INEL-95/00106
CONF-950627I--1

Discovery Of Water Ice
Nearly Everywhere In The Solar System

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ABSTRACT

During the last decade we have discovered sources of accessible water in some form nearly everywhere in the solar system. Water ice has been found on the planet Mercury; probably on the Earth's Moon; on Mars; on near Earth objects; on comets whose orbits frequently come close to that of Earth's orbit; probably on Ceres, the largest inner asteroid; and on comets previously and incorrectly considered to be out of practical reach. The comets also provide massive quantities of hydrocarbons, similar to oil shale. The masses of either water or hydrocarbons are measured in units of cubic kilometers. The water is key to space transportation because it can be used as a rocket propellant directly, and because thermal process alone can be used to convert it and hydrocarbons into hydrogen, the highest performing rocket propellant.

This presentation outlines what is currently known about the locations of the water ice, and sketches the requirements and environments of missions to prospect for and assay the water sources.

INTRODUCTION

A key need filled by space mining interests is to bring some of the unlimited resources of space back to Earth itself. To do this requires a space transportation system. The key to such space transportation is having a large amount of reaction mass for each of the rockets doing the transporting. The key to an affordable rocket propulsion system is to have an essentially unlimited supply of propellants (reaction mass) that can be directly usable in simple, powerful rockets. We only know how to use water and hydrogen in the kinds of simple, powerful rockets we can build today.

We must reject just having access to dust as the reaction mass. We would need electricity to use the dust as propellant. But electricity is simply to difficult to produce in space at the Gigawatt levels we would need, in deep space, and using space tug vehicles that only weigh as much as we can plan to launch in the next several decades. For example, the current largest launchable payload of about 100 tonnes would make between about 10 and 20 Megawatts of electricity, using untested, very complex systems. If the same 100 tonnes were dedicated to 10 nuclear rockets, we could count on 20,000 Megawatts. These tested reactors heat either water or hydrogen.

Observers of the space near Earth found water and hydrocarbons in about equal parts, in quantities measured in Giga-tonne units (1E9 tonnes, 1E12 kg), and in the inner part of the Solar System (between the planet Mercury and the Planet Jupiter).

Engineers discovered how to use the water and the hydrocarbons to provide propellants for

Prepared for the U.S. Department of Energy under DOE Idaho Operations Office
Contract DE-AC07-94ID13223

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rockets. The missing element is the method to extract these materials from their sources. What follows here is a sketch of the current state of knowledge of the location and form of the water.

RESOURCE DESCRIPTIONS

The water appears in one of two kinds of space geological formations:

1. frozen mud-ice permafrost, at the poles of heavy, inner Solar System objects such as planets, the Moon, and the largest asteroid
2. frozen water/hydrocarbon/dust mixtures, protected from rapid evaporation by a blanket of fine tar dust, on inner Solar System comets.

Table 1 summarizes the state of knowledge of these water sources, and includes measures of difficulty of the mining situations expected.

The measures of difficulty of obtaining the water include some measure of the difficulty of lifting the water off the resource object. The amount of material a given rocket thrust can just barely lift off the surface of the object gives a measure of the payoff a mining interest receives when it launches that rocket. The more material a given rocket can lift, the more profit.

The orbital maneuver difficulty indicates a measure of how much of the propellant must be consumed to deliver the payload. One measure is the delta_V a rocket and its propellant will impart on the payload/ space tanker system. An upper bound on the propellant mass used per payload mass is given approximately by the exponential of the ratio of the total delta_V divided by the propellant specific velocity (Vsp). Steam propellant rockets achieve between 1500 and 2500 m/s Vsp. Hydrogen propellant rockets achieve between 5000 and 9000 m/s Vsp.

The table includes only those water sources where some orbital maneuver and rocket combination can bring back the payloads without using more than about 20 units of propellant for one unit of payload.

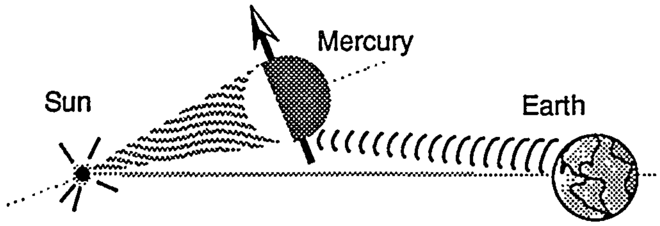
The frequency of orbital alignments and the orbital travel times give measures of economic accessibility. Times less than a few years are essential for reasonable net present value and return on investments.

The environment expected gives a measure of the difficulties to be expected in the mining operation.

Planets, the Moon, and an Asteroid

Mercury

Slade, Butler, and Muhleman (1992, 1993) discovered that the radar images of the North Pole of Mercury have the same unique, ice signature characteristics as those of Calisto, a large ice moon of Jupiter. The startling discovery required that there be permanently dark regions at the poles of Mercury. Harmon, Slade, Velez, Crespo, Dryer and Johnson used radar to verify the existence of tens of kilometer dimension craters at both of the poles of Mercury, which provide the permanently dark recessions in which ice exists. Thermal studies by Paige (et. Al, 1992) suggest that the permanently shaded floors of the large polar craters are cold enough to preserve water ice in a stable state over eons, in spite of Mercury's proximity to the Sun.



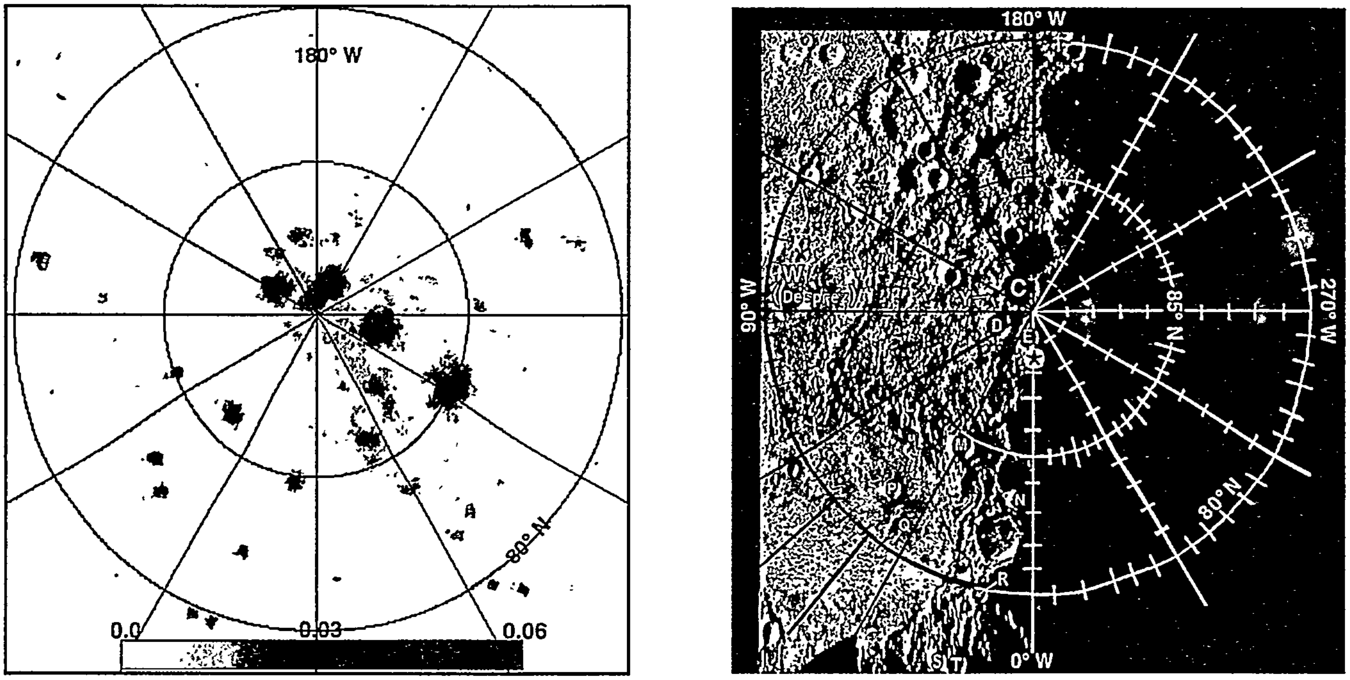
The bottom of a crater at a pole of Mercury is always shadowed from the Sun. A radar from Earth can see the into the crater because the plane of Mercury's orbit around the Sun is tipped with respect to that of Earth.

The pole of Mercury is nearly always shaded from the Sun because the axis of rotation is nearly perpendicular to the orbital plane, and has been so for eons. The pole is visible to Earth radar but not to the

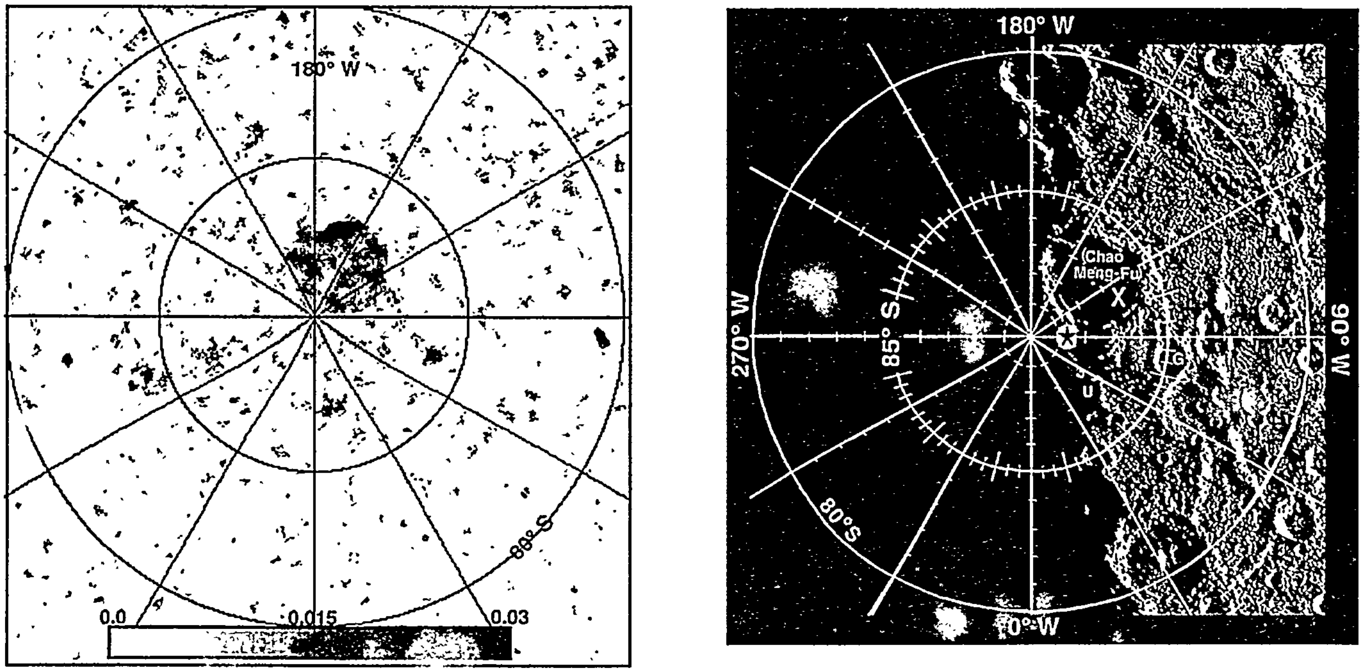
Table 1. Location of water resources in Solar System, including measures of difficulty to get to the resource, to remove material, to transport it and to mine it.

Where	Form of water	Difficulty to transport off	orbital maneuver difficulty	frequency of good orbital alignments	Orbital travel time	environment
Mercury (poles)	ice and rocks or dirt; massive signal suggests volumes like large inland lakes	2.7 pounds lifted per pound thrust; 4262 m/s ΔV to escape	Hard to get to compared to Mars or NEOs. 6300 m/s to cross Earth orbit; 13,000 m/s to capture	Most frequent good windows of all objects except moon. very good orbit every 90 days	3.7 month one way trip	pitch black; gravity 1/3 of Earth; sun 10 times hotter than on Earth, but only away from resource
Moon (south pole)	presumed ice and rocks or dirt; unknown and uncertain amount	6 pounds lifted per pound thrust; 2,380 m/s ΔV escape	Very Easy to get to, compared to Mars. less than 2380 m/s frees from Moon; already in Earth capture orbit	continuous.	6 day one way	pitch black
Mars (poles)	ice, mixed with CO_2 (dry) ice	2.6 pounds lifted per pound thrust; 3551 m/s ΔV escape	Reference mission. approx. 3000 m/s to go to Earth Capture	Reference mission. about every 2.2 years	between 3 and 11 months	atmosphere has trace carbon monoxide -- dangerous; otherwise like airless subarctic
Ceres	water ice, possibly 10 meters below surface	33 pounds lifted per pound thrust; 530 m/s ΔV escape	harder to get to than 25% of NEOs. 3900 m/s to transfer to Earth orbit; V_∞ 7660 m/s to capture	about every 1.3 years	about 1.3 years one way	8 times less sun than Earth, expect cavernous, large body
Comet Wilson Harrington	expect for all comets: 1/3 water ice = "comet water" 1/3 hydro-carbons 1/3 dust; 5-10% CO_2; ~1% nitrogen compounds	100,000 pounds lifted per pound thrust; 15 m/s ΔV escape	Easiest of all comets to get to. Harder than going to Mars. 500 m/s to transfer to Earth orbit; V_∞ 8500 m/s to capture	Comets cross orbit of anything you wish, connecting you with anywhere. This one: bad about 2 of every 5 years Good about 1 of every 5 years	about 2.2 years one way orbit spans from Earth to outer asteroid belt	**comet-like** === dust always, CO, CN and other corrosive gasses present; fluff surface probable; can lasso entire object
Comet Encke	comet water	100,000 pounds lifted per pound thrust; 15 m/s ΔV escape	3500 m/s to transfer to Earth orbit; V_∞ 9000 m/s to capture Venus gravity assist possible often	about every 1.5 years	about 1 year for payloads orbit from Earth to outer asteroid belt	**comet-like**
Periodic Comets	comet water	100,000 pounds lifted per pound thrust; 15 m/s ΔV escape	up to 3500 m/s to transfer to Earth orbit; up to V_∞ 9500 m/s to capture	nearly always a candidate available	2-4 year for payloads orbits from Earth to past Saturn	**comet-like**
Comet Haley	comet water **orbit nearly inaccessible**	10,000 pounds lifted per pound thrust; 15 m/s ΔV escape	nearly inaccessible when near Earth	about 1 per 80 years	80 year round trip	**comet-like**
Kuiper Belt	massive comets	like Ceres	past Neptune	always available	50 - 100 year trips	Water and hydrocarbon giants strong CO content

Figure 2: Radar and photos of polar caps of mercury, showing radar signals and corresponding craters



North polar cap of Mercury
left: radar image of strong, ice signal
right: photo of craters



South polar cap of Mercury left: radar image of strong, ice signal right: photo of craters

Photo courtesy of Martin Slade and John Harmon. Arecibo Observatory is operated by cornell University with support from the NSF and NASA.

Sun because the orbit of mercury is canted about 7 degrees from that of Earth.
The unique radar signature indicates ice that is pure enough not to attenuate the radar signal, and fractured so that it gives the unique polarization signature. The signature is patterned after that of Callisto, the very well studied moon of Jupiter. See Figure 2, courtesy of Martin Slade and John Harmon.

Moon

The existence of water ice on Mercury gave a measure of the initial comet water flux or volcano water flux that would have brought the water to the poles. This flux suggested that there should also be water in forever dark Lunar craters. The Clementine probe (1994) used a bistatic radar as well as a visual observation to probe the South Pole of the Moon.

Col. S. Pete Worden of the USAF initiated this program and stated that a water signature was found (Worden, 1994). He anticipates or interprets data yet to be completely analyzed. More conservative scientific analysts on his team declare that we must wait for other verification data, such as contact probes on the surface of the moon.

A Lunar or Mercury crater will be completely dark and therefore devoid of solar power resources. One could expect crevasses that either must be illuminated or fallen into.

Mars

Photos and analysis of the poles of Mars have indicated since the mid 1970's the existence water ice with the carbon dioxide dry ice at its poles. See Figure 3.

Ceres

A'Hearn (1992) observed hydroxyl molecules near the pole of Ceres, the first and largest asteroid to be discovered. His January 1990 search for OH in what he predicted to be a transient atmosphere around Ceres was based on widespread evidence suggesting moderately high bulk water content in Ceres. A'Hearn observed OH emissions after perihelion (closest approach to sun) but not before. Photo-dissociation of water, with about a 6 day lifetime, is the source of OH. Fanale and Salvail (1989) calculate ice will be found below up to tens of meters of regolith.

Discovered during 1801, Ceres is about 940 km across and has a mass about 1 E 9 times mass of a 1 km diameter comet. Because it's gravity is so low (less than 1/30 of Earth at its surface, and decreasing with depth), burrowing deep into Ceres may be rational. It would offer access to a volume like that of an ocean, but without the extremes of hydrostatic pressure.

Comets

Near Earth Object Comets

Bowell discovered during July 1992 (Bowell, 1992) that at least one of the near Earth objects (NEOs) is in fact a comet, and not a "rock in space," as are most of the more than 250 known NEOs shown in Figure 4. Shoemaker had suggested that up to 40% of the NEOs should be water objects of some kind. Most of these NEOs would contain hydrated minerals holding between 5% and 25% water of hydration.

Some percent of NEOs should be comets or spent comets. Spectral data of the dark surfaces of this class of object are like that of carbonaceous objects. The data from comet Haley data showed that comets are "off" most of the time. A very black, less than a meter thick, carbonaceous fluff on the outside of the NEO insulates and covers the ice within. Comets do in fact appear like some NEOs most of the time.

One can nearly always find a comet or NEO whose orbit passes close to the orbit of any other object. A refueling station needs this ubiquitous location.

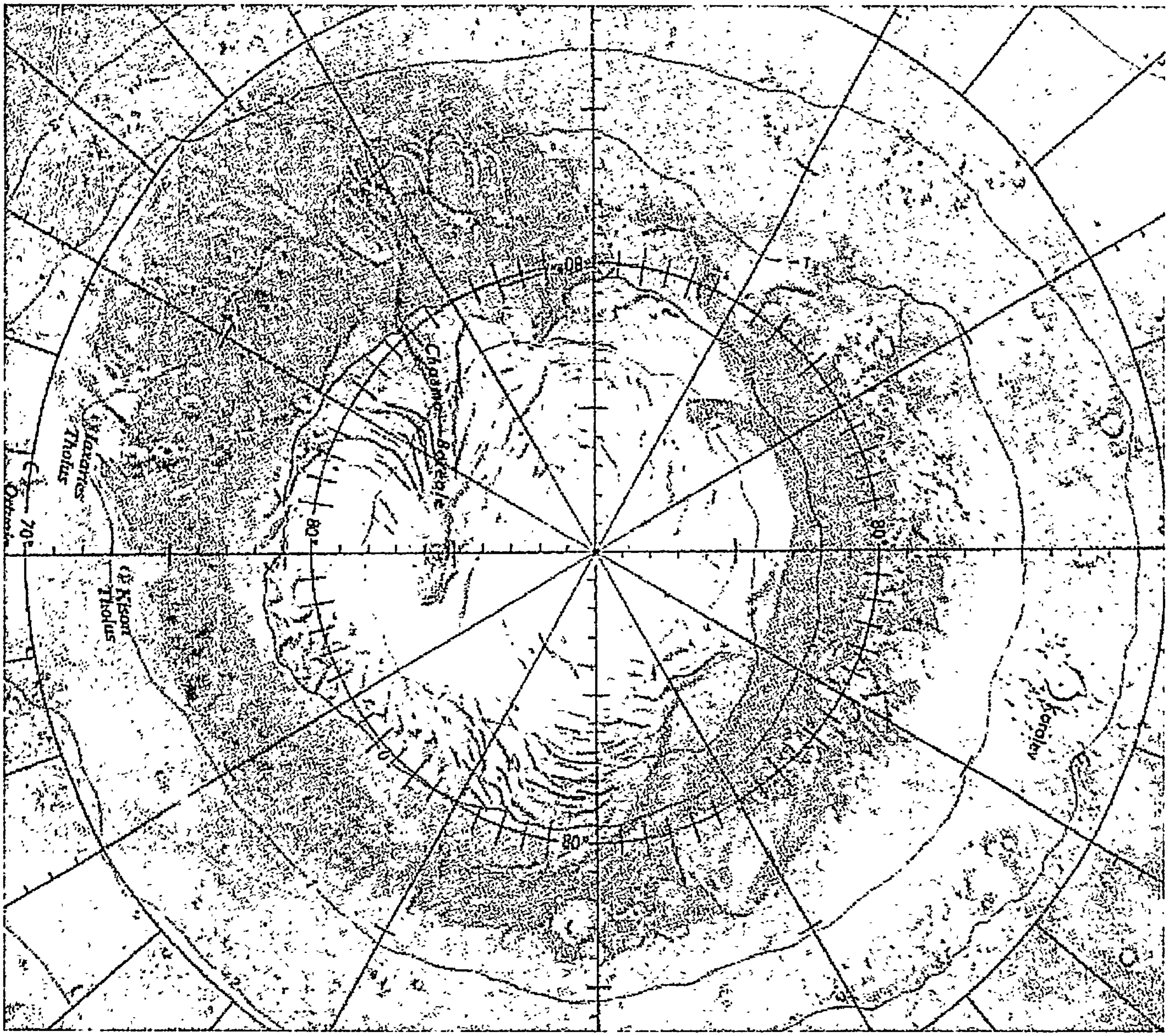


Figure 3: North polar cap of Mars composite satellite photo showing ice cap

Comet Encke

Encke was first discovered during 1820, had a very faint comet signature, the "tail." The tail is barely visible because the comet is active only when near the Sun and difficult to observe. A 1980 radar signal from its nucleus suggests it has a 1 to 4 km diameter. Enough water evaporates in jets from its surface, characteristic of comets, to push it and change its orbit. The IRAS sky survey showed it spews a very pronounced dust trail. It is known to slowly spin with a period somewhere between few hours and a few days.

Comet Encke is accessible about once every 3 and 1/4 years. It passes as close to the Sun as Mercury and swings out past Ceres at aphelion. Figure 5 shows the dust trails of some comets and asteroids, including that of Encke.

Comet Wilson Harrington

From 1979 to 1992 the NEO named "1979 VA" was thought to be just another rock in space whose orbit comes alarmingly close to that of Earth. Is now classified as a comet. Its orbit is nearly tangent to that of Earth's orbit around the Sun, passing within 20 Earth-Moon distances of Earth orbit once every 4.3 years. Its exact size is unknown and somewhere between .5 and 2 km. Its water content is certain, but the amount is unknown.

Photometric data of 1979 VA, shown in Figure 6, had always been erratic. Interpretation attributed "poor observation technique" to the bad luck people had with measuring its luminosity. The puzzle was solved when observers realized their electronic sensor designed to view a point of light was viewing different parts of a comet tail some of the time, resulting in sometimes erratic light output.

Astronomers found it exceptionally interesting because it verified their theory that some "rocks in space" were not rocks at all, but comets. It "became" a comet when Bowell discovered its orbit was identical to that of the Comet Wilson-Harrington, first observed during 1949.

Because its orbit comes so close to that of Earth, the delta_V required to move payloads from it to a captured orbit around Earth are "reasonable," as defined by what a steam rocket could achieve. The steam rocket would use water taken from the comet.

Other "Nearby" Periodic comets

A few dozen comets are accessible. About 150 comets are captured in orbits related in some way to that of Jupiter. Almost all have orbits within about 15 degrees plane of Jupiter's orbit. Most have orbits with period similar to that of Jupiter.

We classify them "accessible" because of relatively achievable total delta_V needed to bring payloads back to captured Earth orbit. (Zuppero, 1991) The required delta_V is less than to go to comet Encke or to Mercury. Some of them have never been seen again. They may have broken up and evaporated. Most of these never come closer to Sun than Mars. Virtually all are rich in hydrocarbons and water ice.

The closest of these, based on a 6500 m/s delta_V for payload capture into an orbit around Earth itself are: P/du Toit-Hartley, P/Neujmin 2, P/Finlay, P/Tuttle-Giacobini-Kresak, P/Howell, P/Haneda-Campos, P/Schwassmann-Wachmann 3, and P/Wirtanen.

The "P/" in front of each of these indicates that it is "Periodic" and in the Jupiter formation.

Those with delta_V less than about 7500 m/s are: P/Churyumov-Gerasimenko, P/Wild 2, P/Forbes, P/Tritton, P/Kopff, P/Clark, P/du Toit-Neujmin-Delporte, P/Tempel 1, P/Helfenzrieder, P/Boethin, P/Kohoutek, P/Reinmuth 2, P/Bowell-Skiff, P/Neujmin 3, P/Gehrels 2, P/Schwassman-Wachmann 2, P/de Vico-Swift, P/Shajn-Schaldach, P/Chernykh, P/Van Biesbroek, P/Kojima, P/Kowal-varova, P/Kowal-Mrkos, P/Gehrels 3, and P/Oterma.

Comet Halley

Satellite fly-through of the tail of Comet Halley during 1986 showed that comets consist of massive amounts of an organic material almost identical to high grade oil shale (kerogen). (Huebner 1990)

A close-up picture of comet itself revealed it was 4 times as much black than white, as shown in Figure 7. Only the white was visible from Earth. The factor of 4 excess black implied 4-cubed more comet mass

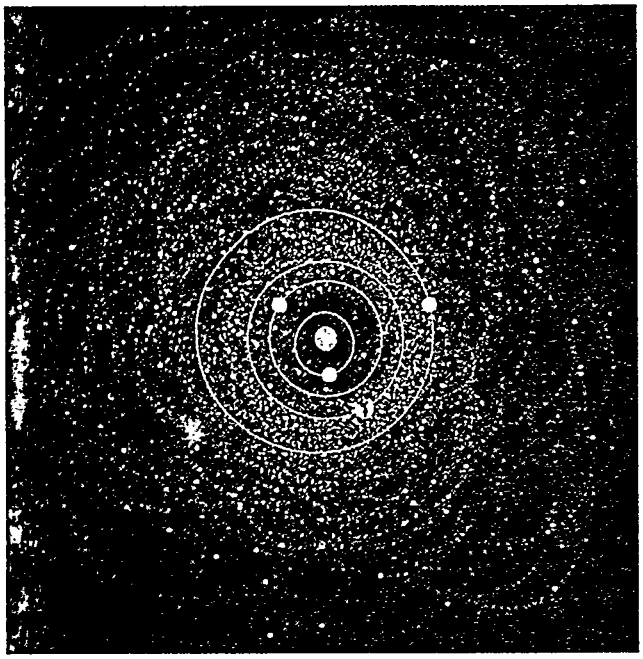


Figure 4: Near Earth Objects (NEOs) are mountain sized objects whose orbits cross or come close to that of Earth. It is believed that up to 40% contain water in some form, such as water of hydration.

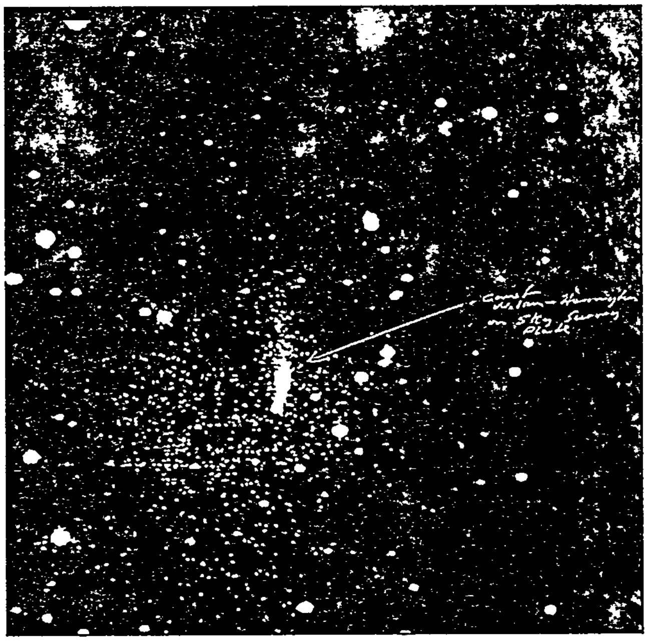


Figure 6: During 1992 one of the NEOs on the left was discovered to have been observed during 1949, as an active comet. Comets are now known to consist of water ice,hydrocarbons and dust. This comet, named Wilson-Harrington, comes within 20 times the Earth-Moon distance to Earth's orbit around the Sun, once ever 4.3 years.

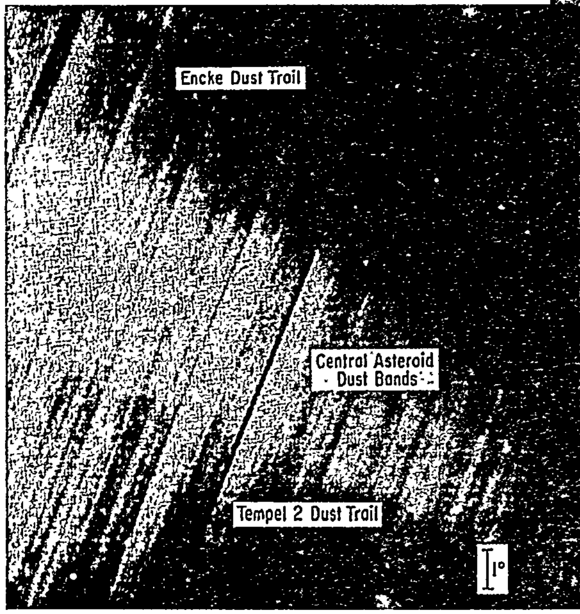


Figure 5: Comet Encke swings out past Mars and in about as close to the Sun as Mercury, about every 3 years. It is seldom actually seen because it is active only when closest to the Sun. It does leave a dust trail, very faintly visible in this IR satellite photo.

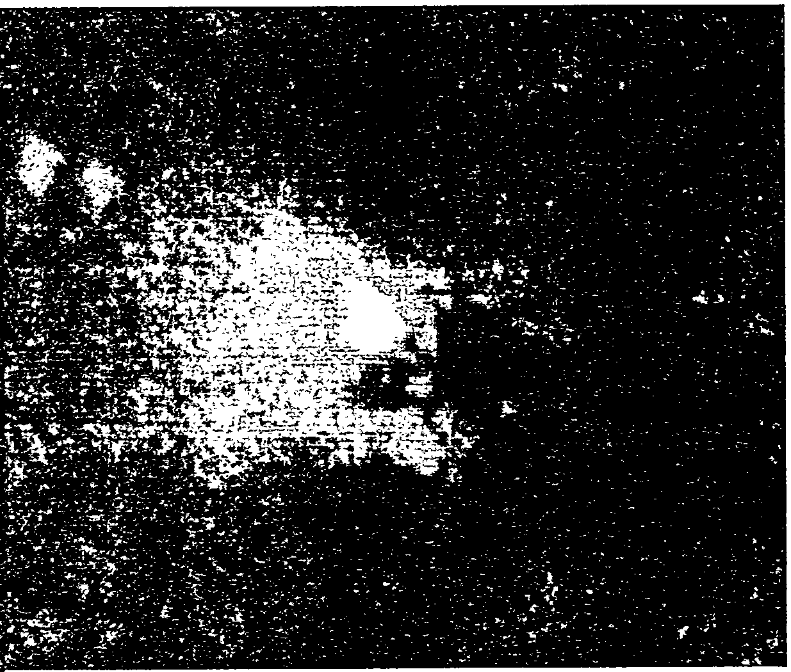


Figure 7: Comet Halley is shown in this composite photo spewing hydrocarbons and water mist, and displaying its intense black insulating coat. Its hydrocarbon content may exceed 500 years of OPEC output. Though inaccessible, this comet was the Rosetta Stone letting us know what comets are made of.

than had been suspected.

The mass collectors flying through the tail found a mixture of carbon, hydrogen oxygen and nitrogen compounds, labeled "CHON."

The particle size and blackness explain why a comet is inactive most of time and for a majority of its orbits.

The inactive part of the comet surfaces are the darkest objects known. The comet interior consists of 1/3 water ice, 1/3 hydrocarbons, 5-10% CO2, some % CO, and about 1% nitrogen compounds, like ammonia or urea.

Kuiper Belt

Past the orbit of Neptune, inaccessible only because of the 30 year, one way travel time humans would suffer, lies a small universe of comet objects whose mass may exceed that of Pluto, our Moon and all other planetary satellites combined. During 1992 a team including Jane X. Luu of Harvard, University of Hawaii astronomers, David Jewitt, Jun Chen and others, found 17 bodies larger than 100 km in the "Kuiper belt." The statistics of the observed population of these objects suggests the Kuiper Belt must contain at least 35,000 similar comet objects larger than 100 km. This would be several hundred times the estimated number of main-belt asteroids in that size range.

Senay and Jewitt of the University of Hawaii in Honolulu measured heavy CO emission from a comet in that vicinity. This suggests these objects may provide quite poisonous environments. They will surely spew dust everywhere.

These represent more carbonaceous material than has been processed by our carbonaceous life form since the formation of the solar system. Low gravity makes virtually all their material minable and usable.

Significance of Water in Space

Water requires only heat energy at less than 800 Celsius for use as a propellant in the space transportation system thermal rockets. It requires only heat energy at about 1200 Celsius when mixed in about equal parts with hydrocarbons to yield hydrogen gas. Hydrogen gas requires only heat energy at less than 2500 Celsius for use as a high performance thermal rocket propellant.

The anomalous low vapor pressure (less than 5 mm mercury) of water at a convenient high liquid temperature (0 to 5 Celsius) permits use of relatively low mass container tanks. For example, a thin, mylar bladder can hold 10,000 times its mass as water in the vacuum of space. Such a bladder with mass equal to the 25 tons of the Shuttle payload would hold 250,000 tonnes propellant. This is enough propellant to bring back 10,000 tonnes payload to an orbit around Earth from the "nearby" periodic comets named earlier.

Mining Issues

What are the issues related to mining the water? How difficult is it to exploit these resources? The issues include those related to the high and low gravity environments, the purity of the product water, the economics, and the environment humans can expect to find when there.

The two classes of space water mining environments, at high gravity objects and at low gravity objects, have completely different problems.

High Gravity Objects

Mining on an object with some gravity is similar to such mining on Earth, where up is up, down is down and all things fall. The key difference is the lack of an atmosphere. Any wells will probably leak. That is, pressurizing the hole will not work.

The ice on the poles of moons and planets is almost certainly not directly at the surface. But it is probably not farther down than the tens of meters a radar can penetrate. The ice is expected to be at least colder than about -50 Celsius. It will be permeated with sand, very much like permafrost. One can almost certainly expect cracks and slippage planes. The Alaskan drilling experience indicates new methods will be needed to dig space permafrost. One may need to develop tools drill by heat.

One can not easily have "drilling mud" because it will freeze solid in the extreme cold, or boil or sublime away into the vacuum of space. None of the water objects has enough gravity to keep an atmosphere.

The operations will almost certainly be completely in the dark. And dust will be a major problem if it comes in contact with any joints, gears or rubbing surfaces.

The composition of the water bearer is not known.

Lowering mining hardware down to the surface of the Moon, or to a planet like Mercury or Mars, requires powerful reverse thrusting maneuvers. This limits the mass of hardware payloads to be less than what a single train car can hold, and certainly to less than 100 tonnes at a time.

Lifting payloads off these high-gravity objects is only slightly easier because the rocket fuel is abundant on the object surface.

Low Gravity Objects

Drill rig floats Mining a low gravity object requires that the rig grab the NEO and pull itself into the region to be drilled. Drilling mud will not stay put, nor will it fall into the hole. The drilled hole will almost certainly leak if an attempt is made to pressurize it. Even an overburden hundreds of meters deep may be lifted with very little pressure. If you pressurize a hole drilled into the comet, you risk blowing the comet to pieces.

Comet May Explode The billion year irradiation by Galactic Cosmic Radiation (GCR) dissociates the water ice in its path, causing about 1% of the energy to go into radiolytic dissociation. The products, a solid solution of stoichiometric hydrogen and oxygen gas, are locked in a matrix of the permafrost. The ice would burn if put in an airtight bell jar and lit with a match. A 1 billion year residence time in the 50 rad per year bath of GCR would cause the first meter of ice to store an energy of about 2 Megajoules per pound, or the same energy as the high explosive Baritol. The entire comet could detonate and vaporize in a brief flash if mistreated.

Equipment May Sink No one knows how competent the material will be, that is, whether it is as delicate as fluffy snow, or as sturdy as permafrost. The mining system may find the "soil" to be a fine powder, incapable of supporting hardware.

Foaming Corrosion Possible The composition of the comet interior is expected to be more like a frozen solid, -50 Celsius cesspool, saturated with organic poisons, tar and sand. The drilling device may become stuck or corroded in the tar and what may likely be highly corrosive free radical materials. The material may foam upon heating under sufficient pressure to keep liquid water.

Water Purity Issue

The water must be pure enough to be put into red hot stainless steel reaction vessels without causing reactions or precipitation. The dissolved salts and hydrocarbon concentrations must be low enough to be measured in units of tens of parts per million. The separation of hydrocarbons may not be trivial because the only simple separation method, distillation, does not readily remove all the hydrocarbon.

Economic Factors

Mining claims must be honored before the resource discovery rights can be sold as assets. The rights must be sellable to raise capital to mine them. The current laws are unclear and may inhibit sales of claims.

All operations must be either performed by autonomous robotics or with people. The support systems for people are very expensive. The use of robotics is uncertain.

The robots must be autonomous because the radio wave transmission delay is so large, typically several tens of minutes for a control signal to reach the robot and for any feedback signal to return.

Risks to humans

Virtually all the environments will subject humans to a constant flux of Galactic Cosmic Radiation. If shielded only by the hull of the Shuttle, a human would receive 50 R per year. To shield GCR requires that the humans place at least a meter of a dense material (such as water, ice or dirt) between them and space. The result will be to keep people in small spaces and in the dark.

SUMMARY & CONCLUSIONS

Accessible water in the form of ice or permafrost has recently been found at nearly every location in the inner Solar System.

Radar signatures indicate water ice at the forever-dark North Pole of the planet Mercury and possibly in a dark crater at the South Pole of the Moon. Visible and other data indicate water ice on the poles of Mars. Dissociated water has been observed in the transient atmospheric region above the north pole of Ceres, strongly suggesting the asteroid may contain massive quantities of water ice. Ceres is the largest asteroid and is located in the inner region of the asteroid belt.

During 1992 a somewhat common type of Near Earth Object (NEO) was found to be a comet, now referred to as the comet Wilson-Harrington. Its orbit comes within 20 Earth-moon distances to the orbit of Earth about every 4.3 years. Observations and comet tail fly-through experiments of a similar comet revealed that comets contain about 1/3 water ice, 1/3 hydrocarbons very similar to high grade oil shale, some ten percent CO2, and about 1% nitrogen compounds.

About a dozen comets in the Jupiter family formation have accessible orbits, based on travel time and propulsion considerations.

Water is key to the exploitation of space because as a rocket propellant it requires only heat energy to provide thrust. The simplicity is the value. Further, mixed with the equally abundant hydrocarbons recently discovered on comets, and heat, it produces hydrogen, also a premier rocket propellant.

The principle barriers to mining the water include the darkness, the vacuum of space, low gravity, and most important: our near total ignorance of the composition or environment in which the water resides.

Space laws inhibit mining because they do not provide a way to own and sell the mineral rights necessary to provide the capital for prospecting, assay and development.

The orbits of the objects with water pass close to the orbit of every location humans may want to travel in the Solar System, and in this sense the discovery provides a bridge to space.

The accessibility, location and amount of the water and hydrocarbons recently discovered provide the raw materials needed to transport the nearly unlimited resources of space back to Earth itself.

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