USING COMETS AND ASTEROIDS AS CYCLING SPACECRAFT
AN INTRASYSTEM TRANSPORT FLEET

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The cost of moving materials out of planetary gravity wells and between celestial bodies has long been one of the barriers preventing mass human migration into the solar system. Many researchers have suggested using the Moon, other planets, their satellites, asteroids and comets as resources to expand the human presence off-planet; usually suggesting that they be mined and/or dismantled to provide resources and the basis for economic intercourse with Earth and between colonies.

It is suggested that asteroids and comets are useful in other ways. Periodic Near Earth Objects (NEOs) are already passing near Earth with regularity. If they threaten to hit the Earth, plans are afoot to bombard them with nuclear missiles to alter their trajectory. It is suggested that these objects can instead be controlled. They can be stabilized in a useful orbit near the Earth's ecliptic plane and stability maintained by using the object as part of an Intrasystem Transportation System. The size, mass, velocity *and resulting* ΔV of these objects are precious resources which must be conserved since objects with the required combination of these attributes are excellent candidates for use as natural pre-positioned cycling spacecraft.

The author sketches out a possible transport vehicle development sequence, then concludes with a proposal for proof-of-concept test platforms which can be developed and sent into solar orbit using existing launch vehicles.

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1. INTRODUCTION

This exploration began with:

(a) the basic understanding that NASA and other national agencies have adopted assembly-line manufacturing methods for space probe construction-to increase the availability of probes of specific classes at any one time for operational and policy purposes, to reduce overall costs, and to increase the amount of scientific data collected while making sure that it *will* be collected; and

(b) the understanding that NASA and other national agencies have responded to the loss of the Mars *Observer* probe by adopting the Russian practice of dispatching more than one vehicle (gener-ally two) on a mission, to provide backup in the event of equipment failure and/or transmission interference.

The author initially began considering the problem of resource loss which result from space probe failure (including the vehicle itself, scientific data, time, energy, and monetary expenditure). Author Huer then began to focus on the assumption that there is a need to have more than one vehicle on a mission and an additional need to perhaps have more than one set of spacecraft in a region of space at any one time.

While musing, this author realized that a shuttle fleet is already passing nearby regularly, that is, periodic Near-Earth Objects (NEOs) which include asteroids and comets [here the latter are also named "ExtraSolar Visitors" (ESVs)]. The purpose of this article is to suggest a set of initial designs

for piggybacking probe array transports which use NEOs, including ESVs, as carrier vehicles. Piggy-back arrays can place multiple probe pairs in various select regions of space at the same time.

A series of conceptual vehicle designs is proposed. It is suggested that each could be used to support an array of scientific probes. The fourth could be used as the vehicle of choice for an intra-system fleet of cycling spacecraft which supports an associated network of populated facilities throughout the solar system. **And, in the very distant future, the**

Design D concept might be used to boost a planet (perhaps a terraformed Mars or a planetary satellite) on an interstellar journey.

2. BACKGROUND

Generally, it has not yet been suggested that comets and asteroids of themselves provide a resource other than their physical constituents or presence in a region of space. Writers have consistently focused on the metals, gases and other materials which comets and asteroids can provide to support human expansion throughout the cosmos.

Finney and Jones (1985) have suggested that comets and asteroids "may prove to be stepping stones for a human expansion throughout the solar system:"

> Being much smaller than Earth of Moon, they never melted and still retain their primordial burdens of heavy and light elements. Most asteroids occupy a belt between the orbits of Mars and Jupiter, whereas the vast majority of comets populate a realm far beyond the orbit of Pluto. Both populations constitute an enormous resource of materials for eventual human use. Because comets and asteroids have very weak gravity, the cost of extracting their materials is the cost of reaching them. No big rockets or even mass drivers are needed-only mining equipment...[They are] a potentially vast and economic source of extraterrestrial metals, carbon and hydrogen...in the form of ice.[i]

Others, including O'Neill,[ii] Shoemaker and O'Leary[iii] have also proposed mining the asteroids and comets for materials; O'Neill even envisioning a mining colony prospecting for the resources of asteroids-"once in operation, a space community would be quite capable of moving itself, in a leisurely fashion, to another point in the solar system."[iv] Mallove and Matloff (1979) have investigated "a laser-electric powered interstellar rocket fuelled with hydrogen stolen from comets, one of the most abun-dant resources in the solar system for that propellant."[v] Other researchers are now looking into using asteroids as a source of propellant for nuclear reactors.[vi]

Researchers are also exploring novel uses for NEOs. Mallove (1973) has explored the possibility of "elastic collision propulsion," proposing that the force of an asteroid hitting another object can be used to impel the movement of a vehicle in a game of "space billiards:"[vii] "Imagine that we have comman-deered an asteroid with twice the mass of Icarus (2X5X10 tonnes) [and] collided [it] elastically with a "series of smaller masses, "the last mass would have a velocity [many] times the asteroid velocity relative to the first velocity."[viii]. Penson and Mayer (1986) have also proposed that asteroids could be used as anchors for passing spacecraft. Spacecraft could tether to them for gravity assist flybys in a "slingshot-like" effect.[ix]

Other authors have suggested that asteroids and comets will support the migration of human groups to other regions of space. In their 1985 text, editors Finney and Jones describe the resources that comets can provide to support the migration of a hypothetical interstellar nomad "human population living off cometary resources and diffusing slowly out into interstellar space."[x]

Many researchers have espoused similar ideas. Dyson (1959) has suggested that "some of us may col-onise asteroids, some of us will colonise planets, some of us may colonise comets;" fashioning "artificial space cities" which will gradually fill up the space around the sun, culminating in the now-famous "Dyson sphere" concept-a belt of habitats almost completely surrounding the sun.[xi]

However, each of these ideas seem to point in one direction. It is generally assumed that asteroids and comets provide only tangible resources-materials to be mined, or their physical presence to be used for other purposes. This author has found only a single pair of researchers who have explored another line of inquiry, the idea that these bodies also provide resources which, while intangible, can nevertheless be quantified. Adelman and Adelman (1981) have suggested that comet nuclei could act as platforms for scientific probes: "Nonperiodic comets with aphelia far beyond the orbit of Pluto may become mankind's first deep space probes."[xii] Nevertheless, no previous author has, as yet, apparently suggested that asteroids and comets provide another resource which is eminently useful.

We already have these bodies passing near Earth with regularity. Small asteroids and comets burn up in our atmosphere frequently and occasionally, a larger one falls to the surface with enough impact to cause a major catastrophe. Although debate continues, it is now generally thought that the impact of a large celestial body 65 million years ago led to the extinction of the dinosaurs-for over 100 million years, our planet's dominant species.

The problem with NEOs is that their orbits are not stabilized. Many will eventually be pulled into the Earth's gravity well. Some will be large enough to cause major damage to planetary ecology and the largest bodies could decimate enough species to a point where mass human extinction might have been inevitable. However, it now appears that our civilization has developed to a point where we may be able to prevent these events from happening.

Plans are afoot to prevent a similar catastrophe by objects such as Comet Swift-Tuttle, which may pose a threat to us in the future. Researchers propose to establish a system of six astronomical surveillance telescopes to catalogue "more than 90 percent of possible threats 1 km and larger (or 65 percent of those 0.5 km and larger) during a period of 25 years."[xiii] Authorities then plan to use anti-missile technologies developed for the U.S. Ballistic Missile Defense Organization [BMDO (formerly tagged as "Star Wars")] to bombard these objects with neutron bombs if they threaten to hit the Earth; "with 20 years notice, a velocity change of perhaps 1 centimeter per second is all that would be required."[xiv]
However, impact prevention is only a short-term response, part of disaster-response management and planning by national and planetary authorities. Much faith is placed in our supposed ability to observe all dangerous objects with sufficient time to mount a nuclear response-knocking each object sufficiently off-course that it will not pose a threat. However, there is every possibility that we might nudge an object in the wrong direction, or even instigate calving. If the latter occurred, survivors struggling to recover among the remnants of our home civilization could be bombarded with material over several centuries. Impact prevention planning does not deal with the fundamental problem, which is that these objects will continue to pose a threat to the Earth unless their disintegration is controlled, or they are kept intact and their orbits stabilized. It seems that many researchers and governments see only a threat to the planet. It is suggested that these objects also provide a unique opportunity that we can exploit: while keeping these objects stable, we can use them as part of an Intrasystem Transportation System (ITS).

Dr. John Niehoff of Space Applications International Corporation (SAIC), near Chicago, Illinois, USA, has proposed that a manned mission to Mars use a pre-positioned cycling spacecraft, the Versatile Station for Interplanetary Transport (ViSIT), which will travel between Earth and Mars at regular intervals using Hohmann transfer orbits. ViSIT will use the gravitational forces of the Earth, Mars, the Sun and other bodies) to maintain a continuous flight paths which does not degrade.[xv]

Lessons learned from the ViSIT concept can be applied to the problem of NEO stabilization. It is suggested that the ΔV (a product of the size, mass and velocity of a body travelling through space) of asteroids and comets is an equally precious resource. Both NEO types should be catalogued for their ΔV resource potential. Material extraction or object dismemberment should be contemplated only if the object does not provide useful size, mass and ΔV. If it does, then the object should be reserved. Its qualities are a precious resources which must be conserved since objects with the required combina-tion of these attributes are excellent candidates for use as natural pre-positioned cycling spacecraft.

Our civilization can develop a fleet of spacecraft [probe arrays, habitats and 'traditional' (rocket-powered) vehicles] which are tethered to or which enclose NEOs which already naturally-cycle (orbit) the sun; regularly travelling "between" the desired Ecliptic Space [first the Earth's (EES), then Mars' (MES), etc.] and the outer solar system. It is suggested that passing asteroids could be used as a passive fuel source for a intrasystem cycling spacecraft and habitat. Select candidates can be used to establish several regular shuttle services between the ecliptic planes of the Earth, other celestial bodies, and other regions of the solar system.

The remainder of this submission focuses on proposed designs for a series of transport concepts, then concludes with a proposal for (proof-of-concept) comet flight management testing.

4. DESIGN A.

Design A (Fig. 1.a.) consists of a set of probes arrayed the length of a spaceframe, primary (main antenna) and probe telecommunications arrays and a retransmissions telecommunications array. The latter is needed to maintain line-of-sight (L-O-S) (Fig. 1.b.) to the probe array which is on the far (starward) side of the object.

Each array would be joined to the surface of the NEO by an Anchor Tether Assembly (ATA). Each ATA would be anchored to the NEO using mobile anchors which move in unison as the ESV orbits the sun. Each array could have an aeroshell to ward off debris from any disintegration occurring as a result of solar-induced stresses. This design may be most useful for an asteroid.

5. DESIGN B.

Design B (Fig. 2.0.) consists of an ablative shield which attaches to the sunward side of the NEO using tethers and anchors. The probes could be arrayed along secondary Piggyback Tethers (PIT) streaming behind the shield, protected from the solar wind yet unhampered when needing to launch. Each probe could also have an aeroshell which doubles as an ablative shield to ward off radiation exposure (this can affect the performance of scientific instrumentation). The shield will also support a telecommuni-cations antenna.

As with Design A, the shield and tethers would be joined to the surface of the NEO by a Anchor Tether Assembly (ATA). Each ATA would be anchored to the NEO/ESV using mobile anchors which move in unison as the ESV orbits the sun. Each ATA could have its own photovoltaic array to power on-board instruments and a communications system to receive probe "launch" signals. It is suggested that the PIT cable could be lubricated with fullerenes to ease the passage of each array to launch position. This craft could be attached to both asteroids and comets.

6. DESIGN C1.

Design C1 (Fig. 3.a.) consists of an ablative heat shield which attaches to the sunward side of the NEO using tethers and anchors. Unlike Design A or B, the shield would be attached to a torc-like structure. The torc could be tethered to the surface of the NEO using mobile anchors which move in unison as the NEO orbits the sun. An Anchor Tether Assembly (ATA) could tie the tether into the torc struc-ture. A spaceframe could spread out on either side of the shield, one supporting a telecommunications array, the other supporting a nuclear reactor for backup power supplies. Each frame could have its own photovoltaic array to power on-board instruments, an on-board communications system, and instrumentation for a probe array hidden behind the shield. This craft could be attached to a comet or asteroid; the shield stabilizing it, the torc allowing the craft to attach to the NEO host while remaining mobile.

7. DESIGN C2.

The Design C1 concept can be modified for mining operations; Design C2 could be used move a comet (Fig. 3.b.) to EES, MES or another destination.

For the Design C2 concept, imagine a circular funnel with a large bell mouth and a colander inside its smaller end; the funnel with an ice-ball inside it, the three objects facing an oncoming wind of hot gases. The funnel is a gatherer of the gas and dust of the disintegrating comet, collecting and funnel-ling it back to the colander, an internal structure with intakes which can be used to direct a controlled flow of particles in the desired exhaust pattern. In effect, operators would be able to direct the gas/dust flow to alter the comet's trajectory. Operators would furthermore be able to gather the disintegrating material beyond the outgassing vents and convert it to fuel, using it to provide addi-tional power. Operators might also be able to screen the on-coming solar particles in some way, to direct the process of disintegration and hasten passage to the desired destination.

8. DESIGN D.

In form and purpose, a Design D spacecraft (designated a **Shieldship**) is reminiscent of a Dyson sphere (Fig. 4.a., 4.b., 4.c.). It consists of an Ablative Shield and inner heat shielding protecting a spacecraft assembly [toroidal habitat, cargo holds, tether docking ports, external spacecraft park and maintenance hangers, piggyback probe arrays and telecommunications arrays, fuel stores, engine bays and rockets, and radiation gatherer/converters (perforated light sails or photovoltaic cells), attached to a NEO (for the illustration and discussion, a comet is used)].

In this design, the spacecraft is moved from an assembly area in Geosynchronous Earth Orbit onto a converging path with the target comet, probably using Hohmann transfer orbits. The spacecraft velocity would be such that the spacecraft would be moving slightly faster than the comet. At convergence, the spacecraft would assume a position slightly ahead of the NEO. The pilots would reduce velocity to slightly less than that of the comet. Travelling in formation, the spherical insulator shell would then be opened and the comet, now stabilized by Shieldship's protective ablative shield, would move inside the spacecraft. If an ice comet were targeted, this might be the same as putting a ball of snow in a freezer, shutting off solar wind, heat and radiation pressure (the suspected causes of cometary disintegration). The craft would then increase its velocity slightly so that an even distance
would separate the surface of the NEO from the inner hull of the spacecraft's insulating sphere.

The spacecraft might then latch on to the NEO, using structural assemblies inside the sphere or by filling the intervening spaces with a web of frozen attachments (comet materials could be refashioned
into stalagmite/stalactite-like struts, for example). Alternatively, at this time the spacecraft might induce a gravity field for its habitat by spinning the habitat around the NEO in a counter-clockwise motion (I do not know how this would affect the effect of solar tidal forces on the comet body), while both move in the NEO's predestined flight trajectory. As with Niehoff's ViSIT concept, the ITS concept is "unaffected...by the question of whether the travelling [spacecraft] will be given spin."[xvi] However, induced gravity will be required for human passengers. The habitat could rotate separately, of course.

Protected by its massive Ablative Shield, the ShieldShip (a small craft compared to other theoretical spacecraft; roughly 6-10 km diameter for a comet of 1 km diameter) would travel the now-stabilized path of its comet host, or alter its trajectory to take it away from an orbit threatening Earth; travel-ling before it or behind it, always shielding it; always using its mass and the added or subtracted fuel mass of additional tethered spacecraft to maintain a regular orbital passage through the solar system; establishing a known orbit and regular contact between Earth and the far-flung human outposts later founded along its flight path. The motion of the craft in relation to the comet would in some way resemble a ball-and-socket joint, the difference, of course, being that the craft has the ability to move completely around its companion. Moving in space, they would perhaps be very much like a miniature solar system.[xvii]

The comet's constituents could be used as a resource, it is true-but they should only be used in a dire emergency as this would affect object mass and hence, ΔV; the crew could use cometary ice as an emergency fusion energy fuel source and for atmospheric gases. However, the loss of mass would be mitigated if the comet orbit was not periodic; that is, took passage *through the outer solar system, including either the Kuiper Belt or the Oort Cloud*, especially if there were indications that the crew could capture another comet to use for the journey back to Earth. If the orbit were periodic, that is, within the orbit of Pluto, additional fuel mass could be gathered from spacecraft which tether to the Shieldship during its return to the inner system.

9. A WIDE-RANGING SCIENCE FLEET

Like the preceding designs, a Shieldship has as its most basic function the gathering of scientific data. A Shieldship is, first and foremost, a scientific research expedition vessel. However, if the initial test vessel operates successfully, a series of shieldships could be made operational.

Four conditions may need to be satisfied to make a fleet operational. If:
(a) there are two or more asteroids or comets passing near highly-populated and/or economically- valuable regions of space, with sufficiently-small size that each could fit inside a hull (or hulls of the required size were developed); and
(b) their orbits are sufficiently different; and
(c) their passage though regions of space where population growth is planned is sufficiently far apart; and
(d) their passage in relation to each other is sufficiently near;

a basic interplanetary shuttle service could then be put into service. The fleet would operate contin-uously, with regular departures from and returns to EES or MES, much as Niehoff's cycling spacecraft cargo delivery system is planned for use between Earth and Mars. For example, if we used Comet Encke (CE), the vessel would return in 3.3 years; if we also used Halley's Comet (HC), a vessel would return in 72-82 years; a Comet Oterma (CO) Shieldship would return in 7.9 years.

Humans suffer severe psychological effects when isolated in cramped quarters for even short periods during spaceflight (Soviet experience suggests that 30 days marks the beginning of affectation caused by fatigue). This effect would be magnified aboard a vessel whose crew would not have physical contact with Earth, families and loved ones for many years, although it is hoped that humans will have adapted to multi-year isolation by the time a fleet of shieldships is developed.

A fleet of Design D vessels could reduce the psychological threat of isolation from Earth in two ways: One, the combination of spacecraft and toroidal habitat increases the amount of living area available to crew and passengers. This helps to reduce tension, a normal byproduct of close personal contact over long periods. Two, when a shieldship passes within "hailing distance" of another -or near the ViSIT craft-at one or more points in their mutual passage through the solar system, crew, data and cargo could be transferred between vessels-creating a time frame that may appreciably affect the psychological well-being of crew and/or passengers; the *effect* of long-term isolation would not be there since each person would *know* that they "can go home" on the next rendezvous. In other words, a Design D fleet may provide the unexpected, serendipitously-realized benefit of a psychological "escape valve" which presently hampers long range spaceflight operations planning.

10. AN INTERPLANETARY TRANSPORTATION VESSEL

In addition to its function as (1) a scientific research vessel and (2) a psychological "escape valve", a Shieldship also provides additional benefits which may more than offset the initial cost in energy, time and other resources. It can also function as:

(3) an intrasystem shuttle which other vessels and supplies could tether with ("piggyback") as it passes by (supplying fuel mass could be part of the price of passage for tethering spacecraft);

(4) an intrasystem survey vessel which can calibrate star maps and emplace the equivalent of geodetic survey markers (beacons or buoys);

(5) a supply vessel for bases, facilities and scientific research establishments throughout the solar system [especially the outer system, including stations beyond the orbit of Pluto (it could, for example, place the second of a pair of telescopes near Pluto-establishing a observatory with a baseline of greater than 38.52 A.U.[xviii])];

(6) a communications relay vessel for probe and other vessel signal retransmissions;

(7) an Kuiper Belt or Oort Cloud harvester - it could be used to establish economically-feasible and technically-supportable Comet-Gatherer operations beyond the orbit of Pluto. Mining and smelting equipment could be transported to the Belt/Cloud, operations established and materials boosted to a converging orbit with a ShieldShip; materials tethered for transport to Earth, where the cost to ship water and its constituents out of our gravity well is both prohibitive and environmentally-unwise.

11. PROOF-OF-CONCEPT

As noted, Adelman and Adelman (1981) have suggested that comet nuclei could act as platforms for scientific probes.[xix] It is proposed that when more is known about the structure and densities of comets and asteroids, that a piggyback array spacecraft be launched for attachment to either body type. Researchers can build on the data acquired from asteroid and comet flybys [Halley's Comet (*Giotto*, *Vega 1* and *2*, *Sakigake*, *Suisei*)[xx] and Comet Giacobini-Zinner (*International Cometary Explorer*)].[xxi]

In the meantime, we can prepare for the development of a Design D Intrasystem Transport System by conducting initial experiments in comet flight management. An initial test regime can be developed to test proof-of-concept.

A. Comet and Asteroid Surveys: Additional surveys of NEOs can be carried out to determine structure, densities, and constituents. Missions could follow the U.S.-sponsored *Comet Rendezvous/Asteroid Flyby (CRAF)* (if reactivated), the *Comet Nucleus Sample Return (CNSR)*, the *Near Earth Asteroid Mission (NEAR)* and the *Light Exoatmospheric Projectiles (LEAP)* missions.[xxii]

B. Materials Development: Initial experimentation depends on the development of materials which can withstand the broad range of temperatures, tidal gravitational stresses, and gas/dust debris associated with near-solar operations. Also, the complexities of trajectory calculation will require major advances in the miniaturization, computational speed and artificial intelligence capabilities of onboard computers.

C. Proof-of-Concept Flight Tests:

(a) Comet Platform - A small probe can be launched, consisting of ablative and heat transference shields, a standard instrumentation package (IP) and another IP at the centre of an hollow insulating sphere (Fig.4.a.). The inner package must be able to withstand moisture since the space between the sphere's inner hull wall and the package will be filled with frozen gases or water to replicate the structure of a water-ice comet.[xxiii]

The probe could be launched aboard a standard vehicle, then sent into orbit around the sun where the effectiveness of shielding can be evaluated (once in orbit, the insulating sphere can be discarded; it could perhaps have its own instrumentation and be used as a simple sub-probe or radio beacon until it falls into the sun).

(b) Asteroid Platform - An identical probe can be launched, consisting of ablative and heat transference shields, a standard IP and another IP at the centre of an hollow insulating sphere. In this configuration, the space between the sphere's inner hull wall and the package will be filled with solid material to replicate the structure of an asteroid. As with (a), the insulating sphere would be jettisoned.

(c) Shieldship - A similar probe can be launched (Fig.5.b.). However, it might be configured so that the "ice-ball" and inner IP be separated from the main ablative shield, heat transference shield and external IP by a truss arrangement. The probe could be launched aboard a standard launch vehicle, then sent into orbit around the sun where the effectiveness of shielding can be evaluated. In this configuration, the insulating sphere would not be jettisoned.

12. CONCLUSIONS

Researchers have suggested mining asteroids and comets for materials to expand the human presence off-planet. It is suggested that these celestial bodies are useful in other ways: their size, mass, velocity *and resulting* ΔV are unique and precious resources which must be conserved since objects with the required combination of these attributes are excellent candidates for use as natural pre-positioned cycling spacecraft. Asteroids and comets which orbit around the Sun must be catalogued and their physical constituents not be used if it is decided that they can be used for an Intrasystem Transportation System. When they approach NES, they can be captured, stabilized and put into ser-vice as cycling spacecraft. The ITS may provide a cost-effective way to expand the human presence
beyond the inner planets and could become the foundation of a system of transportation infrastructure which embraces the entire solar system.

Space agencies can investigate the possibilities of NEO-based transport by launching space probes into solar orbit to test the concept. Probe platforms can be launched using existing technologies to investigate the concepts further.

13. REFERENCES

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ii. O'Neill, Gerard K., The High Frontier: Human Colonies in Space, (New York, William Morrow), 1977, p.191-198.
iii. Calder, Nigel, SpaceShips of the Mind, (New York, Viking), 1978, p.70-77.

iv. O'Neill, High Frontier, p.196.

v. Mallove, Eugene F. and Gregory L. Matloff, The Starflight Handbook, (New York, Wiley), 1989, p.86.

vi. "Icy asteroids could power reactors in space," New Scientist, 137:1867, 19 , p.6.

vii. cf. Mallove and Matloff, Starflight, p.146.

viii. Ibid., p.146-147.

ix. Penson, P.A. and Mayer, H.L., "Tethers and Asteroids for Artificial Gravity Assist in the Solar System," J. Spacecr. Rockets, Jan.-Feb. '86, p.79-82.

x. Finney and Jones, interstellar migration, p.96.

xi. Dyson, Freeman J., cf. Nigel Calder, Spaceships of the Mind, (New York, Viking), 1978, p.22.

xii. Adelman, Saul J. and Benjamin Adelman, Bound for the Stars: Space Travel in Our Solar System and Beyond, (Englewood Cliffs, Prentice-Hall), 1981, p.165.

xiii. Marsden, Brian G., personal communication in response to a request for review of a proposal to establish an international project for preserving representative human records [International Earth Records Survival Project (INERSURV)] in the event of a threantened comet strike. reply dated 27 May, 1993.

xiv. Ibid.

xv. Miles, F. and N. Booth (eds.), Race to Mars: the Mars Flight Atlas, (New York, Harper & Row), 1988, p.46.

xvi. Ibid., p.46.

xvii. I regret to say that although I can imagine the intrinsic beauty of the motion of such a craft in relation to its host comet and their motion in relation to the gravitational forces around them, I am unable to describe the motion mathematically and will leave this task for others with much greater aptitude than I.

xviii. Adelman and Adelman, Bound for the Stars, Table 3.1, p.28.

xix. Adelman, Saul J. and Benjamin Adelman, Bound for the Stars: Space Travel in Our Solar System and Beyond, (Englewood Cliffs, Prentice-Hall), 1981, p.165.

xx. Burroughs, William, Exploring Space: Voyages in the Solar System and Beyond, (New York, Random), 1990, Table 10, p.137.

xxi. U.S. Government. NASA. Solar System Exploration Committee of the NASA Advisory Council, Planetary Exploration Through the Year 2000: An Augmented Program, (Washington, DC, NASA), 1986, p.113.
xxii. Ibid., p.102-125, 170-71.

xxiii. In this regard, perhaps designers can take an idea from Project Habbakuk, a World War II Anglo-Canadian project to develop aircraft carriers for service on the North Atlantic supply route. The vessels were actually a sort of giant ice-cube, formed from a mixture of frozen water and sawdust; seen as a cheap alternative since they were to have operated on the already-cold North Atlantic-with any melting to have been halted using refrigerator equipment. An experimental vessel was tested on Lake Louise in Alberta but the war ended before production actually began. Project Habbakuk material may suggest applicable mixtures for the proposed spacecraft test vehicle. Interestingly, J. Desmond Bernal (for whom Gerard K. O'Neill's Bernal Sphere space colonies were named) worked on this project as a member of Combined Operations [cf. Calder, Spaceships, p.20.]