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

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ABSTRACT

Volatile solids occur naturally on most planetary bodies including the Moon, Mars, asteroids and comets. Carbon dioxide and water ices have been detected remotely at the poles or in permanently shadowed craters on Mars and on the Moon. Comets consist mostly of ice (>85% of mass), and some asteroids also contain solid ices in various amounts. In the outer Solar System, moons of the giant planets host the same resources; Ganymede, Europa and Callisto are composed of silicate rock and water ice to varying degrees, and the Cassini-Huygens probe has revealed methane snow and water ice crusts on Titan.

We investigate the concept of sublimating these ices and minerals to form gases where favorable environmental conditions prevail on many bodies in the Solar System. The applications offered by this resource sublimation concept range from powering surface systems during planetary missions to deflecting Near Earth Objects (NEO) threatening our planet by in-space propulsion.

INTRODUCTION

To date, the use of solar radiation to provide onboard electrical power remains the sole application of a space resource that has been exploited to sustain exploration missions. Even if one includes vacuum and the thermal sink offered by interplanetary space as exploited resources, our fleet of spacecraft is designed to operate in space environments without tapping their vast potentials. We propose to break through the paradigm and demonstrate the feasibility of a novel architecture concept based on the extensive use of volatile space resources to generate propulsive and mechanical power for a variety of space missions. The concept also departs from other In Situ Resource Utilization schemes by its inherent simplicity in applying heat to cause a change of state rather than to induce a chemical reaction. Furthermore, we explore the possible application of the concept to propel large near-Earth objects (NEOs) off their course and address a critical issue confronting us in the coming decades; how to protect Earth from threats of impacts by asteroids and comets.

The paradigm shift in space exploration created by the use of space resources extends beyond ensuring the survival of human crews. It is transformative also in its ability to offer in-situ solutions to the need for power generation and to mitigate spaceborne threats. We explore here a potentially widely applicable concept of using low ambient pressures and heating various compounds to generate propulsive power or to actuate mechanisms through the release of formed gases. The concept opens possibilities for missions to planetary surfaces by accessing a local resource that greatly extends the mobility of crews and robotics and increases the capability for power generation. Both of these challenges are among the greatest to be faced in missions to remote worlds. The confirmed presence of volatile solids such as carbon dioxide (CO_2) and water ice on the moon, Mars, asteroids, and comets makes these resources good candidates for use in mission architecture. The concept is also being studied to include compounds such as methane and other hydrocarbons that are thought to exist in solid form on some of the planetoids and moons in the outer Solar System (e.g., Europa and Titan).

The reliance on a single form of energy for all surface activities remains an issue for exploration missions. Radioisotope thermoelectric generators (RTGs) and their successors are now very reliable for many years (e.g., Voyager spacecrafts) but they power only electrical systems, as do solar photovoltaics. We propose that making extensive use of volatile space resources to convert their potential energy through gas heating and compression to generate propulsive thrust and mechanical force can revolutionize the capability of planetary surface missions by complementing the all-electrical approach.

ENERGY CONVERSION SCHEMES USING PLANETARY RESOURCES

All space endeavors require power and their success depends critically on the ability to balance the supply of energy to systems that must operate concurrently. As space missions venture further and further beyond Earth's orbital space, they require power systems of higher reliability over longer mission time but the choices become more limited. Missions operating on planetary surfaces have faced specific needs that include powering mobility systems, communication devices, operating thermal control systems and performing a variety of performing tasks. Exploration tasks include collection and transport of material, drilling and excavation, and powering and controlling scientific instrumentation. All planetary exploration missions have and continue to rely on electrical energy as a sole source. Photovoltaic solar panels have been typically used for missions within the orbit of Mars (inner solar system) and RTGs must be used in the outer solar system. The decision to power the Mars Science Laboratory with RTG is a departure from the use of solar photovoltaics on Mars rovers; it allows the selection of more landing locations where solar illumination is lower and makes more power available to the larger craft. It also offers greater thermal control through the use of the heat from radioactive decay into the craft systems.

In the past two decades, science missions to the Moon, Mars, several asteroids and the moons of Jupiter and Saturn have gathered strong evidence of the presence of water ice in the solar system (Dalton, 2010; Colaprete, 2010; Showman, 1999). If this resource can be harvested, this in itself could revolutionize space exploration. The recent Lunar Reconnaissance Orbiter (LRO) / Lunar LCROSS mission put an exclamation point on a decade-long suite of international missions by providing remote sensing maps of lunar water ice at polar latitudes and direct detection of such ice that resulted from an impact into Cabeus crater. According to Colaprete et al., "the water contained in just Cabeus crater would be enough to launch the Space Shuttle 2000 times" if hydrogen/oxygen cryogenic liquid propellants could be produced in-situ from it (Colaprete, 2010). On Mars, orbiting remote sensing platforms Odyssey and Mars Global Surveyor have repeatedly detected (Demidov, 2011) a hydrogen signature presumed to come from sub-surface permafrost ice deposits. Moreover, the Mars Phoenix lander mission established convincingly that water ice is present in the sub-surface near the Martian North Pole (Arvidson, 2009). Beyond Mars, asteroids such as the dwarf-planet Ceres are thought to contain an icy mantle above a rocky core (Rivkin, 2010). In 2010, The EPOXI mission spacecraft revealed a cometary snow storm around comet Hartley 2 created by carbon dioxide jets spewing out tons of golf-ball to basketball-sized fluffy ice particles from the peanut-shaped comet's rocky ends. At the same time, a different process was causing water vapor to escape from the comet's smooth mid-section. The Galileo mission to the Jovian system and the Cassini-Huygens mission to Saturn and its moons have added a wealth of knowledge to the Voyagers data in the past decade. Around Jupiter, Ganymede and Callisto appear to be composed of approximately equal amounts of silicate rocks and water ice. Callisto has also revealed the presence of carbon dioxide and organic compounds (Kuskov, 2005; Showman, 1999). Europa’s surface contains much water ice under a tenuous atmosphere of oxygen. In 2004-2005, the Saturnian moon Titan was explored by the Huygens landing probe that unveiled an extraordinary world of hydrocarbon seas (methane and ethane) on a body of silicate rocks and water ice, with methane snow. The atmosphere of Titan is denser than Earth’s, with a surface pressure about 1.45 times that of Earth’s (Coustenis, 2008). The atmosphere is so thick and the gravity so low (0.14 G) that flight is a viable mode of mobility across the moon (Zubrin, 1999). After landing, Huygens photographed a dark plain covered in small rocks and pebbles, which are composed of water ice (ESA News, 2005).

This abundance of data makes these solid volatile resources good candidates for use in the proposed mission architecture concept. In low-pressure environments, direct sublimation of ices in propulsion chambers could provide mobility for roving or hovering and for the actuation of pneumatic systems to lift, transport, and operate machinery. The RTG provides an obvious heat source for efficient conversion of these solids into gases at the right temperatures. Solar collection systems can also provide this in the same way, and other heat systems can be powered electrically as well (laser, resistive heaters). This new energy architecture is then complementary and acts as a multiplier for existing energy sources. The local accessibility of consumables that can be used to power systems will change the paradigm of the mission architecture and increases safety factors and capabilities. It also changes the economic equation that controls the cost of the scientific exploration of planets; the large investment in time and direct costs puts pressure on these missions to accomplish their goals because a follow up mission may not come for a long time. The addition of a new power source such as “sublimation pneumatics” would afford greater flexibility to accomplish or extend mission objectives. The same logic will apply to human exploration of planetary surfaces to an even greater extent by empowering those best able to respond to changing situations. On worlds such as Titan, endowed with a thick atmosphere and very low gravity, the sublimation of volatile solids could power steam propeller engines. In contrast, sublimation rocket engines would find application in the near-vacuum atmosphere of Europa to propel surface and flying vehicles in low gravity.

ORBITAL CHANGE OF NEAR-EARTH OBJECT BY IN-SITU PROPULSION

The above concept is extended to a larger scale by considering whether the sublimation of volatile solids (CO_2, water) and the volatilization of mineral compounds all found in asteroids and comets can provide the propulsive force needed to alter their orbits around the Solar System in order to avoid a catastrophic encounter with Earth.

By definition, NEOs are objects whose closest approach to the Sun (perihelion) is less than 1.3 AU units. Potentially hazardous objects (PHOs) are objects that pass within 0.05 AU of Earth (7.5 million km) and can penetrate Earth's atmosphere. Although an accurate threat assessment requires knowledge of the characteristics of the object, the current view is that a stony asteroid of about 50 m or more in diameter is hazardous to Earth. In 2006, there were about 340,000 known asteroids and comets and about 700 known NEOs with diameter greater than 1 km; current estimates now list 1100 NEOs with diameter greater than 1 km and approximately 100,000 NEOs with diameter greater than 140 m. The current list of PHOs contains roughly 800 objects (NASA Report to Congress, 2007). To change the orbital course of an asteroid or comet threatening the Earth, applying a sustained force over a long period of time is considered a more controllable approach for changing the orbits of small NEOs (tens of meters in diameter to ~100 meters in diameter) and larger NEOs en route to keyholes than detonating high-energy weaponry at the target (National Research Council, 2010) if sufficient time is given. However, it also requires mastering yet-to-be-developed space technologies on unprecedented scales (Ahrens, 1992). Among the concepts being advanced are gravity tugs by massive spacecraft and irradiation of the asteroid surface to produce jets of materials. The former requires the launch of a large spacecraft with a mass in excess of tens of tons and flying it in precise formation of the target for nearly a decade. Focused irradiation of the solid surface by lasers or solar beams to sublimate surface mineral materials has been proposed to create outgoing jets capable of imparting a propulsive momentum to the asteroid. Such concepts are attractive in principle but run into significant obstacles that raise doubts about their implementation: (1) solar collectors with diameters on the order of hundreds of meters must be flown in precise formation with a rotating NEO and (2) the sublimated material ejected is likely to contaminate the optics of the system over time. Mass drivers have also been studied recently (Olds, 2007) describing the attachment of multiple landers equipped with mass drivers capable of drilling and ejecting materials from an asteroid to generate propulsive force.

FEASIBILITY

The study focuses on assessing the feasibility of using sublimation of frozen volatiles in some cases and the volatilization of mineral oxides in others to generate gases to produce mechanical work at various planetary bodies.

Sublimation of water and carbon dioxide ice in the Solar System

The vast range of locations where water and carbon dioxide ice has been discovered throughout the Solar System focuses our attention on these materials. The phase diagrams presented in figures 1 and 2 display the conditions of both water and carbon dioxide on various planetary and other solid bodies.

Vacuum or rarefied atmospheres on satellite moons, comets, asteroids such as Ceres where water ice is present create favorable conditions for sublimation. By contrast, the dense atmosphere of Titan rules out sublimation of water ice on its surface. On Mars, a permanent polar cap of water ice is an attractive resource but sublimation may require more complex engineering as the conditions hover around the triple point. These initial considerations will be examined further through experimental testing of non-pure CO_2/H_2O ice mixtures with embedded regolith dust grains.

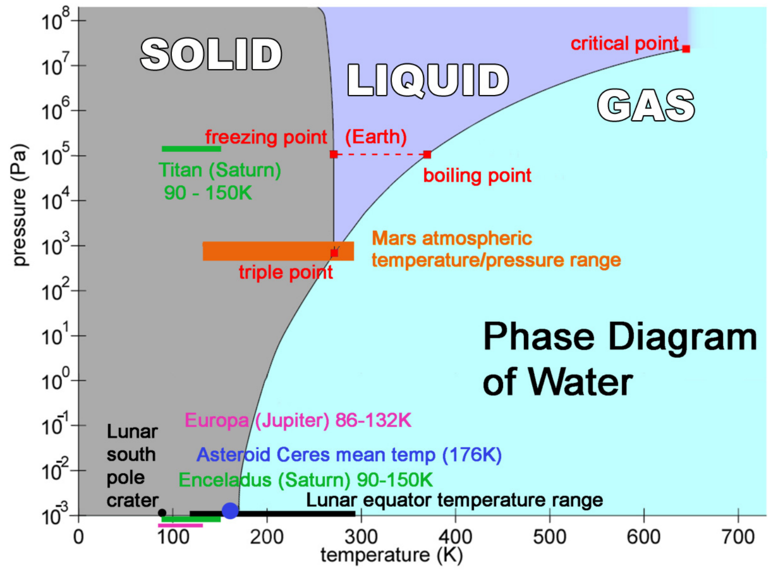

Figure 1. Phase diagram of water with conditions existing in the Solar System.

The Martian environment is dominated by the ~95% carbon dioxide atmosphere and its changing surface temperatures. The phase diagram of pure CO_2 indicates that relatively small amount of heat should suffice to sublimate this ice. Experimental data under these conditions confirm the fact that radiative transfer between the warmer Martian atmosphere and the surface ice is enough to sublimate the latter (Blackburn, 2008). Experimental work on impure ice is planned.

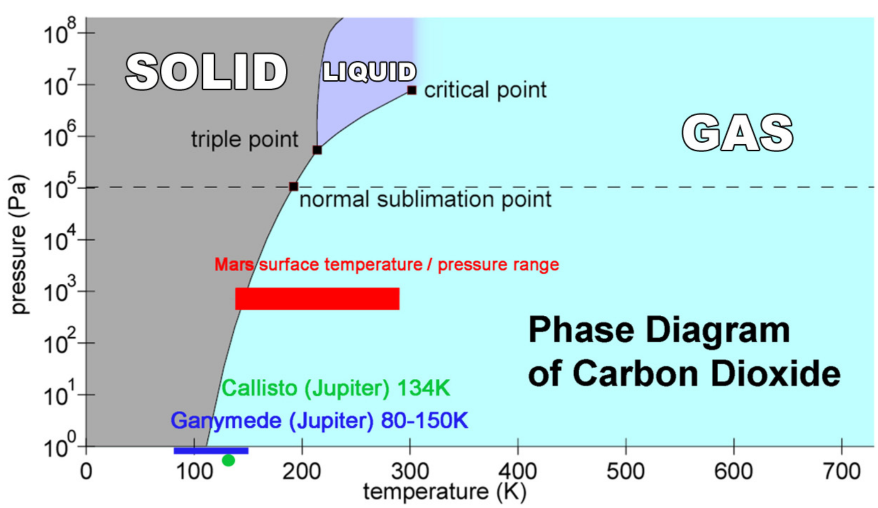

Figure 2. Phase diagram of CO_2 with conditions existing in the Solar System.

Volatilization of mineral oxides

Vacuum pyrolysis of mineral oxides such as silicates melts the oxides and separates the oxygen from the metal elements. At temperatures nearing 1000 ºC and very high vacuum, the kinetic energy gained by the oxygen decomposed from the mineral oxides makes it an attractive choice for in-situ propulsion, reinforced by the fact that oxygen is about 40-50% by weight of mineral oxides found in bodies characterized to date. However, the concept is found to be very challenging at best; the volatilization of oxygen under these conditions require large energy values of the order of 12 MJ/kg (i.e. 4.7 kWh/kg) and the recombination of volatile specie is very rapid at these temperatures and would change drastically the thrust characteristics. A reactor using this concept would be applied in an attempt to deflect a rocky asteroid devoid of water.

APPLICATION CONCEPTS OF IN SPACE PROPULSION USING PLANETARY RESOURCES

The phase change of several compounds found across the solar system is feasible at various energy costs. Thus the energy argument gives direction to the imagination of possible applications on planetary surfaces. Two of the imagined concepts that illustrate the proposed ideas are presented as artistic depictions in figures 3 and 4. Here are the applications that were considered.

Cold-gas propulsion for hopper

See modeling done for water, CO_2 and methane. Results show that the use of water for propulsion is problematic for two reasons: the sublimation of water requires a lot of energy (2.6-2.8 MJ/kg for pure ice; ~3.1 MJ/kg for ice in regolith) and requires pressurization of the extracted steam at high pressure and temperature values (15-20 bars; 700ºC) to generate sufficient thrust while avoiding condensation or freezing at the nozzle. The use of CO_2 is far more feasible on Mars for example, and presents some interesting possibilities for hoppers and other applications described below. In fact, a CO_2-powered hopper using the gas compressed from the Martian atmosphere is under study within NASA. The case of nitrogen and methane under the right conditions also show promise because these gases do not require initial high tank pressures and temperatures to perform as propulsive gases while avoiding condensation. Propulsion on sublimated methane on Titan is particularly interesting because the oxygen rich atmosphere of the Saturnian moon offers the possibility of combustion of methane combustion to realize chemical propulsion entirely from space resources!

Compressed gas launch of ballistic objects

The use of the same gases under similar conditions is examined for the launch of ballistic objects during surface missions. This type of operation is imagined to pre-position surface assets such as beacons, radio-markers for surface navigation or landscape surveys. Instrumentation such as seismological detectors, sample acquisition microbots can also be sent to different locations in this way. The efficient use of sublimated gases in this application limits the launch to low mass objects. These small payloads may participate also in aerial surveys if the system assists the launch of aircrafts. Rovers may be helped or extend their range of accessible targets by using the system to launch harpoons across canyons or up-slope. Reference: Ballistic charts for small mass payloads.

Hovercraft (surface sublimation of ice sheets)

The surface of Titan is covered with ice sheets that represent the major landscape feature. While rovers properly equipped with spiked wheels may do fine, the sheets also offer the possibility of traversing at higher speeds by hovercraft. In this case, energy input directly from the underside of craft is conceived to generate vapor under a skirt designed to create the desired pressure given the ambient conditions.

Regolith transfer on compressed gas

Experimental work shows that air, CO_2 or other gases like N_2 can be effectively used to excavate and transfer large masses of regolith while recycling these gases.

Asteroid and comet deflection (subsurface heater with expeller tube)

The ejection of volatile materials from these bodies was examined to assess the potential of deflecting these threatening objects from a collision path with Earth. While the case of dry rocky or metal asteroids would require a reactor capable of volatilizing oxides or metals at high energy costs as treated previously, we considered the sublimation of various ices in comets and icy asteroids as more promising. Figure 3 shows the projected masses that must be ejected from a given asteroid/comet to change its orbital parameter by a Dv of 1m/s. It gives an order of magnitude of what is required given the amount of time available: this deflection is feasible if ~3 kg can be ejected per second continuously for 100 days.

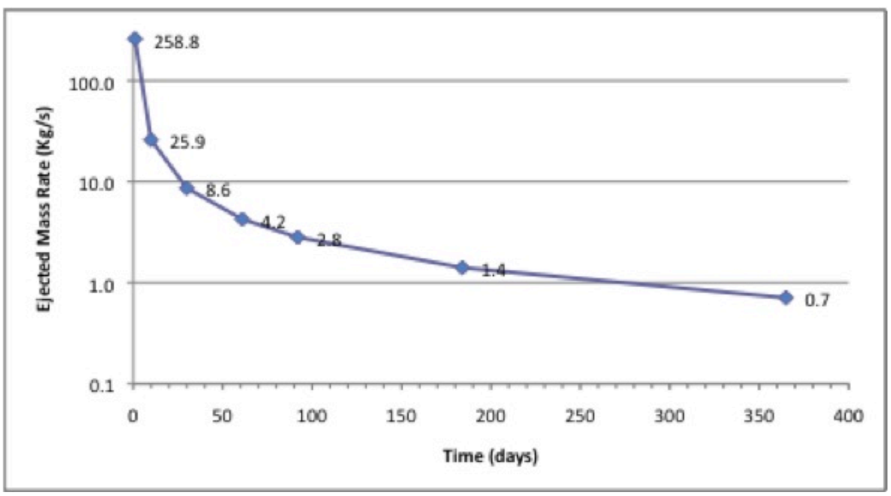

Figure 3. **Ejected mass flow rate from a comet or asteroid** to propel it on a deflected orbit with a DV of 1m/s. Example assumes a gas/solid material velocity of 3 m/s, and an object of 400 m in diameter with a density of 2 g/cm^3

For comparison, the comet Wirtanen ejects 7.5 kg/s of gas at peak activity and temperature near the perihelion. Energetically, the reactor would have to sublimate water at ~2.8 MJ/kg but comets do contain many other more volatile specie; CO, CH_4, HCN, NH_3 whose sublimation energies range from 0.2 to 1.7 MJ/kg. Furthermore, comets are described as reservoirs of amorphous ice and the phase transition of amorphous ice to crystalline ice is exothermic of the order of 1.6 kJ/mol. This transition is a possible cause of large bursts of ejected gases in comets even far from their perihelion when they receive little energy from the Sun. A concept that we advance is to insert a subsurface expeller tube with heaters into layers of mixtures of rocks and ice and trigger sublimation of trapped gases at a lower energetic cost than a 3MW reactor that would be required for volatilization of water ice.

Such a system has potential to cause deflection at specific points of orbit and create directed jets to gain even a fraction of a degree of deflection. It also present serious issues of feasibility and uncertainties based on our knowledge of the subsurface of comets and icy asteroids.

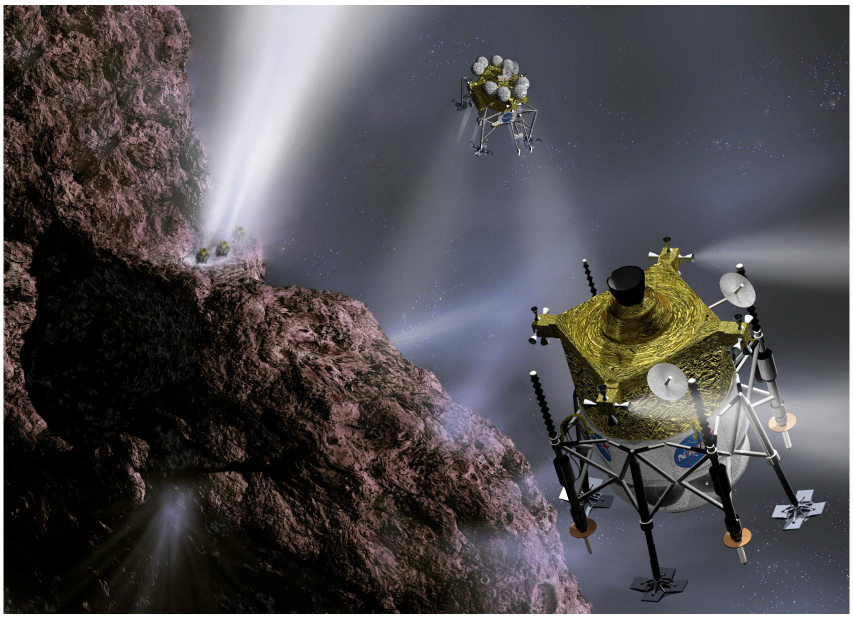

Figure 4. Conceptual mission to deflect a comet by using in-situ propulsion. Robotic spacecraft approach the comet and anchor themselves into the surface where they drill and collect icy material. The ice is sublimated and ejected through an on-board propulsive chamber. Image Credit: JPL (Comet) / Bruce Hardman, KSC (spacecraft and overall image)

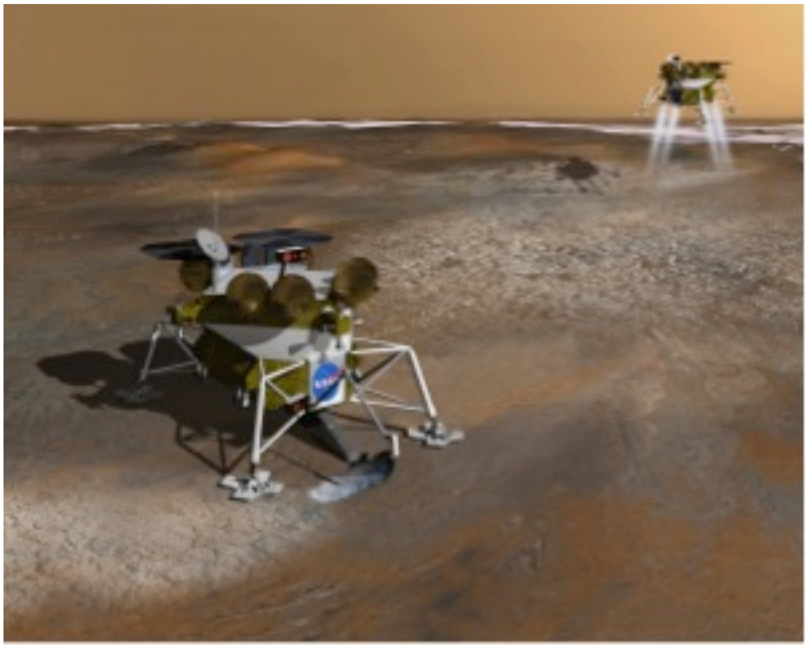

Figure 5. Small robotic exploration spacecraft collect and sublimate CO_2 ice at the Martian polar cap to use in attitude-control thrusters. Image Credit: JPL (Mars landscape) / Bruce Hardman, KSC (spacecraft and overall image)

CONCLUSION

This project, sponsored by the NASA Innovative Advanced Concepts examines how the systematic use of space resources such as frozen volatiles can create a new paradigm in surface power generation for deep space missions. The ubiquitous presence of ices of water, carbon dioxide and other compounds throughout the Solar System under conditions favorable for their sublimation will enable novel in-space propulsion and actuation concepts to become a reality and to address one of NASA's Grand Challenges of "All Access Mobility." Accessing such a resource in the far corners of our interplanetary neighborhood let us conceive exploration missions capable of refueling in the Jovian and Saturnian systems to achieve new goals or reach new destinations. The concept also has potential to apply in-situ propulsion to a comet or an asteroid to deflect its orbit slightly to avoid a future encounter with Earth.

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