Tapping the Waters of Space

by John S. Lewis

That space travel must be exorbitantly expensive is a modern myth. The high cost of today's space missions is partly because of the failure of governmental agencies to reduce the costs of launching spacecraft. For example, a one-way trip on the space shuttle to low orbit around Earth costs about $20,000 per kilogram. Soft-landing a ton of anything on the moon costs about $100 million. But the high price of space travel also reflects the fact that astronauts must take everything they will need on their journey with them, rather than putting the natural resources found in space to good use.

Ironically, most of what we launch into space is intrinsically cheap rocket propellant. To get a gallon of gasoline or liquid oxygen to the moon would cost $400,001—$1 to purchase it on Earth and $400,000 to deliver it to the moon. And whether it is a communications satellite bound for geostationary orbit, an Apollo flight to the moon or a manned Mars expedition, any ambitious spaceflight requires copious amounts of propellant.

The absurdity of such a logistical system is obvious. But how can we do better? Certainly any accessible reservoir of propellant on the moon or Mars would be enormously attractive. Even if it were to cost $400 to extract or manufacture a gallon of propellant on the surface of the moon or another planet, we would save 99.9 percent. Thus, we could reduce the cost of propellant on a particular mission 1,000-fold, or we could move 1,000 times as much payload. We only need a scientifically, technically and economically sound extraterrestrial source of propellants.

Although there are no oil wells on Mars or the moon, there are two abundant commodities—sunlight and water—that in combination can provide the propellant we need. An array of solar cells could capture sunlight and convert it into electricity, which would then be used to electrolyze water; this process breaks apart the water molecules into hydrogen and oxygen. Burning hydrogen in the presence of oxygen offers the best possible chemical rocket engine performance. And of course, water is the key to life-support systems—a crucial part of the astronauts' diets, a source of oxygen to breathe and an essential component of agriculture in space. Water is arguably the most important material resource we could hope to find in space.

Fortunately, water (in the form of ice) has been found recently in space in a number of surprising places. The Clementine mission in 1994 and the Lunar Prospector mission in 1998 identified and verified the presence of a billion or more tons of ice in the polar regions of the moon, thereby raising the prospect of establishing permanent, self-sufficient lunar bases or even lunar colonies. Just a few years earlier, in 1991, a team of radar astronomers found similar deposits of ice in the bottom of permanently shadowed craters near the poles of Mercury.

In addition, astronomers have known for many years about the presence of ice on Mars. The planet's polar caps are covered in water ice and, during the winter, carbon dioxide snow. Mars is so cold that permafrost exists over more than half the planet's surface. Water-bearing clay minerals and hydrated salts appear to be ubiquitous on the planet. Even the Martian atmosphere, which is 95 percent carbon dioxide, should not be ignored as a source of propellants and material for life-support systems: Kumar N. Ramohalli of the University of Arizona and his co-workers have demonstrated how to manufacture oxygen and carbon monoxide (a medium-performance propellant combination) out of carbon dioxide under conditions similar to those on Mars. Adding Martian water to the process would permit the manufacture on Mars of storable rocket propellants such as methanol.

And in what could prove to be the most promising development, evidence has accumulated that water is probably a common constituent of more than half of the so-called near-Earth asteroids, which revolve around the sun and frequently cross Earth's orbit. As it turns out, water is a widespread resource in the inner reaches of our solar system.

Getting to the Water

This water must be accessible to us, however, if we are to exploit any of the reservoirs profitably. Availability depends on how much energy it takes to get equipment to where the water is, how easy it is to extract the water and process it into useful products, and how much energy it takes to transport the products to where they are needed.

First, let us consider the moon. Because of the amount of energy required to escape from the moon's gravity, it is important to distinguish between water that might be used on the lunar surface and water that would be exported off the surface. Un-

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Space travel could be considerably cheaper if astronauts could produce their own food and propellants from the resources already out there

NEAR-EARTH ASTEROID could serve as a refueling station for interplanetary spacecraft. For the swarm of roughly 3,000 asteroids and comets that enter the inner solar system, roughly 25 percent of their mass is water, which translates to some 6,000 billion tons of water. Spacefarers could extract water from the asteroids and convert it to hydrogen and oxygen—important rocket propellants.

fortunately, both options may prove hard to implement.

A lunar base that could take full advantage of water from the polar-ice deposits would have to be located near one of the poles because of the difficult logistics of moving materials long distances over the moon's rugged terrain. Building a base at the poles would be extraordinarily challenging: to capitalize on the sun's energy, the base would have to be constructed high on a permanently illuminated mountaintop. Mining the permafrost for water is also a daunting prospect, requiring work in temperatures below 100 kelvins (–280 degrees Fahrenheit) in the permanent darkness of the valleys where the ice is found. Exporting water from the moon (or even flying a payload from the pole to the equator) requires overcoming the moon's substantial gravitational field, a feat that would dramatically lower the desired energy savings motivating the mission in the first place.

Another place to mine for water could be Mars. Mars has a substantial gravity field, requiring an escape velocity of 5,400 meters per second (around 18,000 feet per second). Lifting water or propellant off Mars would be somewhat easier than exporting these products from Earth (where the escape velocity is 11,200 meters per second). But we would still have to fight against Mars's gravity to deliver material generated there to anywhere else—which would eat up a large portion of the propellant that had been produced. Making propellant for a return trip from Mars to Earth is an attractive option, but exporting items from Mars for use elsewhere in the solar system is simply too costly.

Mars's two moons—Phobos and Deimos—have also been considered potential water sources. Indeed, as early as 1939 a British engineer named Arthur C. Clarke pointed out that these moons might be sufficiently rich in water to make them attractive way stations and refueling stops for missions to and from Mars. But Larry A. Lebofsky of the University of Arizona, working with Jeffrey F. Bell and his group at the University of Hawaii at Manoa, has searched for the telltale signal of water, an absorption band in the near infrared, and has failed to detect water on either Phobos or Deimos.

Although the Martian moons have not lived up to early expectations for them as extraterrestrial filling stations, their resemblance in size and appearance to a particular class of asteroids has pointed astronomers in a much more encouraging direction. Like the Martian moons, carbonaceous (or C-type) asteroids are dark, low-density stones containing carbon, magnetite, salts and abundant clay minerals. But whereas the surfaces of Phobos and Deimos have been baked free of water and other volatile compounds by repeated heating from impacts and reaccretion of dried materials, C-asteroids should still carry water-rich materials on the surface.

Under observational scrutiny, however, C-asteroids behave with a shocking disregard for theory. Lebofsky and Thomas D. Jones, a planetary scientist turned astronaut, have found that only about half of the C-asteroids in the main asteroid belt between Mars and Jupiter have prominent water absorption bands. Evidence bearing on the water content of these asteroids is sparse. The only C-asteroid yet visited by a spacecraft—the Near Earth Asteroid Rendezvous mission, or NEAR—is 253 Mathilde.

But even if we had overwhelming proof of the presence of ice or water in a C-asteroid in the main asteroid belt, it is far from clear that this source of water would have any practical significance. The main asteroid belt is simply too far away from Earth and too remote from any place where we might soon have a demand for materials produced in space. Fortunately for us, however, complex dynamic processes constantly shower the inner solar system with asteroids ejected from the main belt.

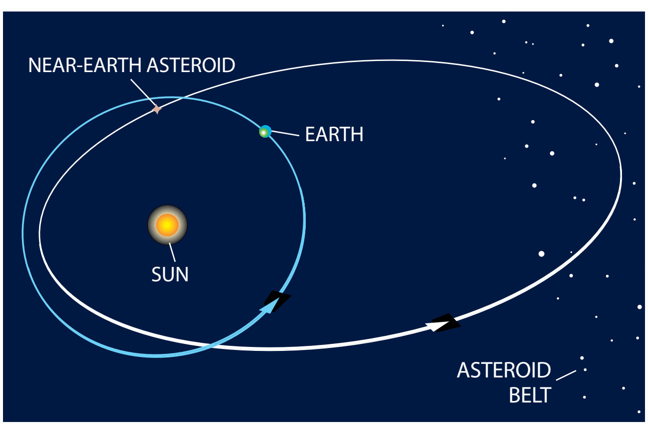
Near-Earth Objects

Such asteroids—along with the comets that travel into the inner solar system—are collectively termed near-Earth objects, or NEOs. These NEOs have relatively short life expectancies: most last only 30 million to 100 million years before being destroyed by collision with any of the planets whose orbits they cross or ejected from the solar system after a close encounter with Jupiter. Many even crash into the sun or come so close to the sun that they evaporate. Comets may dissipate completely, or their surfaces may dry out enough so that they start to resemble C-asteroids. Small pieces of debris knocked off these bodies by minor impacts can fall to Earth as meteorites. Indeed, the large majority of meteorites that strike Earth's upper atmosphere probably originate from NEOs. Meteorites are therefore powerful clues to whether the asteroids in the inner solar system (called near-Earth asteroids, or NEAs) carry any water.

Of the meteorites that reach Earth's surface and are recovered, only about 3 percent are water-bearing, carbonaceous types. But spectroscopic and photographic studies of fireballs in the upper atmosphere suggest that well over half of the meter-size objects that strike are carbonaceous bodies so weak that they disintegrate high in the atmosphere. Few of these fragile fireballs succeed in delivering meteorites to Earth's surface. So if the meteors seen in Earth's atmosphere provide an accurate representation of the different types of NEAs, then half or more of those asteroids should carry abundant supplies of water.

The best test of this hypothesis would be to analyze samples taken from asteroids. But because no spacecraft has yet to touch down on an asteroid, we must rely on astronomical spectral studies. The spectra of about 45 near-Earth asteroids have been published, and 60 others have been studied recently.

These data suggest that about 25 percent of the NEAs consist of some variant of C-type material that carries water. But this number is somewhat skewed. Astronomers detect NEAs by visible light, and carbonaceous asteroids are much darker than other types. Thus, the traditional method of discovering asteroids discriminates against C-asteroids simply because they are harder to see. As a result, astronomers know that at least 25 percent of NEAs are C-asteroids; in practice, most estimates put the figure as high as 50 to 60 percent. Each of these asteroids contains 5 to 20 percent water. In addition, dynamic studies suggest that about half of the NEAs are actually extinct comet cores,



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ORBITS of the near-Earth asteroids have been dislodged from the main asteroid belt between Mars and Jupiter. Experts estimate there are roughly 2,000 of these asteroids.

bearing up to 60 percent water. In total, for the swarm of roughly 3,000 asteroids and comets that enter the inner solar system, roughly 25 percent of the mass is water, which translates to some 6,000 billion tons of water. There is water, water everywhere in our solar system—but is there any drop we can afford to drink?

Mining an Asteroid

Fortunately, missions from Earth to the near-Earth asteroids are surprisingly straightforward. About 15 percent of the known NEAs are easier to reach than the moon. Because of the moon's gravity, a large amount of propellant is required to slow the descent of a rocket vehicle to a soft landing. But asteroids have such feeble gravity that landing on them is easy. Thus, a given rocket could land a larger payload on one of these NEAs than on the moon.

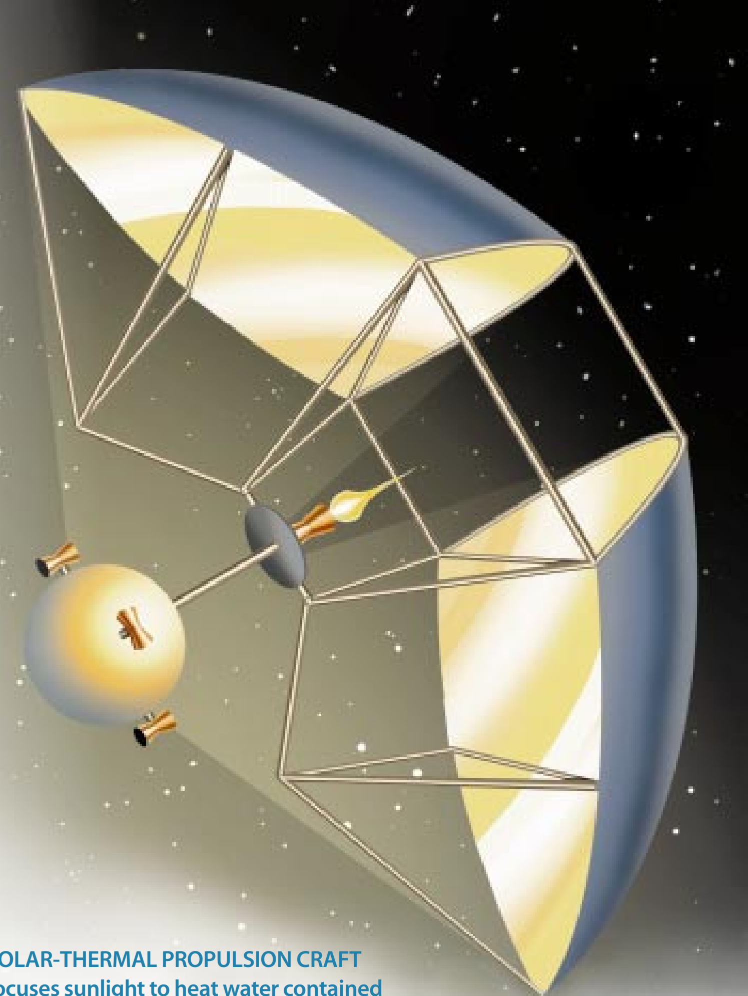
After landing on an asteroid, water could be extracted from the permafrost simply by warming it enough to evaporate or melt the water ice. A solar furnace—essentially a mirror the thickness of aluminum foil that would direct solar energy to the asteroid's surface—would do the job admirably. It could either be attached directly to the asteroid or be held in place close to the surface in the precise spot where the sun's gravity cancels that of the asteroid. An asteroid containing water-rich clays and hydrated salts would require heating to somewhat higher temperatures, again well within the capabilities of a solar furnace.

The crowning touch to this plan is that it would be far simpler to lift water off asteroids than it would be to lift water off the moon. A kilometer-size NEA has an escape velocity of about one meter per second, compared with 2,380 meters per second for the moon and 5,400 meters per second for Mars. Also, little propellant is needed to launch a spacecraft from an asteroid at a speed that would allow it to return to Earth. The spacecraft could then rendezvous with a space station in low orbit around Earth.

A tanker returning from an NEA with a shipment of water could off-load its cargo at the station. There, as described earlier, electricity from solar panels could electrolyze some of the water into hydrogen and oxygen to fuel a small chemical rocket engine on the tanker sufficient to carry the empty tanker back out to another water-bearing asteroid. Each return trip could provide enough propellant for several dozen outbound flights. Over the lifetime of the craft, it could make multiple round-trips, returning 100 tons of propellants to the refueling depot for every ton of equipment launched from Earth. This bootstrapping scheme is said to have a "mass payback ratio" of 100. Of course, the tanker could be refurbished at the station between flights, lengthening the lifetime of the vehicle severalfold—and increasing the mass payback ratio to 500 or 1,000.

How would the tanker propel itself around the inner solar system? Would we have to put a complex electrolysis plant on an asteroid where there would be no one to tend to it? There are two techniques by which a rocket could use water itself as its propellant. In one scheme—nuclear-thermal propulsion—a nuclear reactor heats water to generate steam for the rocket engine. In a second method, called solar-thermal propulsion, sunlight is used to heat water inside a thrust chamber to produce superheated steam [*see illustration above*]. This concept of a solar-powered rocket was first described in the student notebook of American rocket pioneer Robert H. Goddard in 1908.

Such a transportation system, with the capacity for payloads



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SOLAR-THERMAL PROPULSION CRAFT focuses sunlight to heat water contained in a metallic thrust chamber; the resulting jet of steam powers the vehicle. Water is quite abundant in the inner solar system and could be mined for use as a rocket propellant.

dozens of times heavier than the propellant needed to power the vessel, could convey other commodities around the inner solar system. Metals extracted from stony asteroids, for example, could be retrieved for use in building large structures such as solar-power satellites in orbits around Earth.

All these benefits could accrue even if the high launch costs bemoaned at the outset of this article continue. But there are bright prospects for slashing launch costs by abandoning 1960s technology in favor of single-stage-to-orbit vehicles, hybrid or plug-nozzle engines or any of a variety of potentially reliable and cheap alternatives. A cost of $400 per kilogram appears achievable with fully reusable boosters and airline-style operations. Suppose we pay $400 per kilogram to launch equipment to a near-Earth asteroid, from which we have a mass payback ratio of 100. The costs of construction materials in Earth orbit would then amount to $4 per kilogram—comparable to the expense of building a home here on Earth. And when we can build a habitat in space for the cost of a house, then the space age will truly have begun. SA

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