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Discovery Of Abundant, Accessible Hydrocarbons Nearly Everywhere In The Solar System

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Abstract

Analysis of the data gathered during the Comet Halley encounter during 1987 resulted in a body of literature asserting that all comets contain substantial percentages of hydrocarbon solids. These solids appear to have a strong similarity to petrochemicals. Arguments are made that the amount of hydrocarbon material in the accessible comets of the inner Solar System can substantially exceed the known reserves of hydrocarbons on Earth.

An example is given of at least one conceptually simple method to use comet material as feedstock for space transportation schemes that can move masses through the solar system comparable to the mass carried by oil supertankers.

The presentation concludes we need to send prospecting and assay probes to a sampling of the accessible comets to determine the amount of hydrocarbons and the form and location of materials needed for space transportation systems.

Introduction

Hydrocarbons similar to petrochemicals have been physically collected from the dust in the tail of Comet Halley. The body of data also suggest that the amount of hydrocarbons in that comet are comparable to the known reserves on Earth. Though published in the literature, these facts and their implications are almost unknown outside of the small circle of enthusiasts.

Comet Halley has been dismissed as a resource because it has an orbit that makes it practically inaccessible to rendezvous (soft landing) with our spacecraft. However, it is part of a formation of more than 150 comets associated with Jupiter, and dozens of similar comets in that formation are accessible to rendezvous. Recent discoveries added to the list of accessible comets.

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Comets apparently also contain water ice. If true, this would be the first time in the history of space exploration where we found a key ingredient to manufacture massive quantities of rocket fuel or rocket propellant. This could enable economic, massive payload space transportation systems. The discovery that comets are composed of about 1/3 water ice as well as about 1/3 hydrocarbons provided a key resource that could render space resources useful.

To be "accessible resources" the space materials must have at least three properties:

1. **existence:** abundant quantities of something very useful;
2. **closeness:** either easy, quick or simple to get to and from the objects; and
3. **transportability:** affordable way exists to transport economically significant amounts through space.

The short presentation that follows sketches data suggesting where hydrocarbon resources exist in abundance, that at least a few resource objects are close enough to land on and assay, and that we discovered at least one way to use the resources to transport massive payloads through space.

Existence

Hydrocarbon resources have been either collected or detected in some way on comets, near Earth comets, some asteroids and near Earth asteroids (NEOs), and on moons of planets.

Comet Objects Analyses of the many different data sets obtained from comet Halley and from a large body of comet, asteroid, and planetary moon measurements all point to a composition description of comets (Huebner 1990). Data suggests after they have outgassed methane or other light gasses during their early life, they are composed of tar-like solids similar to oil shale, called CHON (Carbon, Hydrogen, Oxygen, Nitrogen), and roughly equal amount of water ice and clay-like silicate materials. Sulfur compounds are present in significant amounts, probably at the 1/2 percent level (Huebner 1990, pp 306 thru 309). Particle collectors and mass spectrometers produced data suggesting that the composition of the hydrocarbon appears to be similar to a xylene polymer, probably like $(CH_2)_n$. Nitrogen compounds such as CHN, urea and/or ammonia are believed to be present at about the 1% level. Carbon dioxide (CO_2) and carbon monoxide (CO) appear to be present during some part of the life of the comet at about the 1% to 15% level. All the percentages may vary by a factor of ten or hundred for any given comet.

Infrared dust trail data suggest that the comet core is similar to a frozen mud ball at -50 Celsius, where the mud contains as much mixed organics as silicates (Sykes 1986, Sykes 1992). The dust collected from the comet tail contained hydrocarbon particles (Huebner 1990). These and other data led to the conclusion that comets contain some tens of percent hydrocarbons similar to petrochemicals.

The low albedo, or darkness, of the material explains why the comets are believed to contain massive quantities of hydrocarbons. Comet size estimates were based on visual observations of brightness and implied similarities to other solar system objects such as asteroids. Telescopes could neither image the comet nor its dark part, so we could not measure the size of the dark part.

The photographic observation of the comet Halley body revealed that the comet dimension was much larger than suspected (20 km instead of 5). The comet nucleus was much darker than expected (albedo of order 1-2% instead of 5 or more percent). Other data lead to estimates of the comet density (of order 0.3 Mega grams per cubic meter). These data permit us to estimate of the quantities of hydrocarbons, and water ice, contained in the comets. Comets are now believed to be between 1 km and 20 km in dimension.

The comet Halley could contain about 200E9 tonnes, or about 200 times as much hydrocarbon

material as the Oil Producing Exporting Countries (OPEC) produce in a year. (1 OPEC is about 1E9 tonnes).

The "Periodic comets" constitute a formation of comets numbering between 150 and 200 objects (Carusi 1985). Comet Halley is a member of this formation. They have periods between 3 and 200 years and are located in orbits related to Jupiter. These comets are believed to be similar to comet Halley, and their dimensions are believed to be between 1 and 20 km. Based on this data one could conclude that a comet would contain between 1/10 and 500 OPEC of hydrocarbons. Given about 150 such objects, one would conclude that the amount of material is between 15 and 75,000 OPEC of hydrocarbons.

For comparison, OPEC has about a 50 year supply, and the coal and oil shale reserves of the planet are somewhere in the 10,000 OPEC range.

Asteroids and Moons Some percent fraction of the asteroids are believed to be "carbonaceous" in the sense that they would be substantially composed of hydrocarbon materials. None are expected to land on Earth without completely burning up. Some remaining percent, increasing to a dominant percent in the outer asteroid belt region, are believed to be comets.

The outer moons of Jupiter, including Ananke, Carme, Elara, Himalia, Leda, Lysithea, Pasiphae, and Sinope, are considered to be captured comets, probably similar to the Shoemaker-Levy-9 comet that hit Jupiter during the summer of 1994.

Two of the smaller moons of Saturn, including Hyperion and Iapetus, show evidence that one or both may be massive hydrocarbon objects trapped into Saturn's orbit (Yenne 1987). The entire leading edge of Iapetus is as black as asphalt while its trailing hemisphere contains a more familiar crater-pocked ice and rock landscape. Some crater floors on the trailing hemisphere appear to be equally dark.

Kuiper Belt Past the orbit of Neptune, inaccessible principally because of a 30 year, one way travel time of a minimum energy orbit, lies a small universe of comet objects whose mass may exceed that of Pluto, called the Kuiper Belt. During 1992 a team including Jane X. Luu of Harvard, University of Hawaii astronomers, David Jewitt, Jun Chen and others (Luu & Jewett 1994; Senay and Jewitt 1994), 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. Since then they have greatly increased their estimate of numbers and sizes. The initial estimate represents of order several Billion OPEC of hydrocarbons (~2E9 units of 1E9 tons).

However, it's location is the region of Neptune and Pluto.

Near Earth Objects Bowell discovered during July 1992 (Bowell 1992; Marsden 1992) that at least one of the near Earth objects (NEOs) is in fact a comet, and not rock-like bodies we normally associate with asteroids. Some tens of the more than 250 known NEOs shown in Figure 1 exhibit spectral and orbital features similar to the comet Bowell identified, now called P/Wilson-Harrington and then identified as 1979 VA. Shoemaker had suggested that up to 40% of the NEOs should be water objects of some kind, and that comets should be among them.

The hydrocarbon and water NEOs would not survive reentry into our atmosphere. We would never see them on the ground because they would either burn or evaporate due to the re-entry heating and environment. The Tunguska, Siberia, event of 1908 provides a clue that this may have happened relatively recently. The object is believed to have detonated 6 km above the ground and released the energy equivalent to a 20 Megaton nuclear device. The hydrocarbon burning energy is insignificant, of order 1%, compared to the orbital kinetic energy of the object. This means the NEO's atoms are moving much faster than and with about 100 times more energy than they could release by burning. This guarantees that upon deceleration and heating during reentry, the entire object is vaporized into a plasma similar to that of the fireball of a detonating high explosive or nu-

clear weapon device.

It is now unclassified that the USA DSP satellite system to monitor atmospheric nuclear explosions had routinely observed about a dozen objects per year entering the atmosphere, detonating at altitudes typically well above cloud tops, with optical signals characteristic of detonations, and releasing energy in the range between 1 and 100 kilotons nuclear equivalent. This is evidence that pieces of these hydrocarbon or water objects have been bombarding Earth, and that they would not be recovered on the ground.

Invisibility of Ubiquitous Comets Prior theoretical analyses (Fanale 1991; Fanale 1982) suggested that the particles making up a comet would be a fine dust that would encrust the entire comet. The particle sizes confirm theories that predict that a comet will be covered by a 4 cm to 1 meter thick layer of this dark, soot-like material. The fluffiness of the material apparently forms an layer around the comet similar to an ideal evaporative cooler. That is, the pore size would be smaller than the mean free path of water molecules. This accounts for the observed fact that comets are almost always turned off and not spewing material into space to form a visible tail.

The dust envelope would effectively shut off most of the comet activity for most of its life. Without a tail, the comet would be nearly invisible. Further, the brightness of the comet envelope (albedo) is of order 0.5% to 2%, which is the darkest matter observed in the Solar System.

For these reasons we do not see the more than 150 comets in the Jupiter Family when we look up at the night sky. These comets are always present in the Solar System and have orbits between 3 years and 200 years. If they were all active with their characteristic tails we would see (1/3 of the 150) about 50 comets in the sky on any given night.

Closeness

Space objects are "close" if either they are easy to get to, or if the trip time can be "small" and less than several years, or if the rendezvous maneuvers to get to them are simple. About a dozen Periodic comets are close enough that launch systems like those used to send probes to Mars can affect a rendezvous with them. About two more dozen are close in the sense that rockets like those used to access Jupiter can rendezvous with them.

In general, CHON objects are considered close if an affordable rocket can send a prospecting probe to cross their orbit. Nearly all periodic comets and all the objects as far as Saturn or closer, are "close" in this sense. Calculations of comet flyby opportunities indicate that about 4 opportunities per year become available to McDonnell Douglas Delta, Orbital Science Taurus, the Clementine system of the Department of Defense, or Lockheed-Martin LLV-2 rocket class launches. Crossing their orbit takes relatively little energy.

Comet P/Wilson-Harrington (formerly thought to be a NEO named 1979 VA) comes physically close to Earth's orbit every 4.3 years. The rendezvous energy is like that needed for a fast trip to Mars. Comet P/Encke is accessible to flyby often, every 3.3 years. The flyby energy is like that of a fast trip to Mars.

Shoemaker and Helin (Shoemaker 1978) derived the expression for the ΔV accessibility used in these calculations.

Comet P/Wilson Harrington is the recently discovered, very close and closest known comet, shown in Figure 2. From 1979 to 1992 the NEO named "1979 VA" was thought to be just another rock object NEO whose orbit comes alarmingly close to that of Earth. It 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 believed to be somewhere between .5 and 2 km. Its hydrocarbon and water content are certain, but the amount is unknown.

Photometric data of 1979 VA 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 that 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 ΔV 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 itself, for propellant. Impulse maneuver rockets that can achieve 4500 m/s ΔV above an escape orbit, such as the Delta, the Taurus or the LLV-2, can rendezvous with P/Wilson-Harrington.

Electric propulsion rockets or any slow-thrust rocket can cross the orbit of this comet and sometime achieve rendezvous with only about 9000 m/s ΔV above an Earth Escape orbit; and can rendezvous with it nearly anytime for something of order 12,000 to 20,000 m/s (Zuppero 1991)

Comet P/Encke was first discovered during 1820 and exhibited 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. It could contain as little as 100 Million tons of hydrocarbon (1 km) or as much as 6 OPEC (6 Billion tons). 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.

Other "Nearby" Periodic Comets Almost all of the over 150 known Periodic Comets have orbits within about 15 degrees plane of Jupiter's orbit. Most have orbits with period related to that of Jupiter. We classify up to several dozen of them to be "accessible" to rendezvous (landing or liftoff) based on a relatively achievable total ΔV of 6500 m/s for impulsive maneuvers performed at Earth's perigee. The ΔV is that needed to bring payloads back to a barely captured Earth orbit. (Zuppero 1991) Some of the P/comets have never been seen again. They may have broken up and evaporated. Most of these never come closer to Sun than Mars.

The closest of these, based on a 6500 m/s ΔV for payload capture into an orbit around Earth itself are, in order of increasing ΔV (difficulty):

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 ΔV 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.

Transportability

Resources are transportable only if they can be removed easily and sent through space practically. The removability is inversely proportional to the object gravity. If a rocket can push with one ton force, it can lift 6 tons off the moon, which has 1/6 the gravity of Earth. On a comet with about

10 micro-G the same rocket launcher can lift 100,000 tons. All the comets and NEOs present micro-G environments.

Sending massive payloads through space requires between 1/10 and 100 times as much propellant or rocket fuel as payload. The highest transportability occurs when the rocket fuel or propellant ore can be found on the resource object itself. This occurs for comets because they contain both water and hydrocarbons. The water can be used to manufacture rocket fuels such as Liquid Hydrogen (LH2) and Liquid Oxygen (LOX). In combination with hydrocarbons, the water can be used to produce hydrogen gas, methane and other rocket fuels. Because all of the objects considered here have at least hundreds of millions of tons of these resources, we conclude that their resources are transportable.

The steam rocket provides an example of how much hydrocarbon or other resource one might push through space using a particularly simple and brute force method. Calculations (Zuppero 1991) showed that a nuclear reactor similar to that found in a nuclear submarine could develop between 100 and 300 Megawatts at 800 Celsius. It would super-heat pure water into supercritical steam. Piping this steam directly from the reactor to a rocket nozzle, in precisely the same way proposed for the liquid hydrogen nuclear thermal rockets designed for the manned Mars mission, would produce a thrust between about 18,000 and 56,000 pounds force and a specific impulse of about 230 seconds. The tank to hold the water could weigh as little as 1/10,000 of its contents. This rocket, whose weight of less than 20 tons (like that of a concrete truck) and size (tens of feet long, like that of a concrete truck) would be able to lift about 2 Million tons away from a typical comet. By comparison, an oil supertanker holds between 0.010 and 0.050 Million tons.

This same rocket would push a 1 million ton payload of hydrocarbons, or anything else, with a ΔV of about 1500 m/s. This is sufficient to cause the required orbit change to intersect the orbit of Earth for about half of the above stated comets and NEOs.

This same rocket would deliver the required 6500 m/s ΔV to bring resources from about a dozen P/comets for a payload of *about 100,000 tons, to a captured orbit around Earth or the Moon.*

Even this brutish solution of a steam rocket would deliver 100,000 ton units to orbits around Earth itself. The propellant tank for 2 million tons of ice slush propellant would weigh about 200 tons. The entire space tanker would weigh about 220 tons and deliver either about 1 Million tons through space or 100,000 tons to orbits around Earth itself (Zuppero 1991; Zuppero 1992). This suggests a proof that the comet hydrocarbons are certainly transportable. If we knew more about the composition and location of the hydrocarbons, the water and the remaining "contaminant" species, we could perhaps design far better space transportation systems.

Conclusion

Hydrocarbons similar to petrochemicals have been discovered in abundance on micro-gravity objects of the inner solar system, dominated strongly by ever-present and most often nearly invisible comets. The amounts are uncertain and range from at least hundreds of OPEC years of hydrocarbons to in excess of tens of thousands to hundreds of thousands of OPEC years. The details of the composition of the hydrocarbons is uncertain, but the strong similarity to organics found in laboratories and on Earth itself is a measured fact. The degree of contamination by sulfur, by dissolved minerals, by fine dust and by potentially corrosive, abrasive or foaming materials is not known. The location on the comets of the water ice, the hydrocarbons and the other materials is not known. The existence of the materials is certain.

The resources are close to Earth in any one of several ways. Comet P/Wilson-Harrington is both energetically and physically closest to Earth of all the objects. Bowell discovered it to be a comet during July of 1992. It comes within 20 Earth-Moon distances of Earth's orbit around the Sun once

every 4.2 years. Comet P/Encke is sufficiently close for flyby and possible rendezvous at least once every 3.3 years. About a dozen periodic comets are sufficiently close that small satellite systems can flyby and possibly rendezvous (land on) them. Another dozen or two are close enough to be accessible to larger rocket systems.

All the comets have sufficiently low gravity that removing resources from them requires relatively small, multi-ton forces. The comets are believed to contain sufficient water ices to permit simple manufacturing of rocket propellants or rocket fuels, and in sufficient quantities to deliver payloads through space comparable to those of oil supertankers on Earth.

We need to know exactly how to separate the water and hydrocarbons from each other and from the ultra-fine dust, and from the probably foaming, corrosive, abrasive mixtures of contaminants. We need to learn how to do this in zero gravity and with only robotic maintenance devices, reliably.

A prudent first step is to go prospecting and assay the resources. We need to learn as much as we can about the composition, location and diversity of the resources. Current electronic and rocket technologies have advanced to the point where nearly any nation can send relatively inexpensive, mini-satellites to prospect for and assay resources on at least dozens the NEO comets.

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Figure 1 Near Earth Objects (NEOs) as of July 1992. The bold dots are the locations and the dotted points depict the orbits of the NEOs known as of July 1992. The closest known comet to Earth, both energetically and physically, named P/Wilson-Harrington, is in this formation and currently inactive. Properties of the known comets lead us to conclude there are more comets like this one, and they are also mostly inactive. The density of orbital dotted points is proportional to the probability of a NEO collision with Earth (of order $1E-5$ to $1E-6$ per year).

Figure 2. Comet P/Willson-Harrington. This comet comes closer to Earth's orbit than all the known comets. Once every 4.3 years it comes to within about 20 Earth-Moon distances to Earth's orbit. The rocket energy needed to rendezvous with it is also the lowest of all known comets. The fact that it displayed a characteristic cometary tail during 1949 assures that it contains both hydrocarbons similar to petrochemicals and water ice. The amount and location of either on the comet is completely unknown at this time. It is currently inactive, which is the normal state of comets, and appears as a point of light. Its appearance is similar to many in the formation of about 300 known NEOs.

KEYWORDS
(in order of importance)

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near earth objects
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Comet Halley
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