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# Mini-Satellite Exploration Of Very Near Earth Space Fuel Objects

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## ABSTRACT

A prospecting plan is presented to assay near Earth objects (NEO) for their potential to yield rocket fuel. The plan calls out small satellites as the near-term means to achieve low cost surveys and deep subsurface sampling of NEO composition. The water bearing classes of NEO to be considered are limited to those accessible in short time and with small thrusters. These include the water bearing clay objects (phylosilicates) at nearly trivial distances from Earth, and the recently identified water ice objects such as comet (#4015) 1979 VA. These objects are evaluated as small satellite prospecting and assay vehicle targets.

## INTRODUCTION

The discovery of a comet in the middle of the formation of near-Earth objects (NEOs) provides the impetus for an intensive search for other, closer, massive and extractable sources of rocket propellant and fuel ore in the space near Earth (see Marsden 1992). The significance of the discovery is that small nuclear powered tug propulsion systems can nudge large masses back to Earth orbits, possibly for commercial use and at costs between 100 and 1000 times less than the cost to launch the same fuels from Earth surface (see Zuppero et. al, 1991-1992). How many other objects of similar kind are there?

Wetherill (1991) predicted that the final meta-stable solar orbit for comets is a swarm centered just past Mars (2.2 AU), on the orbital plane of the Earth and with perihelia that come closer to the Sun than Earth. This formation happens to be indistinguishable from the observed swarm of NEOs, which orbit the Sun between the orbit of Mercury and somewhere past Mars. Figure 1 shows this swarm, courtesy of Sykes. The object "1979 VA" was an object in that formation and was thought to be a carbonaceous, soft rock containing ~10% water as hydrated mineral. On 14 Aug. 1992 Bowell (Marsden 1992) reported through the Central Bureau for Astronomical Telegrams that this object was in fact a known comet, as predicted. Wilson and Harrington observed its "tail" in 1949. Figure 2 shows a segment of this 1949 survey plate, courtesy Shoemaker. They did not have enough observations in 1949 to give a good orbit. The observations of 1979 VA, numbered object (4015), provided the precise orbit required to be able to look back into the photographic plates of astronomical history to see if the object was ever observed in the past. It was, as a comet.

Zuppero and Jacox (1992) detailed how the object could be used as a fuel source in the space near Earth and that an entire formation of such fuel objects should make up about 50% of the existing, observed NEO population. In their paper they also pointed out the ease of access of these objects. The objects of interest are those that come close to Earth. This defines classes of orbits where vehicles in the orbit plane of the Earth about the sun will almost certainly pass close to an NEO. As a significant subset of these orbits, they identified about 10% of the objects as also being accessible in the rendezvous sense. Objects with perihelion close the Earth's orbit and with inclination less than about 10 degrees generally have rendezvous ΔV permitting massive payload transport from the NEO to Earth orbit. Given the great value of the rocket fuels and propellants the water-bearing NEOs could provide, the question of most interest is: What is the closest, most valuable object we can use? We have about 10% of about 400 objects from which to prospect. Can small satellites perform exploration missions?

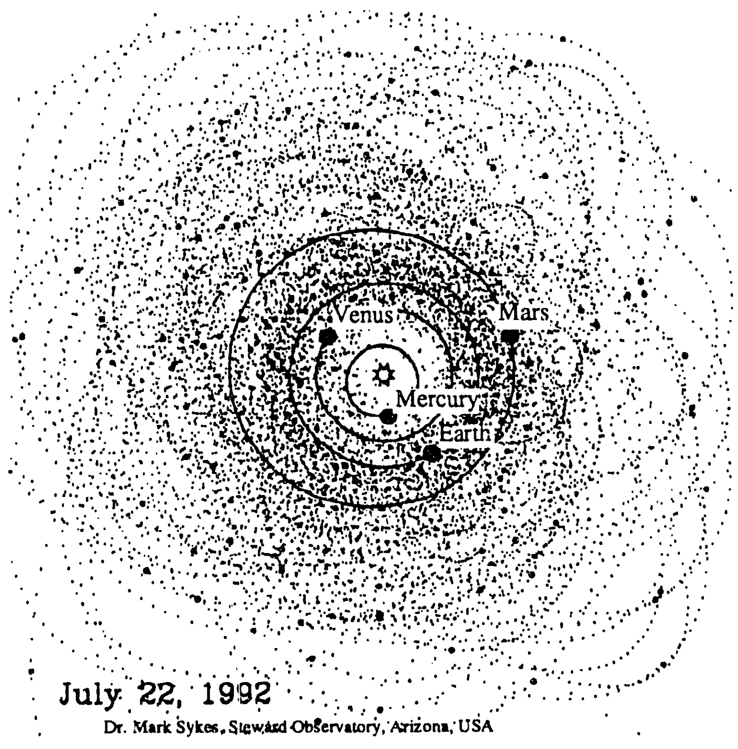


**Figure 1** The chance of encountering a NEO is proportional to the density of dots in a region. The objects (large dots) and orbits (dotted lines) of the 208 known NEO's as of 22 July 1992 form a swarm engulfing the space near Earth's orbit. Half of the objects are expected to contain water in some form. Some fraction are expected to be dormant comets. One is recently discovered to be a comet: (4015) 1979 VA = Wilson Harrington.

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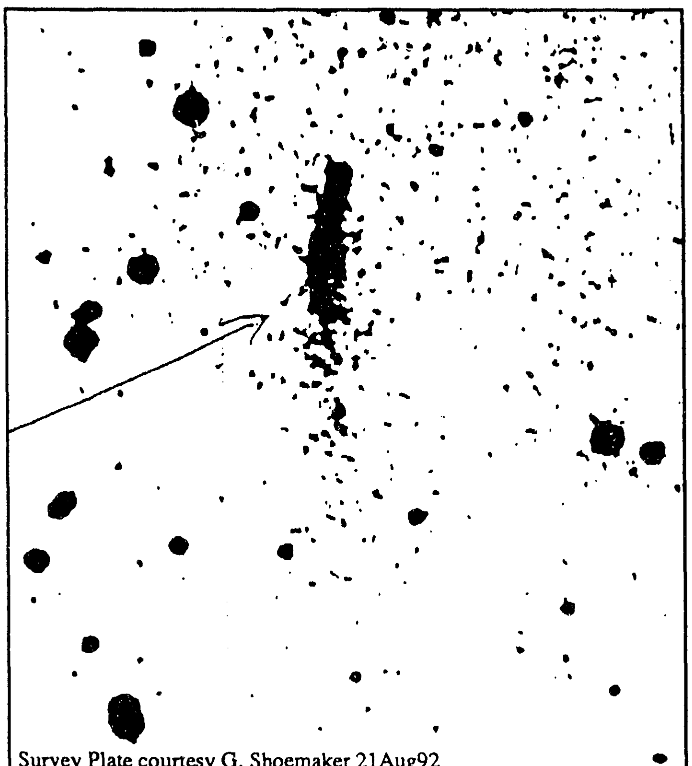
We are in search of either a very close, water-bearing object or one whose ice is very clean and easy to extract. What is the lowest cost prospecting program to perform this search?

## GOAL OF PROSPECTING SYSTEM

Engineering details of a fuel extraction system require the composition of the starting material. How easy is the water extraction process? How deep is the material with the water? How close is the object: What is the mission $\Delta V$ to access the object? What is the round trip period of a material transport system? Small satellite prospecting missions would answer these questions.

The two types of water bearing object a prospecting system must find and assay are comets and phylosilicates. The comets come either as active comets or devolatized comets. Active comets include 1979 VA and its "periodic comet" relatives, also called the "Jupiter Family." These have been observed with a "tail" at least once in their history. The inactive or devolatized comets are the cores or remnants of comets. These are expected to have ices deep in their regoliths. Fanale (1990, 1991) has suggests that Phobos should be a comet core with its ices 60 meters from its poles and 1 km deep into its equator. NEO 2201 Oljato and 2101 Adonis show evidence of being in this category.



Survey Plate courtesy G. Shoemaker 21Aug92
first sighting in 1949, by Wilson & Harrington

**Figure 2** Like a gushing oil well just off shore, comet (4015) 1979 VA = Wilson Harrington showed it tell tale trail in a 1949 plate. About 5 km across it may have 20 Billion (2E10) metric tons of water ice. It's gravity is very low and about 1/10,000 that of Earth, which is crucial for it to be useful to us. Its orbit perihelion is 1.003 AU (Earth is 1.00000) and has a 4.296 year period.

The comet ices are near their surfaces and hence easy to extract (see Huebner 1990). But the problem is that they are generally further away from Earth. This results in a larger velocity at Earth approach ($V_\infty$) and implies a longer orbital trip time. The larger $V_\infty$, between 6 km/s and 9 km/s, results in a higher mission $\Delta V$ both to go to the NEO comet (neo-comet) or to return with a payload.

Phylosilicates, the other type of water bearing objects, are clays with loosely chemically bound water molecules. They have the consistency of dried mud. Their compressive strength is about 100 KPascal (20 psi). Because they crumble so easily, they never land on Earth. We know they exist only by their spectral characteristics. Phylosilicates are expected to be closer, as a class of object, than neo-comets, both in trip time and in mission $\Delta V$.

Their water can be liberated by heating the mud to cooking oven temperatures, of order 300 C. Getting the water out of the clays is relatively easy. But condensing the water is the problem. A nuclear reactor can develop of order 500 to 1000 Megawatts useful thermal energy per ton of reactor, and quickly liberate the water. But the condensers of the resulting 100 Celsius steam can radiate only about 2 to 10 Megawatts per ton into the vacuum of space.

All the rest of the NEOs are space rocks. Some are known to contain water because their category lands on Earth. But those rocks are as hard as granite or sidewalks and therefore not considered so useful. Others contain native metal flakes or blobs. Concepts to use the metal as fuels have been published, but they are not considered commercially interesting at this time.

The preferred object is the closest one. The condenser problem of the closer water-clays has many good engineering solutions. The long trip time problem of many of themore distant neo-comets is more difficult to work with. This means the **goal of the small satellite search is to find a water object with short trip time.**

## METHODS

The prospecting objectives are to determine the presence of water, its form, its concentration, the impurities, and the amount available. The methods to achieve these objectives are all amenable to small satellite techniques. Sensors carried on fly-by satellites can detect comet water vapor. Similar sensors to detect vapor coming off a comet are small, particle collection systems like those flown through the tail of comet Haley. Huebner (1990) describes such systems in detail. The dissociation products of the vapor can be sensed using UV, optical and IR spectral detectors. The solar flux dissociates and ionizes the water. Russell (1984 - 1990) and Arghavani (1984 - 1985) observed data indicating this cloud extends 1E6 km in dimension surrounding 2201 Oljato. McFadden observed UV emission from Oljato consistent with post perihelion passage.

Detecting water content on phylosilicates is more difficult and may require contact probes. The IR spectrum of the phylosilicates provides a signature (see Lebofsky). The compressive strength and the amount of material must be determined by contact.

Determining the mass of material available can be achieved by determining the gravity properties of the object. Visual scans determine the object volume. Orbit changes induced by the object gravity when the satellite flies by and albedo consideratoins provide the data for a gravity field determination. These data together combine to give the mass of the object.

A convenient NEO contact exploration method is a penetrator. It would either penetrate and cause either splattered material to be thrown into space, to be detected and analyzed by a passing sister satellite, or the penetrator would itself take data. The simplest is an inert, splattering penetrator. Sandia National Laboratories (See Young and Ryerson) has pioneered the penetrator technology as a low cost space probe, dating before the 1970's. A most simple penetrator would use the flyby velocity mismatch to drive the penetrator deep into the object. Experiments showed that penetrators would sink 50 meters into the playa at the Nevada Test Site when driven with up to 2000 ft/second (600 m/s) velocity. The typical velocity mismatch between a small satellite and NEO can be in excess of 10,000 m/s. So the penetrator can probably be made to sink deeper than 50 meters, without a drill rig. Sensors would detect the ejecta from the impact, and thereby perform in-depth sampling of the object. If the penetrator does not experience in excess of about 20,000 G's (1 G defined as 9.8 m/s/s) then the penetrator itself may be instrumented with detection systems.

## VEHICLE AND ORBITAL MANEUVER REQUIREMENTS

The kinds of vehicles needed to explore the NEOs are 1) flyby, 2) flyby / penetrators, 3) rendezvous and 4) sample return. These are in order of increasing size. All can be "small satellites" if nuclear power sources are allowed. The first three categories will be considered here.

The flyby satellites would take advantage of the fact the orbits of all the NEOs come close to that of Earth. The definition of a NEO is equivalent to stating that its orbit perihelion be less than 1.3 AU. This means in practice that a satellite sent to some orbit between 0.7 AU and 1.3 AU with some inclination less than about 10 degrees will be able to fly by nearly all NEOs. This means that the $V_\infty$ for such a maneuver is less than 3700 m/s. Figure 3 shows how a satellite would leave Earth orbit on a trajectory that intersects that of a NEO. When they just miss each other their relative velocities may be well in excess of 10 km/s.

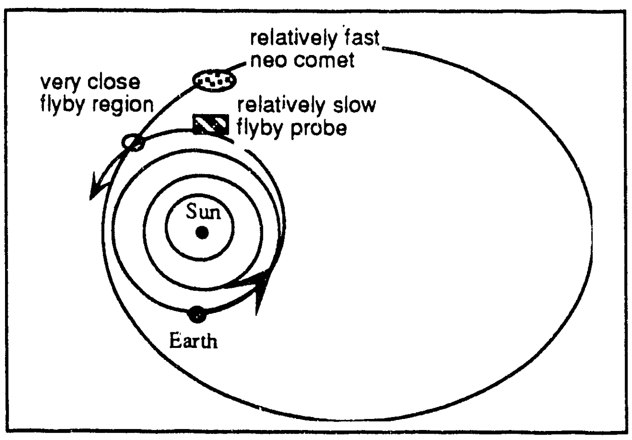



Figure 3: Fly-by satellites can pass close to nearly any NEO without the need for high launch velocities. NEOs are defined as coming close to the orbit of Earth.

A flyby / penetrator would use the same trajectory.The penetrator would not miss the comet, and the flyby sensor would just miss.The 10 km/s velocity mismatch would be put to good use. The pentrator would be a low cost drill rig and create blow-off material from deep within the NEO. However, the high velocity mismatch might be to high and might vaporize the penetrator vehicle, prevent deep penetration and possibly obscure the desired particle data. In this case the vehicle must reduce some of the velocity mismatch.

Shoemaker (1978) developed orbital maneuver $\Delta V$ equations that provide a guideline for the mission $\Delta V$ that might be needed. With Shoemaker's measure, a good fraction of the NEOs might be reached with a $V_\infty$ less than about 7 km/s in a trajectory that would result in less than about 3 km/s velocity mismatch. Friedlander (1990) provides tables of $\Delta V$ values for actual rendezvous that suggest this same result.

A rendezvous vehicle needs to match its velocity exactly with the NEO. Landing requires near zero rocket mass because of the micro-gravity of the NEO. But rendezvous velocities of order 3 km/s may be required, as suggested above for the flyby / penetrator case.

A sample return needs to achieve rendezvous and then completely reverse the process. For the more distant NEOs, this almost certainly requires a nuclear powered propulsion system to keep the system masses in the "small satellite" category. Mission $\Delta V$ in excess of 15 km/s is a minimum requirement. But for the NEOs trivially distant from Earth this may require only enough propellant for an electric propulsion system. Mission $\Delta V$ of less than several km/s may be possible.

Table A-2. Candidate Penetrator Instruments for Outer Planet Satellites

| Penetrator Instruments | Mass (kg) |
|---|---|
| Seismometer | 0.60 |
| Alpha Proton Backscatter/ X-Ray Fluorescence Spectrometer | 0.40 |
| Temperature Sensors | 0.07 |
| Water Detector | 0.15 |
| Accelerometer | 0.03 |
| Surface Imaging | 0.25 |
| Magnetometer | 0.40 |
| Science Subtotal | 1.90 |

Table A-5. Candidate Penetrator Instruments for Asteroids

| Penetrator Instruments | Mass (kg) |
|---|---|
| Gamma Ray Spectrometer | 8.70 |
| Temperature Probe Assembly | 0.50 |
| Accelerometer Sensor Group | 0.20 |
| surface Imaging | 0.25 |
| Magnetometer | 0.40 |
| Science Subtotal | 10.05 |

Figure 4 Instrument packages taken from Yen and Sauer (1991) suggest that small satellites can carry the relatively low mass instrumentation packages needed to conact assay NEOs.

| Object | C3 | Flight time years | Launch year | ΔV km/s |
|---|---|---|---|---|
| Eros | 1.892 | 0.80 | 1995 | 1.37 |
| Oljato | 1.377 | 0.56 | " | 1.17 |
| P/HGonda-Mrkos-Pad. | 3.31 | 0.72 | " | 1.82 |
| P/Churyumov-Ger. | 4.07 | 0.67 | " | 2.02 |
| Dionysius | 0.07 | 0.77 | 1996 | 0.27 |
| 1980 PA | 1.27 | 0.28 | " | 1.13 |
| Quetzalcoatl | 1.54 | 0.86 | " | 1.24 |
| Bacchus | 1.93 | 0.78 | " | 1.39 |
| P/Hartley 2 | 2.15 | 1.02 | " | 1.47 |
| P/Wirtanen | 4.00 | 1.07 | " | 2.00 |
| 1983 RD | 1.14 | 0.86 | 1997 | 1.07 |
| P/Giacobini-Zinner | 1.33 | 0.97 | " | 1.15 |
| Geographos | 2.01 | 0.99 | " | 1.42 |
| 1981 ET3 | 2.33 | 1.02 | " | 1.52 |
| Lick | 4.48 | 0.80 | " | 2.11 |
| Sisyphus | 0.75 | 0.59 | 1998 | 0.87 |
| McAuliffe | 2.28 | 0.48 | " | 1.51 |
| Oljato | 3.31 | 0.52 | 1999 | 1.79 |

Figure 5 A "small" velocity imcrement above escape enables a small launch system to effect a fly-by of many NEOs, including water objects such as the "P/[name]" objects and Oljato. The ΔV is the measure of difficulty, and less than 2 is "small." Table derived from Belton (1992).

## ORBITAL MANEUVERS

The range of available maneuvers is limited and determined entirely by the propulsion systems. Chemical systems require the most launch mass, but generally result in the quickest trips., between a fraction of a year and a few years for the most distant NEO. They provide ballistic launches. Very low acceleration electric propulsion may use very low thrust, very low power solar or nuclear systems available now, or may use medium thrust nuclear systems that could be available within this decade. Either will provide slower, multi-year trips for near NEOs and half-dozen year trips to distant ones. Constraining but mission enhancing gravity assist may be used, but a minimum addition of two years in the trajectory may be expected.

The simplest and cheapest launch vehicles use Pegasus and Taurus to launch 100 kg payloads to Low Earth Orbit (LEO). The booster that can raise an orbit from LEO to earth-escape requires at least 3 and typically 9 times the mass delivered to escape. This might mean a 10 kg payload delivered to the NEO.

If electric propulsion is used, a vehicle could first either spiral out of LEO to escape or be placed into a near escape orbit (GTO, Geosynchronous Transfer Orbit) and then develop the required mission ΔV.

## SMALL SATELLITES

How well can a small flyby probe perform? What kind of sensor/science package can it take? SDIO unclassified information indicates that the technology permits Flyby satellite vehicles to be very small-- on the order of 5 kg for a buss, optical sensor, propulsion and navigation package. Figure 4, taken directly from Yen and Sauer (1991), shows asteroid penetrator instruments weighing 10 kg total, and penetrator instruments for Outer planet satellites at 1.9 kg total. Such small packages are used here as a basis for a sample calculation showing that a 20 kg probe with 120 watts power can perform the flyby and flyby-with-penetrator missions.

The measure of performance of the vehicle is the ΔV it can develop. This calculation will be performed here to show that a small vehicle can perform as required. The data for Figure 5 was taken directly from Belton (1992) to show that the mission velocity needed to affect a rendezvous with several NEOs is small, and less than 2 km/s $V_\infty$. (The "C3" is $V_\infty$ squared.)

The mission ΔV is this plus whatever it takes to leave Earth orbit. From a GTO it takes about of order 30 percent more than the circularization ΔV plus the circular velocity at GEO to escape, which is about 6 km/s. This means the total mission ΔV is of order 8 km/s from a GTO. If the vehicle starts from LEO then the total mission ΔV is about 10 km/s. if the vehicle starts from Earth Escape, the missions ΔV is 2 km/s. The three classes of mission have 2 km/s ΔV, 6 km/s and 10 km/s.

A 20 kg vehicle could consist of 1/3 platform, buss and electronics, 1/3 electric power, and 1/3 scientific payload. How much fuel would such a vehicle need to carry if it were to

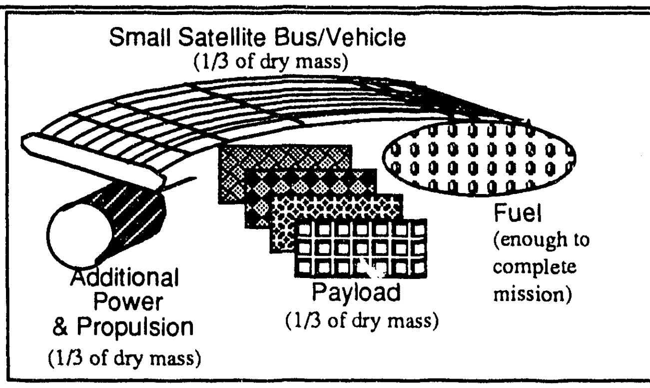



Figure 6 Notional, 20 kg, small satellite for NEO exploration has 1/3 of its dry mass for buss/vehicle , 1/3 for nuclear or solar power, 1/3 for payload, and enough additional fuel and tank to complete the mission.

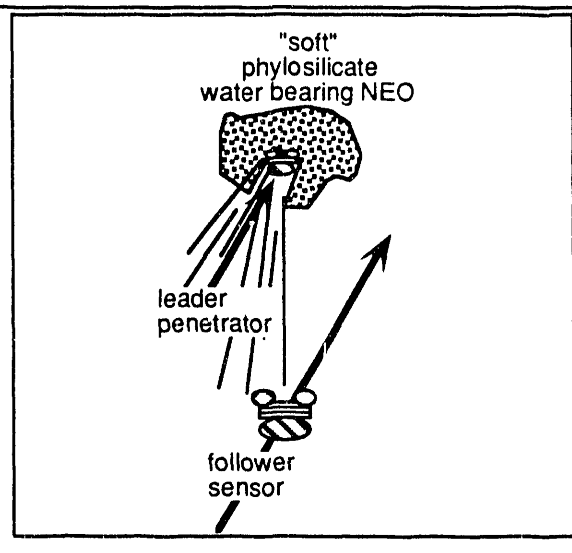



Figure 7 A cheap prospecting drill rig would use one small satellite as a suicide penetrator and the next as a splatter material sensor. The mismatch between NEO and satellite velocities is used to great advantage, allowing low mass launches from Earth and very deep penetration of target object.

| Shoemaker Table 28aug92 | Closest Approach to Sun, A.U. | Farthest Distance From Sun, A.U. | Orbit plane, degrees | Earth capture V∞ | Velocity at comet | Capture | Probe |
|---|---|---|---|---|---|---|---|
| **Recently discovered NEO's** | | | | | | ΔV | ΔV |
| 1991 BN (400 m diam) | 0.9 | 2.0 | 3.4 | 4.8 | 0.8 | **2.5** | **5.2** |
| 1990 MF (100 m diam) | 1.0 | 2.5 | 1.9 | 5.9 | 0.2 | **2.7** | **5.3** |
| 1990 OS (300 m diam) | 0.9 | 2.4 | 1.1 | 5.7 | 0.5 | **2.9** | **5.5** |
| 1990 UQ (1000 m diam) | 0.8 | 2.3 | 3.7 | 5.6 | 1.1 | **3.4** | **6.0** |
| 1990 UA (300 m diam) | 0.8 | 2.7 | 1.0 | 6.1 | 1.2 | **3.9** | **6.5** |
| 1991 BA (10 m diam) | 0.7 | 3.8 | 2.0 | 7.7 | 1.3 | **5.3** | **7.6** |

Figure 8 Shows the accessibility of recently discovered, very small objects. The class from which these come contains thousands of objects. Recent telescopic surveys indicate a significant percent are "trivially close" to Earth orbit in both the ΔV and trip time sense. A fraction of these are expected to be phylosilicates containg water of hydration and have the consistency of dried mud. A "small satellite" using pure electric propulsion would only need to develop tens of percent more than the sum of Earth capture and rendezvous velocity to contact the comet. This is feasible for most of the objects in the table.

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| Shoemaker Table 28aug92 | Closest Approach to Sun, A.U. | Farthest Distance From Sun, A.U. | Orbit plane, degrees | Earth capture V∞ | Velocity at comet | Capture | Probe | 5000 kg gross 590 days Margin | 4500 kg gross 680 days Margin |
|---|---|---|---|---|---|---|---|---|---|
| **suspected neo-comets** | | | | | | ΔV | ΔV | ΔV | ΔV |
| Oljato | 0.6 | 3.7 | 2.5 | 7.6 | 1.7 | **5.7** | **8.1** | **-0.43** | **1.02** |
| Adonis | 0.4 | 3.3 | 1.4 | 7.1 | 3.2 | **6.7** | **9.1** | **-0.43** | **1.02** |
| **neo-comets** | | | | km/s | km/s | **km/s** | **km/s** | | |
| **1979 VA #4015 =Wilson-Harington** | 1.0 | 4.3 | 2.8 | 8.2 | 0.1 | **4.6** | **6.9** | **1.57** | **3** |
| P/du Toit-Hartley | 1.2 | 4.8 | 2.9 | 8.6 | 0.6 | **5.5** | **7.8** | **0.67** | **2.16** |
| P/Finlay | 1.0 | 6.1 | 3.7 | 9.3 | 0.2 | **5.9** | **8.0** | **0.37** | **1.82** |
| P/Neujmin 2 | 1.3 | 4.9 | 5.4 | 8.7 | 0.9 | **5.9** | **8.1** | **0.27** | **1.76** |
| P/Tuttle-Giacobini-Kresak | 1.1 | 5.1 | 9.2 | 9.2 | 0.5 | **6.0** | **8.2** | **0.08** | **1.61** |
| P/Howell | 1.4 | 4.9 | 4.4 | 8.7 | 1.2 | **6.2** | **8.4** | **0.02** | **1.42** |
| P/Haneda-Campos | 1.3 | 5.6 | 4.9 | 9.1 | 0.8 | **6.2** | **8.4** | **0.03** | **1.41** |
| P/Schwassmann-Wachmann 3 | 0.9 | 5.2 | 11.4 | 9.4 | 0.6 | **6.3** | **8.4** | **-0.13** | **1.31** |
| P/Wirtanen | 1.1 | 5.1 | 11.7 | 9.4 | 0.6 | **6.4** | **8.5** | **-0.13** | **1.31** |
| P/Churyumov-Gerasimenko | 1.3 | 5.7 | 7.1 | 9.3 | 0.9 | **6.5** | **8.6** | **-0.33** | **1.1** |
| P/Forbes | 1.4 | 5.3 | 7.2 | 9.1 | 1.3 | **6.6** | **8.8** | **-0.53** | **0.9** |
| P/Tritton | 1.4 | 5.4 | 7.0 | 9.2 | 1.2 | **6.7** | **8.8** | **-0.53** | **0.9** |
| P/Wild 2 | 1.6 | 5.3 | 3.2 | 8.9 | 1.5 | **6.7** | **8.9** | **-0.53** | **0.9** |
| P/Kopff | 1.6 | 5.3 | 4.7 | 9.0 | 1.5 | **6.8** | **9.0** | **-0.63** | **0.81** |
| P/Clark | 1.6 | 4.7 | 9.5 | 8.9 | 1.7 | **6.9** | **9.1** | **-0.73** | **0.71** |
| P/Tempel 1 | 1.5 | 4.7 | 10.6 | 9.0 | 1.5 | **6.9** | **9.1** | **-0.63** | **0.81** |
| P/du Toit-Neujmin-Delporte | 1.7 | 5.2 | 2.9 | 8.8 | 1.8 | **6.9** | **9.1** | **-0.73** | **0.71** |
| **Some Hydrated NEO's** | | | | | | | | | |
| 1988 TA (type C) | 0.8 | 2.5 | 2.7 | 5.8 | 1.2 | **3.6** | **6.2** | **2.87** | **4.3** |
| Ra-Shalom (type C) | 0.5 | 1.2 | 15.8 | 4.4 | 3.0 | **4.5** | **7.2** | **2.47** | **3.9** |
| 1986 JK (type C) | 0.9 | 4.7 | 2.1 | 8.5 | 0.4 | **5.2** | **7.4** | **0.97** | **2.4** |
| 1987 PA (type C) | 1.2 | 4.3 | 16.1 | 9.4 | 1.2 | **6.9** | **9.0** | **-0.73** | **0.71** |
| 1983 SA (type D) | 1.2 | 7.2 | 30.8 | 13.4 | 1.7 | **11.9** | **13.4** | **-5.23** | **-3.78** |

Figure 9 Shows the accessibility of neo-comets and objects strongly suspected to be devolatized comets, along with their orbital parameters. This and Figure 7 are taken from Zuppero, Jacox and Sykes (1992). The Margin ΔV is the margin a 15 ton upper stage probe vehicle with a 2 MW thermal, nulcear power, dual mode propulsion would have for rendezvous and landing on the objects.

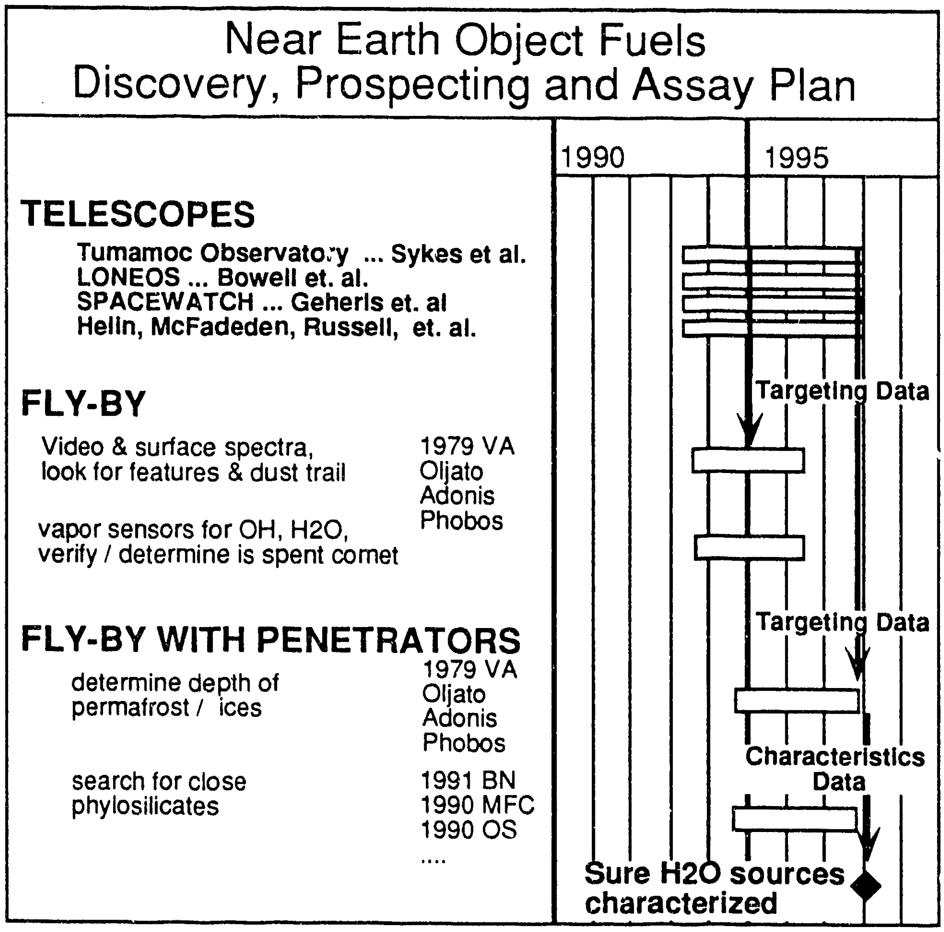


Figure 10 Suggests that telescopes and small satellites can be used to prospect, assay and characterize the object in the space very near Earth. And the results would be obtained relatively quickly and at moderate cost. The results would provide engineering data with which to design and deploy rocket fuel extraction and delivery systems for commercial use in the orbits around Earth.

operate for either 1 or 2 years using ion propulsion with specific impulse of 3000 seconds, electric efficiency of 50% and power input of 120 watts? Which of the 2, 6, and 10 km/s $\Delta V$ missions could our sample vehicle perform? Figure 6 suggests this configuration.

The 2 year operation vehicle would need about 8.32 kg liquid inert gas propellant and could achieve 10,226 m/s $\Delta V$, which is about the $\Delta V$ required if it started from LEO. The 1 year operation vehicle would require half that much fuel, 4.2 kg, and achieve 5555 m/s, which would nearly let it start from a GTO. It could access any object in Figure 5.

This vehicle assumes that an electric power supply can be delivered with weight of order 6.6 (= 20/3) kg. A power supply of this weight would have a performance factor of 55 kg/kW. Solar and Radioisotope Thermoelectric Generators (RTG) have routinely achieved this performance.

## Flyby With Penetrators

A mission that samples to meters in depth into NEOs is almost identical to the flyby mission. Two vehicles would be sent instead of 1, as shown in Figure 7. The first vehicle would impact the NEO directly and a short time before the observer vehicle which follows and flies by. The first vehicle creates a crater. With a velocity mismatch of 10 km/s and a vehicle mass of 20 kg the energy of this collision is equivalent to about 220 pounds of Baritol explosive. The mass of the vehicle is equivalent to a shaped charge. The cratering and penetration capability of such a system exceeds that of tank armor penetrating ordnance.

This vehicle pair would be used to prospect for the high value NEOs. These have orbits reachable in less than a year, have easily released water and are soft like dried mud.

A vehicle designed to thrust for 3 years would use about 13 kg propellant and would develop enough $\Delta V$ for a soft landing on the neo-comet 1979 VA.

Figure 9 sketches the parameters to contact a NEO using a nuclear propelled vehicle. Zuppero, Jacox and Sykes (1992) analyzed the rendezvous capability of a "small satellite," where small meant "use a Titan IV, not a heavy lift launch vehicle." The table includes both the $V_\infty$ and the rendezvous velocity, the sum of which is some percent lower than what a small satellite would need to develop to do the same mission.

## SCHEDULE

These missions would find and assay sources of rocket fuel ore and propellant in the space very near Earth. They start with telescope searches for objects that are close or for objects with tell-tale indicators of H2O content. Then small satellite, flyby and flyby-with-penetrator missions probe the best candidates. These provide the basis for the more expensive contact missions and sample and return missions.

These missions can be accomplished in a relatively short time and using very modest launch systems. Figure 10 shows this. One must note that the more expensive nuclear powered missions need to begin their facility, environmental and safety preliminary work nearly immediately if they are to be available to follow up the work of the small prospecting probes.

## CONCLUSIONS

The discovery of an active comet in the formation of Near Earth Objects (NEOs) provided the basis for an architecture to mine these objects for rocket fuels and propellants, for use in the space and orbits around Earth. Economic analyses showed the very high value of finding any water bearing sources close to Earth in the "time of space travel sense," or of finding easily extracted sources of water close to Earth in the "mission $\Delta V$" sense.

Small satellites, in the 20 kg category, were shown to be able to perform prospecting and assay missions to find these objects. These vehicles would need electric power supplies with a performance factor better than (less than) about 55 kg per kW, which is routinely achieved. Such small satellites would be able to perform the contact mission to the nearest neo-comet.

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