Recombination of species
Summary

Water and Carbon Dioxide ice in our solar system can be sublimated at low pressures.

Exploration Robot applications concepts analysis

Demonstrations of regolith transfer by CO$_2$ gas and pressurization of extracted gas are underway.

NEO mitigation by in situ propulsion

- Multi-year mission with impact away from perihelion. Not for short warning times.
- Thermal management concepts to lower energy inputs
Slim Fast, Now used by NASA to save the world from Overweight Comets!

Image credits: JPL, and Bruce Hardman/KSC
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