NASA/TM—2005–214184

In-Space Propulsion: Connectivity to In-Space Fabrication and Repair

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September 2005

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EXECUTIVE SUMMARY

During July 2003, the In-Space Fabrication and Repair Workshop was conducted at the Marshall Institute in Huntsville, Alabama. This Technical Memorandum, which discusses the connectivity between in-space propulsion and in-space fabrication and repair, is based on a presentation at that workshop by Les Johnson, manager of the NASA Marshall Space Flight Center In-Space Propulsion (ISP) research team.

In-space propulsion options currently under study by the ISP research team include aerocapture, advanced solar-electric propulsion, solar-thermal propulsion, advanced chemical propulsion, tethers, and solar-photon sails. All of these propulsion systems are approaching the technological readiness levels at which they can be considered for application in space-science missions.

Historically, human frontiers have expanded as people have learned to “live off the land” in new environments and exploit local resources. Frontier settlements have also required the development of transportation improvements, such as the Conestoga Wagon and Transcontinental Railroad, to transport tools and manufactured products to and from the frontier. In-space propulsion technological products will assist in the development of the solar system frontier.

In-space fabrication and repair will reciprocally require and assist the development of in-space propulsion systems, whether humans choose to settle planetary surfaces or exploit the resources of small solar system bodies. Following the precedent set by successful terrestrial pioneers, such in-space settlement and exploitation will require increasingly sophisticated surveys of inner- and outer-solar system objects. In-space propulsion technologies will contribute to the success of these surveys and to the efforts to retrieve solar system resources. In a similar fashion, the utility of in-space propulsion technology products will be greatly enhanced by the technologies of in-space repair and fabrication.

As the technologies of in-space propulsion, fabrication, and repair develop, human civilization may expand well beyond the Earth. It is not impossible that, further in the future, small human communities (preceded by robotic explorers) may utilize these techniques to set sail for the nearest stars.

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LIST OF ACRONYMS

CAD	computer-aided design
ESLI	Energy Sciences Laboratory, Inc.
GEO	geosynchronous Earth orbit
ISP	In-Space Propulsion
ISS	*International Space Station*
JPL	Jet Propulsion Laboratory
KBO	Kuiper Belt object
LEO	low Earth orbit
MSFC	Marshall Space Flight Center
MXER	momentum exchange/electrodynamic reboost
NEAP	Near-Earth Prospector
NEAR	Near-Earth Asteroid Rendezvous
NEO	near Earth object
RP	rapid prototyping
SEP	solar-electric propulsion
SMF	space manufacturing facility
STP	solar-thermal propulsion
TAU	Thousand Astronomical Units
TRL	Technology Readiness Level

TECHNICAL MEMORANDUM

IN-SPACE PROPULSION: CONNECTIVITY TO IN-SPACE FABRICATION AND REPAIR

1. INTRODUCTION: A NASA MARSHALL SPACE FLIGHT CENTER WORKSHOP

During July 8–10, 2003, the NASA Marshall Space Flight Center (MSFC) hosted the In-Space Fabrication and Repair Workshop at the Marshall Institute in Huntsville, AL. Coordinated by the NASA Headquarters' Physical Sciences Research Division, attendees at the 3-day event included representatives of U.S. aerospace contractors and academics as well as NASA scientists, engineers, and technologists.

Participants in the workshop included experts in advanced in-space propulsion research, space-manufacturing techniques, and researchers conducting or planning experiments aboard the *International Space Station* (*ISS*). Discussion centered on a proposed space-based infrastructure that could enable the commercial development of the solar system as well as a variety of scientific space missions. Of particular interest to the participants in the In-Space Fabrication and Repair Workshop was the demonstration of pathways whereby current research could naturally lead to development of the necessary in-space infrastructure.

A workshop participant, NASA MSFC In-Space Transportation manager Les Johnson, presented—on July 8, 2004—concepts showing the connectivity of ongoing research in the field of in-space propulsion to the ultimate development of an in-space fabrication and repair infrastructure. A number of MSFC In-Space Transportation researchers, including David Harris, Ann Trausch, Gregory Matloff, Travis Taylor, and Kathleen Cutting, contributed to the preparation of the presentation.

2. IN-SPACE PROPULSION OPTIONS

A number of advanced space transportation options are currently under investigation by NASA. These options include air-breathing rockets and magnetic levitation to reduce the mass of Earth-to-orbit launch vehicles, pulse detonation engines, high-energy propellants, and a host of advanced propulsion concepts and materials. In-space propulsion options under consideration include aerocapture, advanced solar-electric propulsion (SEP), solar-thermal propulsion (STP), advanced chemical propulsion, tethers, solar photon sails, solar plasma sails, external pulsed-plasma rockets, fusion rockets, antimatter rockets, and beamed energy concepts.

The MSFC In-Space Propulsion (ISP) Technology Office is sponsored by the NASA Science Mission Directorate. The function of this program is to support basic and long-term research that will lead to the development of advanced space transportation technologies. Research at ISP is currently concentrated on aerocapture, advanced SEP, advanced chemical propulsion, tethers, and solar-photon sails.

2.1 The Technology Readiness Level Concept

One way of characterizing the relative maturity of selected technologies is the Technology Readiness Level (TRL) system. As described in a white paper by John Mankins of the NASA Advanced Concepts Office, the TRL system provides a summary view of the maturation process for new space technologies under study by NASA. The individual TRL levels are summarized as follows:[1]

- TRL 1: Basic principles have been observed and reported.

- TRL 2: Technology concepts and/or applications have been formulated.

- TRL 3: Analytical/experimental proof-of-concept research has been performed.

- TRL 4: Component and/or breadboard laboratory validation has been performed.

- TRL 5: Component and/or breadboard validation tests in relevant environment have been performed.

- TRL 6: System/subsystem prototype/model demonstration in relevant environment has been performed.

- TRL 7: System prototype function has been demonstrated in a space environment.

- TRL 8: Completed system flight qualified through ground/space demonstration;.

- TRL 9: Completed system flight proven through successful space mission operations.

Current in-space propulsion technologies under consideration by NASA propulsion researchers include SEP, planetary-atmosphere aerocapture, advanced SEP, STP, advanced chemical propulsion, tethers, solar-photon sails, solar plasma sails, external pulsed plasma rockets, fusion rockets, antimatter rockets, and beamed energy systems. Figure 1 shows the estimated TRLs for these propulsion systems in 2003.

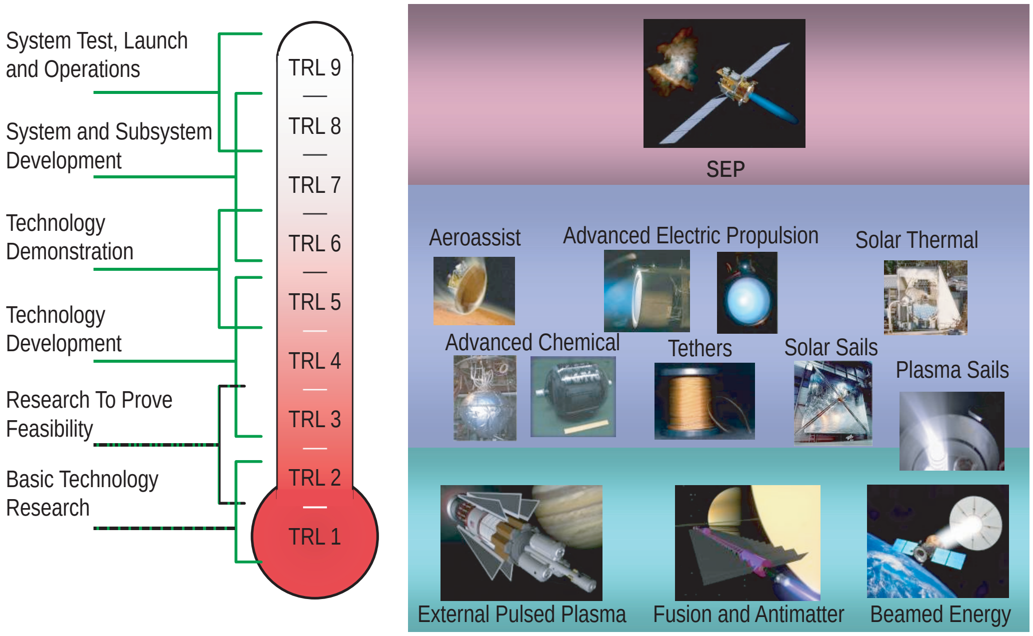


Figure 1. Estimated TRLs for various in-space propulsion options as of July 2003.

2.2 Propulsion-Technology Prioritization and Description

The NASA In-Space Propulsion Technology Project utilized the TRL system and planning for advanced space-exploration missions to prioritize in-space propulsion technologies currently under development, as follows:[2]

- High-priority technologies include aerocapture, the next-generation ion thruster, and solar photon sails:
  - Current aerocapture research emphasizes integrating a low-mass aeroshell with the thermal-protection system and the development of aerocapture instrumentation. Various advanced aerodynamic decelerators, such as trailing ballutes, attached ballutes, and inflatable aeroshells, are under consideration for aerocapture missions.
  - As currently envisioned, the next generation of ion thrusters will include a number of technological innovations. Two of these are the NASA evolutionary xenon thruster and application of carbon-based ion optics.
  - Solar photon sail research and development are currently concentrated on subsystem design, fabrication, and ground demonstration. Structural testing of sail booms is underway, and the long-term effects of long-term exposure of ultrathin sail material to the space environment are being evaluated.

- Medium-priority technologies include advanced chemical rockets, kilowatt-level SEP, and STP:

  - A number of aspects relating to advanced chemical rockets are under investigation. These include fuel development, consideration of cryogenic fluid management, and development of low-mass components.
  - High-power (kilowatt) SEP investigations at MSFC include laboratory demonstrations of 50-kW Hall thrusters. An effort is underway to competitively select thruster technology based on application.
  - The required technology investments related to the development of STP are under study. Directed tasks are focused towards answering fundamental performance questions.

- High-risk/high-payoff and lower priority technologies include solar-plasma sails, momentum-exchange tethers, and ultrathin solar sails (areal mass thickness < 1 g/m^2):

  - Among the high-risk/high-payoff and lower priority technologies, basic research is underway to determine the ultimate feasibility of solar plasma sailing. An improved understanding of the relevant plasma physics is required to determine the lifetime of magnetically induced plasma bubbles in the interplanetary environment.
  - Work on momentum-exchange tethers is proceeding with emphasis on model development and evaluation. This includes consideration of the catch mechanism required to exchange momentum between a rotating tether and a payload and research on high-tensile-strength tethers.
  - Research on ultralight solar sails is concentrated upon investigation of ultralow-mass sail materials. Large-area low-mass structures and mechanisms and the trades involved in Earth-launch versus space fabrication are under study.

3. HISTORICAL PERSPECTIVE

In discussing the future expansion of humanity into and beyond the solar system, it is useful to consider the historical analogies of successful terrestrial exploration and settlement efforts. It is obvious from such an effort that exploration and settlement expansion are not unique to the current phase of human existence.

Starting from an equatorial "Garden of Eden" in or near present-day Kenya, humans (or pre-human hominids) began their spread through northern Africa, Asia, and Europe more than one million years ago. Without the "invention" of fire, which allowed the ancestors of modern humanity to apply in situ resources to functions such as cooking and habitat heating, expansion into temperate and polar climates would have been impossible.

As described by Lee and Finney and reviewed by Matloff, early civilized humans continued in the same tradition of living off the land as their territories expanded.[3–5] Minoan, Mycenaean, Phoenician, and Dorian and Ionian Greek colonies were established when population pressures encouraged emigration from parent cities to the frontier. In order to survive in their new environments, the successful ancient colonists quickly learned to exploit the resources of the lands in which their new homes were situated.

When a colonization vessel crossed an ocean as opposed to an inland sea, the injunction to live off the land became even more stringent. If the Polynesians had been required to carry all their food with them instead of fishing off the sides of their ocean-going canoes, or if early European settlers in the New World had not adapted to native foods, such as the wild turkey, the range of human settlement almost certainly would not be global today.

In the early 19th century, most of the population of the infant United States was huddled close to the Atlantic Ocean. Thomas Jefferson, perhaps the most visionary of the early American presidents, initiated the era of western expansion by commissioning the Lewis and Clark Expedition in 1804. His hope was that the Corps of Discovery would locate a river route to the Pacific. According to Ronda, this expedition began in May 1804 and culminated in September 1806.[6–8] Starting from a camp near St. Louis, the Lewis and Clark Corps of Discovery reached the Pacific Ocean after traversing ≈13,000 km of previously unmapped terrain.

Geographical knowledge regarding the interior of the North American continent was primitive prior to the Lewis and Clark expedition. Without this preliminary exploration, west-bound settlers later in the 19th century would have had no idea of the local resource base required for their survival, nor the capability to establish thriving continental population centers.

The Corps of Discovery numbered 48 men. Supplies were transferred up the Missouri River on a riverboat and several smaller vessels. Overland portage was also necessary, and required minimization of supply weight. To ensure success of the venture, it was necessary for the participants to satisfy much of their food requirement by hunting.

Corps members were aided by Sacagawea, a Shoshone, and her husband, Toussaint Charbonneau, a French-Canadian interpreter. With their assistance, members of the Lewis and Clark Expedition learned how to supplement their diets with local vegetation, such as camas roots.

The success of the Lewis and Clark Expedition led to the opening of the North American continental interior to settlement and economic use. Continental settlement would have been a great deal less successful if an efficient mode of carrying settlers and their baggage westward and frontier produce eastward did not exist.

Conestoga Wagons and the related Prairie Schooners (so called because of their boat-shaped bodies and tall, white canvas bonnets) satisfied the requirements of westward and eastward continental transport during the first half of the 19th century.[9,10]

Able to carry payloads up to 8 t (7,300 kg) with motive force provided by teams of many horses, oxen, or mules, these vehicles were the principle trading vessels of the American prairie for decades. Typically 3 m or more in length, these wagons carried tool kits so that repairs could be made en route, hundreds of kilometers from the nearest wainwright or farrier's shop.

Although Prairie Schooners opened up the frontier, they could not be depended on to keep a rigid timetable; they were also uncomfortable for human passengers and very hard on their animal engines. So as the population of the frontier and the volume of transcontinental traffic increased, a faster and more reliable form of inland transport became necessary. The introduction of the Transcontinental Railroad provided a vast improvement over the Prairie Schooner.

While railways were employed in North America as early as 1764 for military purposes, the first American self-propelled rail vehicle was constructed in Massachusetts in 1826. This horse-drawn tram hauled granite from quarry to wharf, a distance of $\approx$6 km.[11] During the same year, the feasibility of steam-powered locomotion was demonstrated by John Stevens. This experiment was performed on a circular track near Hoboken, New Jersey.[12]

Early American commercial railroads were surveyed and constructed using private funds, usually connecting Eastern population centers. Conceived and promoted by Asa Whitney before 1845, the Transcontinental Railroad was a much greater undertaking.[13] This monumental project, undertaken by entrepreneurs with economic and other support from the Federal Government; e.g., the route was surveyed by the U.S. Army Topographic Corps, was finally completed in 1869. For the first time, the entire North American continent was linked. With this linkage, the western frontier was finally opened to large-scale settlement and exploitation.

Those seeking to open and develop the space frontier could learn from this earlier experience. In a successful exploration/exploitation/settlement enterprise, there is ample room for both private and public initiatives. Pioneers must learn how to successfully live off the land and exploit local materials and resources as much as possible.

3.1 Application of Local Materials

No terrestrial pioneering venture has succeeded that did not make ample use of local materials. Local materials have been applied as farm soils, building-construction materials, and feedstock for manufactured goods. A major justification for resource surveys prior to settlement is the necessity to know what the local resource base is and develop the best plan to tap it.

3.2 Living off the Land

Historically, successful settlers in a new frontier have very rapidly learned how to survive in their new environment with minimum resupply from their home cities or nations. They have accomplished this by quickly developing hunting strategies adapted to the local game herds, learning how to farm local soils, and utilizing local energy sources. Without developing such capabilities, human's would not have expanded very far from their original homes in Equatorial Africa.

4. IN-SPACE PROPULSION AND LIVING OFF THE LAND

Application of new in-space propulsion technologies will allow interplanetary explorers and pioneers to exploit local resources to effectively live off the land in a manner analogous to the experience of successful terrestrial pioneers. Perhaps the first application of these techniques to interplanetary pioneering will be in situ propellant manufacture.

In-space propulsion technologies can also live off the land in a number of ways. Sunlight can be used to propel sails and solar-electric rockets and provide solar power to space settlements and Earth's magnetosphere and can be utilized in the operation of electrodynamic tethers. Local-material application, other than propellant manufacture, will result in application of planetary regolith for radiation shielding. Local water ice can be utilized to provide a source of drinking water and oxygen, and local minerals can be mined for fabrication and energy production.[14]

4.1 In Situ Propellant Manufacture

The expansion rate of human civilization into the solar system would be greatly increased if chemical rocket fuel could be manufactured from in situ resources in or near the surfaces of various solar system destinations. Various options exist to accomplish this task.

4.1.1 Mining the Moon

Ideally, if the Moon has ample deposits of cometary water ice in Sun-shaded craters near the lunar poles, lunar explorers could refuel their spacecraft by utilizing sunlight to dissociate lunar water into hydrogen and oxygen. However, evidence for large-scale water-ice deposits in lunar polar craters is ambiguous.

The Clementine mission payload included a bistatic radar experiment that measured magnitude and polarization of radar echoes from various lunar regions. One interpretation of the results is that water-ice deposits exist in permanently shaded regions near the lunar south pole.[15] Neutron spectrometer measurements from the later Lunar Prospector spacecraft apparently confirmed the existence of lunar-polar water-ice deposits. However, radar-reflection studies performed at the Arecibo radio telescope in Puerto Rico found no evidence for water ice.[16] And, at the end of its useful life, Lunar Prospector was directed to crash into a crater near the Moon's south pole. Astronomers using space- and ground-based observing facilities did not note the characteristic signature of water while they observed the impact site during Lunar prospector's controlled crash.[17] The jury on the existence of lunar water ice has not yet reached a verdict.

Even if water is not a large-scale lunar resource, some lunar rocks are more than 40 percent oxygen.[16] So, it is not impossible that future lunar expeditions could carry a supply of hydrogen from Earth and mine oxygen from lunar regolith or bedrock. A lunar-oxygen-mining capability could greatly reduce the mass delivered to the lunar surface during a future expedition since hydrogen is a much smaller mass fraction of water than oxygen.

4.1.2 Mining Mars

The dominant molecular species in Mars' thin atmosphere is carbon dioxide.[16] Hydrogen oxides, including water, also exist in the atmosphere and on the surface of Mars.

Zubrin et al. have proposed that terrestrial explorers or settlers on Mars could produce rocket propellant by combining hydrogen transported from Earth with carbon dioxide from the martian atmosphere to produce methane and water.[18] Electrolysis would be used to dissociate the water into hydrogen and oxygen. Methane and oxygen could then be exhausted as rocket fuel. The process will be greatly simplified if ongoing martian-surface studies conclusively demonstrate that water is abundant in the planet's subsurface layers.

4.1.3 Asteroid and Comet Mining

The techniques considered for application on the Moon and Mars could also be utilized to refuel spacecraft visiting small solar system bodies. Spectroscopic studies have revealed that water ice is a significant component of comet comas near the Sun—ice layers must also be present on comets closer to aphelion.[16]

Although asteroidal samples have not yet been returned to Earth by spacecraft, meteorites have delivered asteroid fragments to Earth. One class of meteorite, carbonaceous chrondites, is typically about 40 percent oxygen and 2 percent hydrogen by weight. Interestingly, Mars' small satellites, Deimos and Phobos, are suspected to be similar to carbonaceous chrondites. Although hydrogen may be rare in the parent bodies of other asteroidal types, model studies reveal that oxygen is a major constituent.[16]

4.2 Solar-Electric Propulsion and Space Habitation and Fabrication

Gerard K. O'Neill has proposed that large orbiting space habitats and fabrication facilities may be constructed from lunar and/or asteroidal material.[19,20] Further amplified in a NASA design study edited by Johnson and Holbro, O'Neill's High Frontier proposal is a classic example of bootstrapping.[21]

A reusable or partially reusable Earth-to-orbit space transportation system would first be utilized to construct an initial space manufacturing facility in low Earth orbit (LEO). A feedstock of tools, machine parts and biosphere components would be delivered to this facility. Next, a low-thrust drive would be used to deliver mining equipment and personnel to the Moon or near-Earth asteroid.

Materials would be mined and applied to the construction of large space habitats (fig. 2) and solar power stations (fig. 3). Energy beamed back to Earth from the solar power stations would be the initial industrial product of this space-based infrastructure.

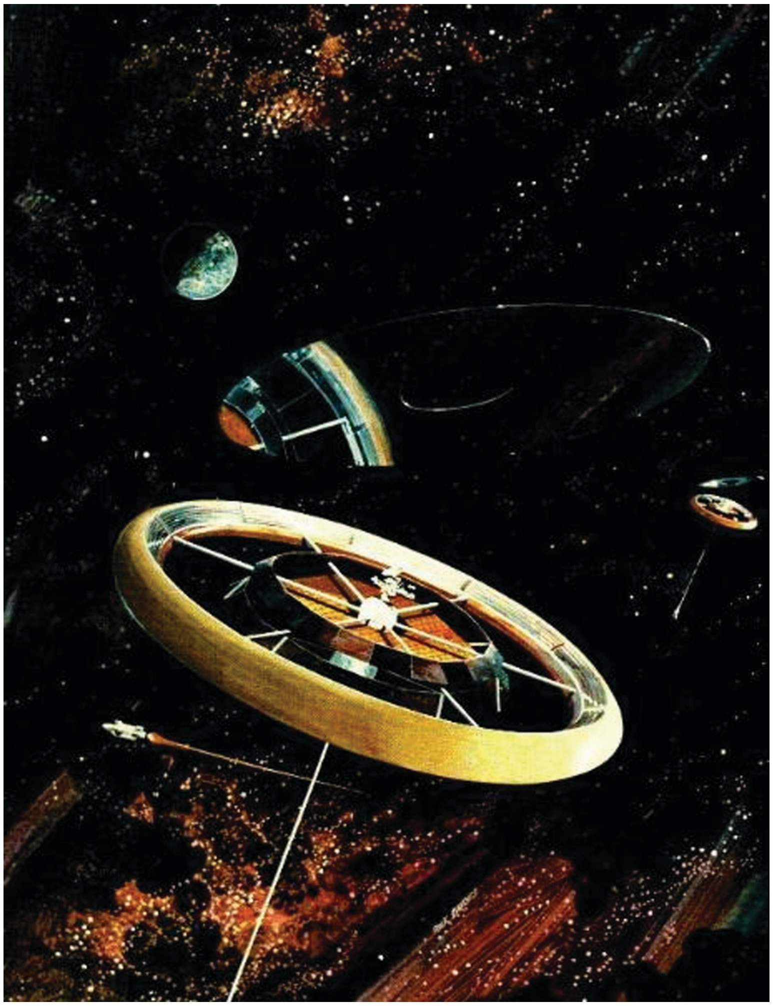


Figure 2. A toroidal space habitat (radius: ≈1 km; population: ≈10,000) under construction in Earth-Moon space. (Copywrite David A. Hardy/AstroArt.)

O'Neill space habitats would have dimensions on the order of kilometers and masses of billions of kilograms. Most of the mass requirement, which is dictated by necessity to shield habitat dwellers from galactic cosmic rays, would be satisfied using lunar or asteroid resources. The environment inside the habitats, which would rotate to simulate gravity, would be as Earthlike as possible.

Solar-power satellites would consist of millions of kilograms of kilometer-dimension thin-film panels to convert sunlight into electricity and a microwave array to transmit the gigawatts of electrical power back to Earth.

SEP is an enabling concept for the High Frontier proposal. SEP research will result in highly efficient and reliable solar-electric thrusters that could maintain large space manufacturing facilities (SMFs) in LEO with much greater cost effectiveness than conventional chemical rockets, due to the much higher exhaust velocity of SEP. SEP could also be utilized as a cost-effective means of moving equipment, personnel, and manufactured material through space.

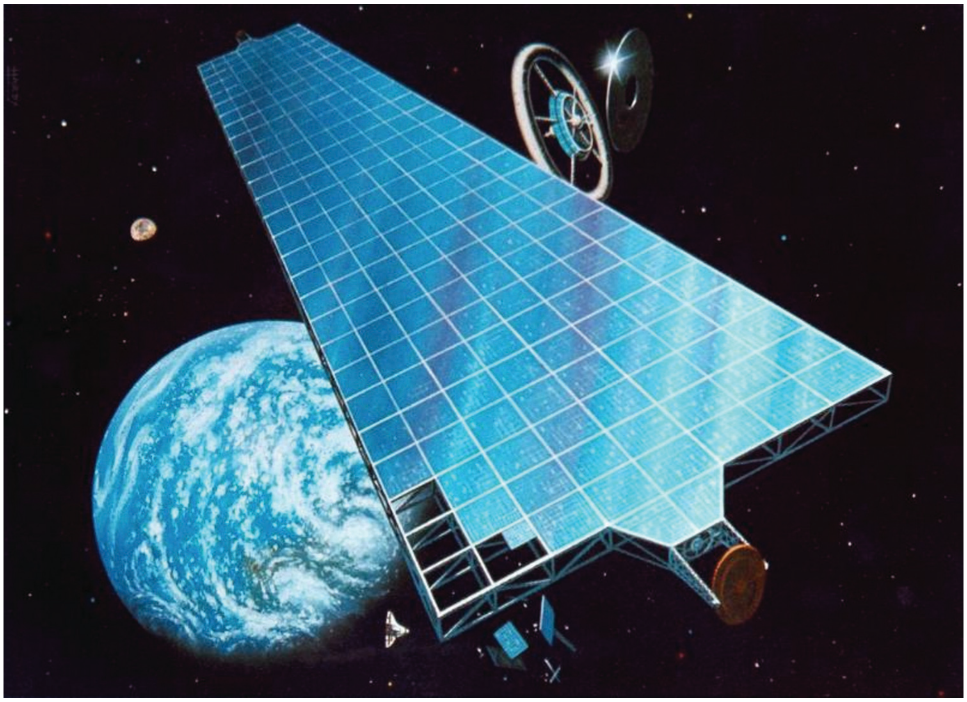


Figure 3. A solar-power satellite under construction in geosynchronous Earth orbit. (Courtesy http://members.aol.com/sandycombs/sunsat.jpg.)

SEP research will also impact the development of the mass driver (fig. 4). Mass drivers, which have undergone small-scale breadboard tests, are essentially electromagnetic catapults that could fling mined materials from the Moon or an asteroid into space, towards an orbital processing or manufacturing facility.

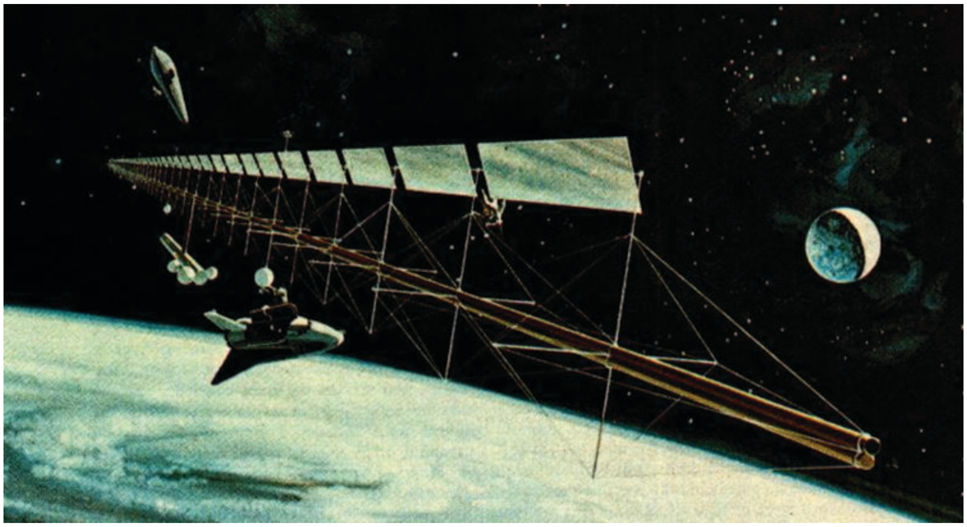
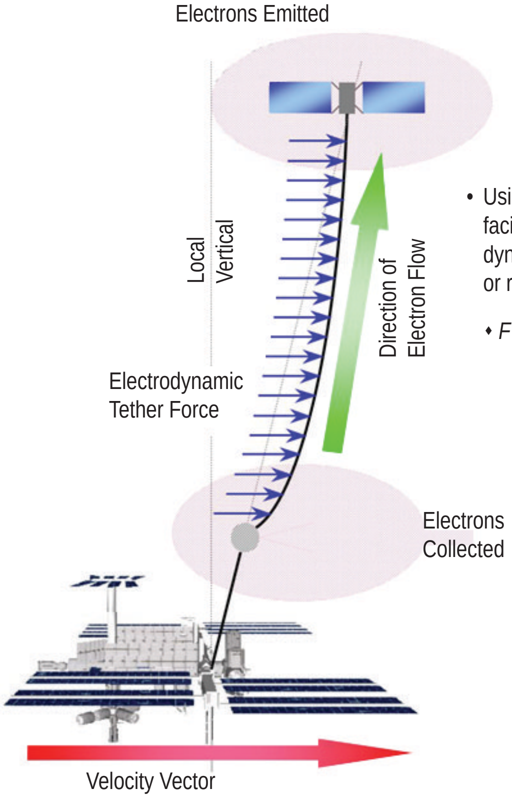


Figure 4. A solar-powered electromagnetic mass driver. (Courtesy http://members.aol.com/sandycombs/sunsat.jpg.)

4.3 Electrodynamic Tethers and Space Fabrication

Another technology with application to in-space fabrication is the electrodynamic tether. Electrodynamic tethers have been described by Samanta et al., Beletskii and Levin, and Estes et al.[22–24]

As shown in figure 5, an electrodynamic tether could be used to reboost SMFs located in LEO without the use of onboard propellant. Such a tether, constructed from a long conducting strand, would be oriented so that the lower end is attached to the SMF. Electrons are collected from Earth's upper ionosphere near the position of the SMF. Powered by the SMF's solar cells, the collected electrons are pushed up the tether and emitted at a higher altitude than the SMF's orbit. The resulting electrodynamic thrust force on the tether's unidirectional current adds energy to the SMF's orbit, thereby raising the orbital height.



- Using the environment of LEO, large facilities can be reboosted electrodynamically, requiring no propellant or resupply.

- $F = I\,dL \times B$

F = Thrust Force
I = Current Extracted From the Ionosphere
L = Length of Conducting Tether
B = Earth's Magnetic Field

Figure 5. Application of electrodynamic tether for orbit reboost.

4.4 The Momentum Exchange/Electrodynamic Reboost Tether and Interorbital Transfer

Another tether concept with application to the development of the space frontier is the momentum-exchange/electrodynamic reboost (MXER) tether. As described by Sorensen, the MXER tether is a hybrid of momentum-exchange and electrodynamic tether designs.[25] A rotating momentum-exchange tether can increase the orbital energy of a payload by releasing it near the tether's farthest height above Earth. But the rotational energy of the tether itself decreases during this maneuver and its orbital height is consequently reduced.

After the payload is released into its higher orbit, the tether's rotation is slowed. A solar power station attached to the conductive tether is then used to direct a unidirectional current through the tether, as shown in figure 5. This process increases the tether's orbital height. Both maneuvers—payload transfer to higher orbit and tether-station orbit raising—are accomplished without the expenditure of propellant.

In the near future, MXER tethers could be used as shown in figure 6 to rendezvous with the payloads of LEO (or suborbital) launches and transfer them to SMFs in higher Earth-centered orbits. To accomplish this feat, the tether must initially be in an elliptical orbit with its rotation timed so that the tether is oriented vertically below the solar power station at its center of mass and is swinging backwards at the perigee of its orbit. A grapple on the lower tether tip captures the payload from its low-orbit location and releases it half an orbit later into a higher-energy orbit.

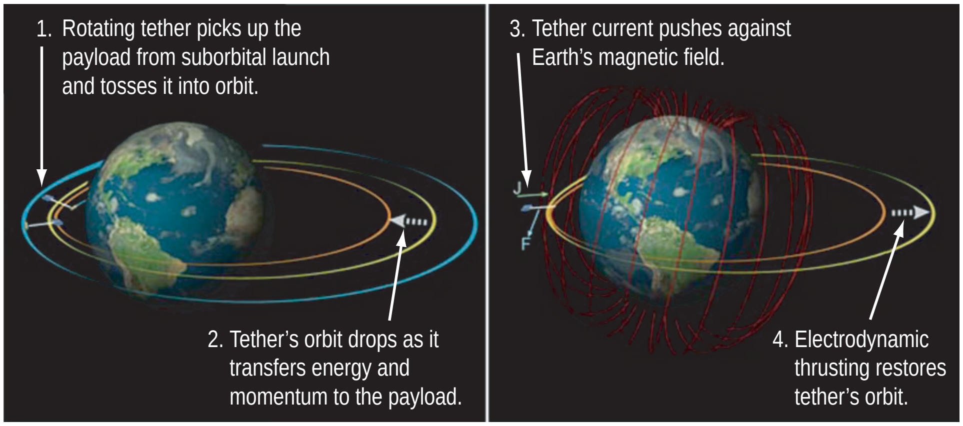


Figure 6. Interorbit transfer using the MXER tether (used by permission of Tethers Unlimited, Inc.).

Further in the future, tethers can be applied as demonstrated in figure 7 to create an extraterrestrial equivalent of the Transcontinental Railroad. Here, a LEO-tether hands a payload to a tether in higher orbit, which catapults the payload towards the Moon. Approaching the Moon, the payload rendezvous with a third tether which deposits it on the lunar surface and picks up a payload to be returned to Earth.

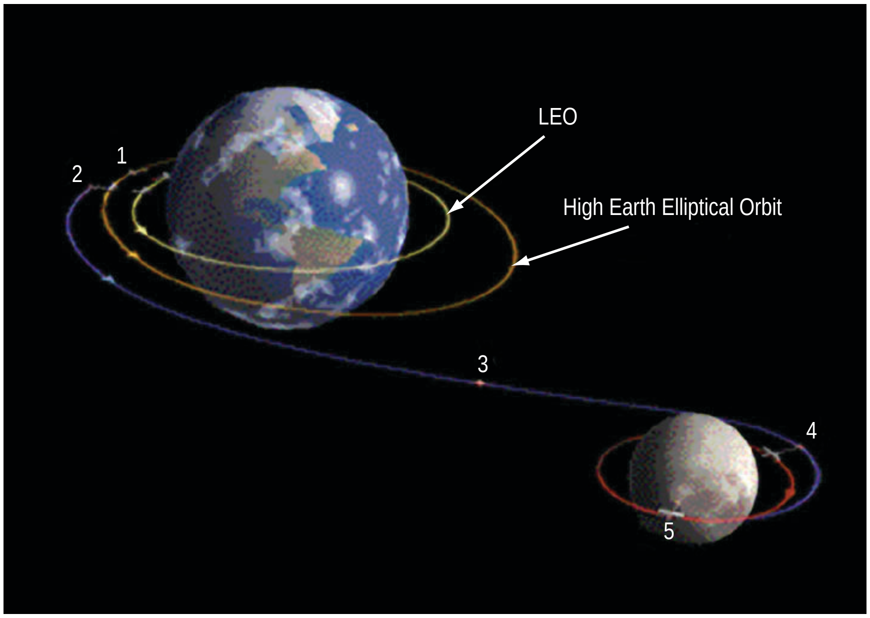


Figure 7. A tether equivalent to the Transcontinental Railroad (used by permission of Tethers Unlimited, Inc.).

4.5 Solar-Thermal Propulsion and In-Space Fabrication

The solar-thermal rocket functions by using collected and focused sunlight (or laser light) to heat a propellant working fluid such as hydrogen.[26,27] The specific impulse of the solar-thermal rocket typically ranges from 800 to 1,000 s, about twice that of the most energetic existing chemical rocket. The comparatively high thrust and propellant efficiency enables 30-day trips from LEO to geostationary Earth orbit (GEO).

As the space frontier develops, STP could see application as a space railway equivalent (fig. 8), in the transfer of equipment and manufactured products between SMFs located in LEO and higher orbits. The technology used in the low-mass STP sunlight-focusing optics may also see application in SMF furnaces for large-scale on-orbit manufacturing.

Figure 8. Application of the solar-thermal rocket for interorbit transfer.

5. DEEP-SPACE RESOURCES: SURVEYS AND RETRIEVAL

Before portions of the space frontier beyond Earth orbit can be settled, a Space Age equivalent of the Lewis and Clark expedition must be conducted. Even after more than 40 yr of space travel, the knowledge base of solar system resources is not adequate to plan the settlement, development, and exploitation of deep space.

5.1 The Scale of the Solar System

Astronomical and space-probe data have revealed that the solar system (fig. 9) is an enormous place both in space and time. Earth's nearest neighbor in space is the Moon, which is, on average, ≈384,000 km from Earth. After achieving Earth-escape velocity (≈40,000 km/hr), Apollo astronauts required ≈3 days to travel one way between Earth and the Moon.

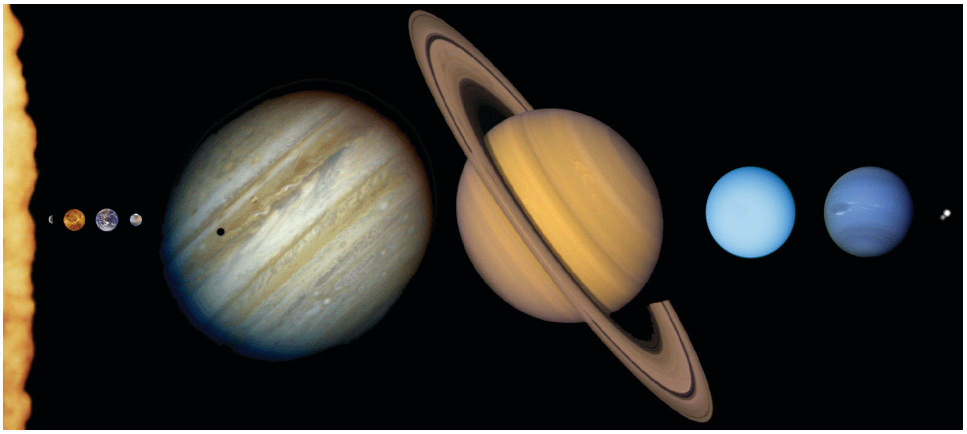


Figure 9. The Sun and planets of the solar system.

Beyond the Moon, are near Earth objects (NEOs). Suspected to be of asteroidal and cometary origin, some of these objects occasionally approach within cis-lunar distances. Known NEOs range in diameter from between a few hundred meters to a few kilometers.[16]

Some NEOs can be visited on round-trip trajectories that require less energy than landings on the Moon. Round-trip travel time to some low-inclination, low-eccentricity NEOs has been estimated to be 1 yr or less.[14] NEOs have collided with Earth many times in geological history; such an impact may have doomed the dinosaurs 65 million years ago. To prolong the lifetime of human civilization and the human species, space-faring institutions must devote attention to the problem of predicting and preventing NEO-Earth encounters.[28]

Although humans may settle and mine the Moon and NEOs, inclement surface and atmospheric conditions may preclude such activity on our nearest planetary neighbor, Venus, which is about two-thirds of the distance from the Sun to the Earth. Because of the high-energy solar orbit required to reach an object deep within the Sun's gravity well, small, hot Mercury may also be off limits for humans in the foreseeable future.

The nearest planet of interest for potential human occupation is, of course, Mars. The fourth planet from the Sun (with a mean solar distance of about 1.5 au), Mars is in a fairly elliptical solar orbit. Even advanced propulsion technologies require several months for a one-way trip to the red planet. Most one-way voyages to Mars would require 6–9 mo. Mars' two tiny Moons, Deimos and Phobos, may be of interest as "way stations" for martian explorers.

Traveling beyond Mars, an explorer would next encounter the realm of the main-belt asteroids, which orbit between about 2.2 and 3.3 au from the Sun. The largest of these irregularly shaped minor planets, Ceres, is ≈1,000 km in diameter.[16] Data from space probes and terrestrial telescope observations have revealed that some asteroids have smaller satellites. Some asteroids are rocky, others are stony. A third class are carbonaceous chrondites, which may contain some water reserves.

One-way travel time to main-belt asteroids would approximate to 1 yr using contemporary propulsion systems. As the wide-scale development of the solar system proceeds, the mining of main-belt asteroids will become increasingly significant.

One-thousandth the mass of the Sun and more than 300 times the mass of the Earth, giant Jupiter orbits 5.2 au from the Sun. Like the other gas giants, it is surrounded by a ring system and accompanied by many satellites. Some of these satellites are captured asteroids or comets. The four largest: Callisto, Europa, Ganymede, and Io were first observed by Galileo and most likely formed with Jupiter.

Life may be present beneath the frozen oceans of Europa, and the other Jovian satellites may serve as an outer-solar system resource base, provided that human and robotic explorers in this realm can be shielded against Jupiter's intense radiation belts. Travel from Earth to Jupiter along a minimum-energy trajectory requires about 2.7 years.[29]

Farther out from the Sun, the explorer next encounters the smaller gas giants: Saturn, Uranus, and Neptune. Each is considerably more massive than the Earth and equipped with satellites and rings.

Ranging from Neptune's orbit (30 au) to ≈50 au from the Sun is another zone of small solar system bodies. Pluto (≈1,200 km in radius) is the largest discovered member of these Kuiper Belt objects (KBOs). KBOs are sometimes dubbed cometoids because of their apparent similarity to icy comets.[16] Current-technology flybys of KBOs require a decade or longer. Decelerated-rendezvous or sample-return missions to these very distant objects will require either considerable improvements in propulsion technology or much longer mission durations.

Although some of the short-period comets are KBOs affected by giant-planet gravitational perturbations, most comets reside in the Oort cloud.[30] As many as 10^{12}–10^{13} comets may reside in this vast reservoir with a total mass as high as 30 Earth masses. Some long period comets have aphelia greater than 20,000 au and require more than 10,000 yr to orbit the Sun.[16] Even with significant advances in propulsion technology, robotic expeditions to Oort Cloud objects will require many decades.

5.2 Destinations and Resources

Low gravity objects—such as NEOs, small planetary satellites, main-belt asteroids, KBOs, and Oort Cloud objects—will provide the basic resource base for an expanding in-space infrastructure. The reason for this fact is accessibility. It will be easier to mine these low-gravity objects than to enter a planet's gravity well, establish a surface manufacturing/mining facility, and launch the manufactured or mined product back into space through that planet's gravity well.

The in situ exploration of these minor solar system denizens began in October, 1991, when the NASA Galileo spacecraft imaged asteroid 951 Gaspra while en route to Jupiter (fig. 10).

Figure 10. Galileo spacecraft image of Gaspra.

Gaspra is a main-belt asteroid with a semimajor axis of 2.21 au, has a mean dimension of ≈12 km, an eccentricity of 0.17, and an orbital inclination of 4.1°. Tiny Gaspra completes one circuit of the Sun every 3.28 yr and has a prograde rotation period of 7.042 hr. Gaspra's mass and density are unknown, but it is suspected to be rich in iron ores.[16]

In August 1993, further along its Jupiter-bound trajectory, Galileo flew past a second main-belt asteroid called 243 Ida (fig. 11). Some of the 47 images returned to Earth during the encounter showed a small satellite of Ida that has been named Dactyl.

Figure 11. Asteroid Ida and its satellite, Dactyl.

Ida has a mean dimension of ≈31 km, and tiny Dactyl is only ≈1.4 km across. The pair are 2.864 au from the Sun and orbit the Sun once every 1,770 days in an orbit with an eccentricity of 0.043 and an inclination of 1.371°. Ida rotates once every 4.63 hr, and Dactyl's rotation rate might be synchronous with its 24.7 hr orbital period around Ida.

Basing their conclusions partially on the asteroids' effects on spacecraft trajectory, scientists have estimated the density of both Ida and Dactyl to be slightly less than that of aluminum. Ida's mass is $\approx 4.2\times10^{16}$ kg and Dactyl's is $\approx 4\times10^{12}$ kg. Ida and Dactyl, like Gaspra, are suspected to be iron-rich bodies.[16]

The first spacecraft specifically intended for asteroid exploration was the NASA Near-Earth Asteroid Rendezvous (NEAR) probe. On June 27, 1997, NEAR flew past main-belt asteroid Mathilde at a distance of only 1,212 km. Unlike previous asteroids investigated by spacecraft, Mathilde has a very low density (1.3 g/cm^3). Mathilde has a mass of ≈1,017 kg, a typical dimension of ≈50 km and a rotation period of 17.4 hr.

With an inclination of 6.89° and an eccentricity of 0.23, Mathilde orbits the Sun with a semi-major axis of 2.647 au. Of great interest to potential space miners is the low density of this asteroid. Future investigation may well reveal that Mathilde's composition includes hydrated silicates, clays and organic compounds.[16]

Figure 12 presents a NEAR black-and-white image of asteroid Mathilde. The spacecraft was ≈2,400 km from the asteroid when this exposure was taken. The depth of the heavily shadowed, central large crater is estimated to be 10 km.

Figure 12. A NEAR spacecraft image of asteroid 253 Mathilde.

Although good science was returned by NEAR during its encounter with Mathilde, this was actually a bonus. The NEAR mission objectives were to orbit the Near-Earth Amor Group asteroid Eros. NEAR achieved Eros orbit in 2000 and performed the first successful soft asteroid landing on Eros at the conclusion of its mission.

Like all NEOs, asteroid 433 Eros is located within the inner solar system with a perihelion of 1.13 au. Its orbital eccentricity is 0.223 and its inclination to the plane of the ecliptic is 10.8º. Eros' mean dimension is ≈22 km, and its mass is estimated to be 5×10^{15} kg.[16]

Before the encounter, Eros was suspected to contain iron ores. The x-ray spectrometer aboard NEAR confirmed the presence of iron as well as finding magnesium and silicon. Aluminum and calcium may also be present. NEAR orbited Eros at a distance of ≈200 km.

NEAR (also dubbed NEAR Shoemaker) was the first of NASA's Discovery missions. It was launched from Cape Canaveral on February 17, 1996, by a Delta II rocket. With an on-orbit mass of 805 kg, it was equipped with a multispectral imager, near-infrared spectrograph, an x-ray/gamma-ray spectrometer, a magnetometer, laser rangefinder, and equipment to accomplish radio science and gravimetry.

Some of the images of Eros returned by NEAR have been combined to produce the three-dimensional image of this asteroid shown in figure 13. Images were returned by NEAR almost to the moment of its landing on Eros.

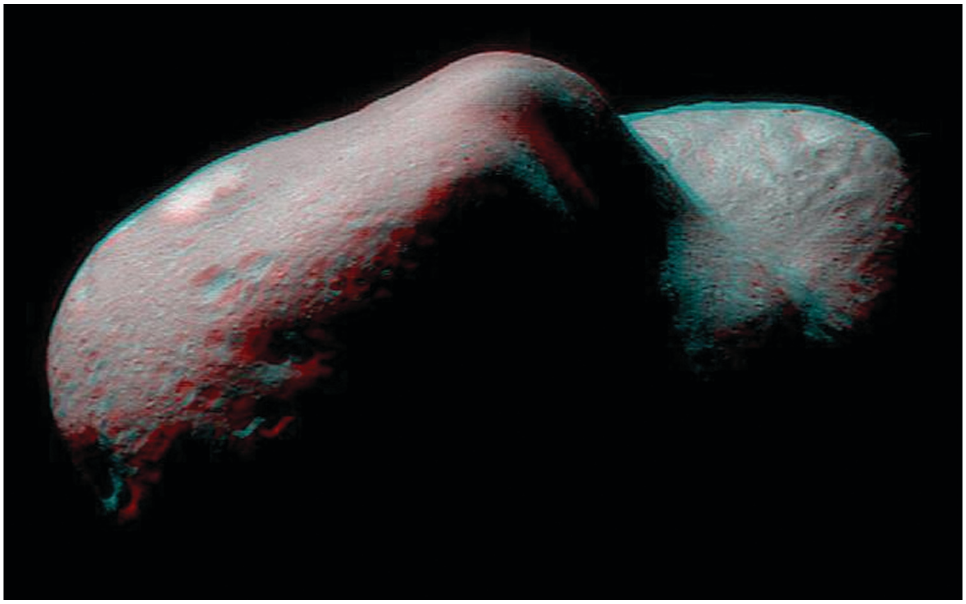


Figure 13. A three-dimensional image of asteroid Eros from the NEAR spaceprobe.

Comets as well as asteroids have been targets for spacecraft. In 1986, Halley's Comet was explored at close range by probes from the United States, Europe, Russia, and Japan. The closest approach to Halley's nucleus was performed by the European Giotto probe on March 13, 1986, when Halley was 0.89 au from the Sun and 0.98 au from the Earth.

Giotto, which was launched by an Ariane rocket on July 2, 1985, had an on-orbit mass of 583 kg. As well as photographing the nucleus of Halley's Comet from a distance of about 60 km, Giotto contained equipment to determine isotopic and elemental composition of material in Halley's coma and investigate physical/chemical processes occurring in the comet during its closest approach to the Sun (apparition), to investigate the dust particles emitted from the comet's nucleus and study the plasma flows resulting from the interaction between the comet and solar wind.

Figure 14 presents a Giotto image of the Halley's Comet nucleus during the close encounter—note the jets of solar-heated material sublimating off the comet's nucleus.

Although damaged by dust during its high-speed encounter with the Halley's Comet nucleus, Giotto survived to perform an encounter with comet P/Griggs-Skjellerup on July 10, 1992. At the time of this second encounter, the comet was 1.01 au from the Sun and 1.43 au from the Earth.

Giotto and its sister Halley's Comet probes (U.S. ISEE–3/ICE, Japanese Sakigake and Suisei, and Russian Vega 1 and Vega 2) confirmed Earth-bound observations indicating that volatile gases (gaseous water, carbon monoxide, carbon dioxide, nitrogen, ammonia, and methane) are present in comet comas and tails.

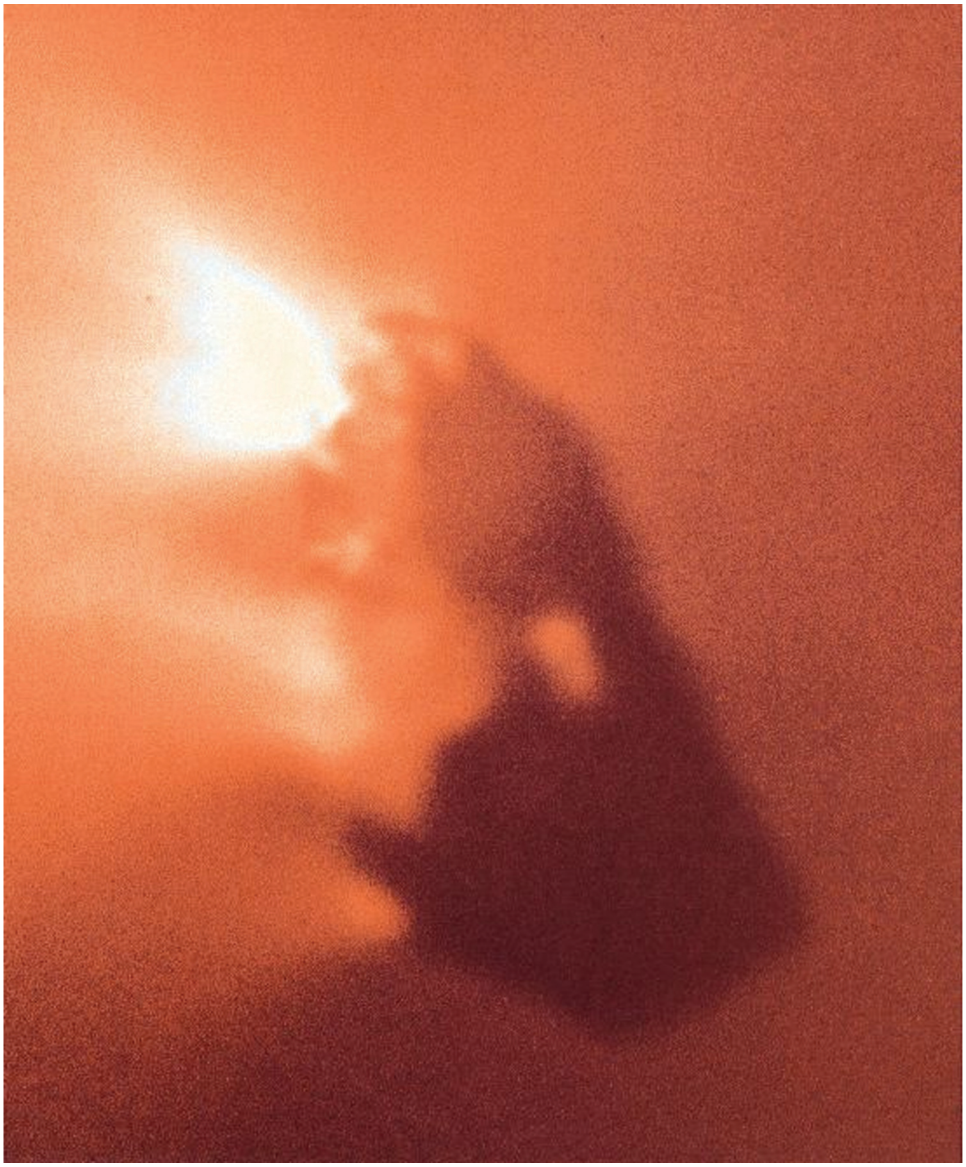


Figure 14. A Giotto image of the nucleus of Halley's Comet.

To perform accurate resource surveys of comets, it is necessary to utilize an in-space propulsion system that can accomplish a comet rendezvous rather than a fly through. SEP systems are ideally suited to perform this type of propulsive maneuver. Ion propulsion had a successful space debut as the primary propulsion system of the NASA Deep Space 1 probe.

Deep Space 1, conceived as a New Millenium program demonstrator of 12 new technologies including SEP, was launched from Cape Canaveral on October 24, 1998. The total mission cost between FYs 1995 and 1999 was 149.7 million dollars.

The solar arrays of the spacecraft provided up to 2.4 kW of electricity. This was used to power the instruments of the science suite—which consisted of imagers, ion and electron monitors, and an infrared spectrometer—as well as the ion engine. SEP propellant fuel on Deep Space 1 was xenon and the exhaust velocity was 30 km/s. After it was turned on following Earth-escape, Deep Space 1's SEP operated successfully in space for several hundred days.

Including propellants, the total on-orbit mass was 486.32 kg. As well as successfully performing its technology-demonstrator role, Deep Space 1 flew by asteroids 9969 Braille, formerly known as 1992 KD. The fly by, which occurred in July 1999, was at a distance of only 27 km. In September 2001, the Deep Space 1 probe encountered comet Borrelly (fig. 15). The false-color image in figure 15, exposed when the space craft was a few thousand kilometers from the comet's nucleus, clearly shows solar-heated dust jets escaping from the nucleus into the comet's coma and tail.

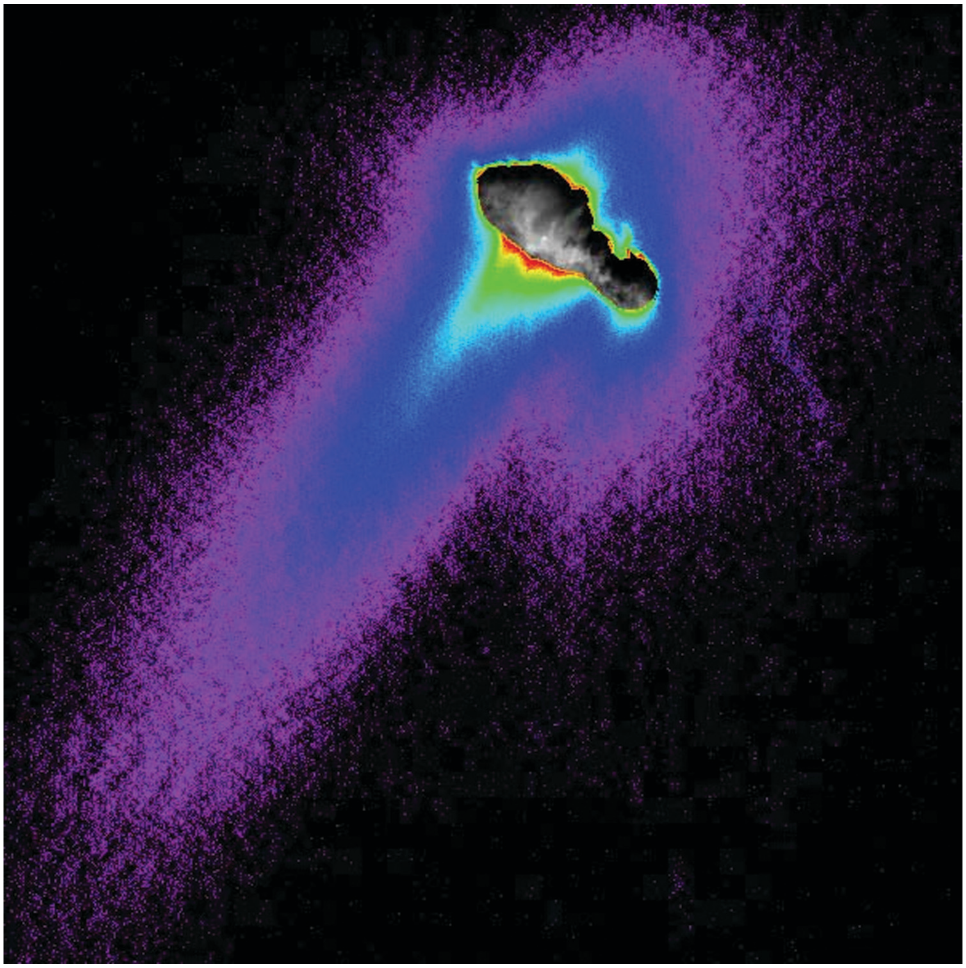


Figure 15. A false-color image of comet Borrelly from Deep Space 1.

A number of ongoing or planned international space-exploration missions will increase humanity's data base regarding asteroidal and cometary resources. These missions include NASA's Stardust and Deep Impact, Japan's Hayabusa (Muses-C), Europe's Rosetta, and the privately funded Near-Earth Prospector (NEAP).

Launched in February 1999, Stardust flew within 236 km of comet 81P Wild 2 on January 2, 2004. As well as photographing the nucleus of this comet (fig. 16), Stardust collected samples of material emitted from the comet's nucleus. These samples are scheduled to return to Earth by parachute aboard a sample-return capsule when Stardust swings by the Earth in January 2006. Stardust's solar arrays have successfully operated at 2.72 au from the Sun, setting a new record for solar-powered spacecraft.

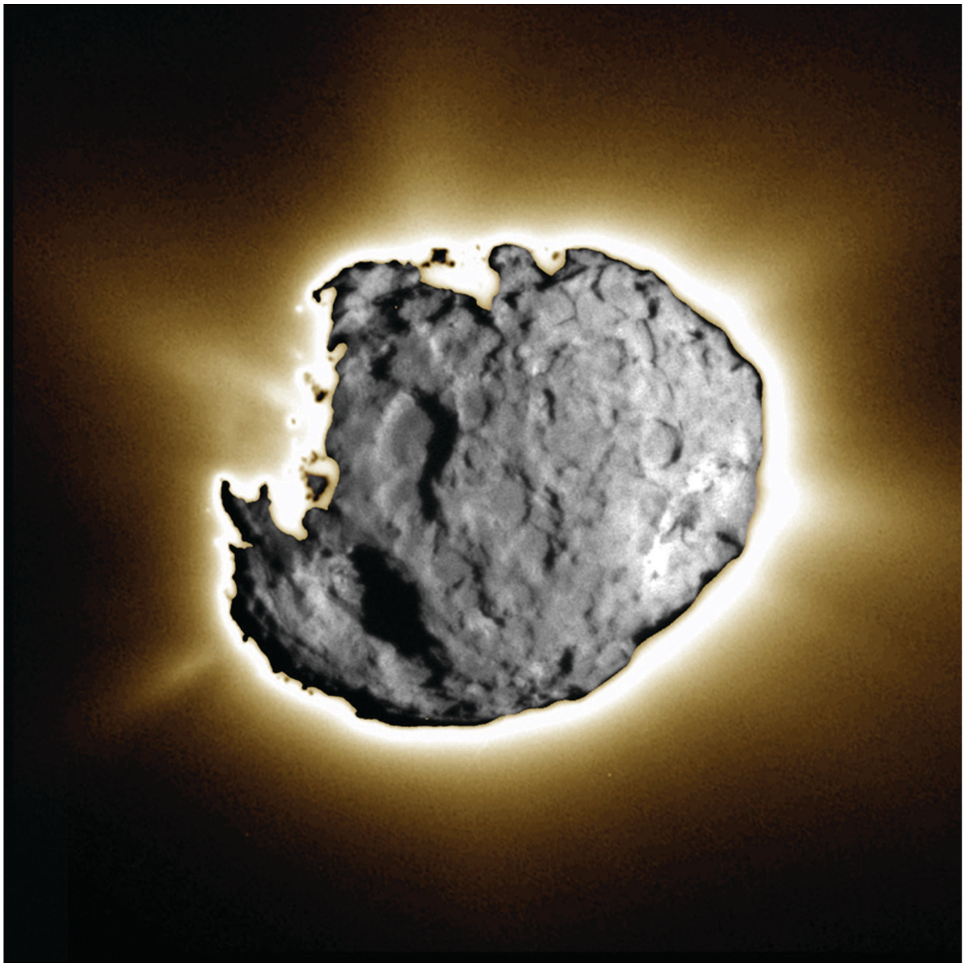


Figure 16. A Stardust image of comet 81P Wild 2.

After its successful launch in May 2003, the 415-kg Japanese Hayabusa (Muses-C) probe was put into a transfer orbit towards asteroid 25143 Itokawa. Utilizing SEP, spacecraft controllers plan to perform station-keeping maneuvers near this asteroid and then perform several soft landings and collect samples of asteroid material. After a stay of several months on or near the asteroid, the spacecraft will utilize SEP to return to Earth. In June 2007, a sample recovery capsule will parachute the samples to Earth near Woomera, Australia.

On March 2, 2004, Rosetta was launched aboard an Ariane-5G. This 3,000-kg spacecraft is equipped with a 31-m solar array that will power a very impressive science suite. Rosetta is scheduled to encounter its target, comet 67P/Churyumov-Gerasimenko in 2014. Plans call for Rosetta to enter orbit around this comet rather than simply flying through it. A 90-kg lander capable of extensive surface studies is to be deposited softly on the comet's surface.

The NASA Deep Impact comet probe launched on January 12, 2005. This Discovery-class mission is scheduled to encounter comet P/Tempel 1 on July 4, 2005. A 370-kg impactor is scheduled to separate from the main spacecraft, which will analyze the ejecta spectra from a safe distance as the impactor slams into the comet nucleus. For the first time, space scientists will learn something about the material in a comet's interior.

Sometime in the 2006–2008 time frame, the privately-funded NEAP is scheduled for launch. The mission of this 200-kg spacecraft to a NEO is being planned by SpaceDev Inc.

5.3 Propulsion: Required Improvements and Options

In-space propulsion technology improvements will greatly expand the knowledge base regarding deep-space resources. Such improvements, along with reduced spacecraft sizes and increases in solar-cell efficiency, will allow space probes to venture farther into the solar system with more scientifically productive payloads. Decreased mission costs resulting from these improvements should allow for more frequent exploratory missions to a wider range of destinations and/or decreased mission durations.

Increases in SEP specific impulse will decrease propellant requirements, increase payload allotment, and decrease interplanetary-transfer time. Increases in solar-cell technology (increased efficiency and decreased mass) should allow for the possibility of solar-powered resource-survey missions deeper into the asteroid belt.

When the solar-photon sail becomes operational, it may become the preferred propulsion system for out-of-ecliptic missions.[31] Even early solar sails could be utilized to rendezvous with NEOs in high-inclination solar orbits. With increased thermal tolerance, sail-propelled probes could explore comets within the orbit of Mercury. Departing from elliptical solar orbits with perihelia <1 au or low-perihelion parabolic solar orbits, sails could propel payloads on fast flybys of KBOs.[31,32] Decreases in sail mass thickness may allow such flybys of objects in the nearer Oort Cloud.

Advances in aerocapture technology should allow the development of aeroshells of lower mass and greater thermal tolerance. One can imagine advanced aerocapture missions decelerated by Neptune's atmosphere for rendezvous with KBOs near that giant planet.[32,33]

Improvements in chemical-rocket technology may include higher specific impulse, greater reliability, and longer in-space storage time. Certain classes of rendezvous and sample-return missions will be positively impacted by these developments.

Tether improvements will include better understanding of tether dynamics and interaction with the space environment. Since tethers may prove very useful in reducing the cost of orbit-transfer, they may improve performance of some deep-space resource-survey missions. For example, a tether could be used to raise the orbital height of a solar sail in LEO to an altitude less affected by atmospheric drag. Another technology that may compete for such lower cost, interorbit transfer is STP.

However, the greatest improvement in propulsion flexibility would result if an antimatter rocket could be developed. Because of the very high mass-energy conversion ratio of a fuel consisting of equal masses of matter and antimatter, the specific impulse of an antimatter rocket might be in the range of 104,000–107,000 s.[34] If interplanetary-probe mass can be dramatically reduced, if the cost of antimatter production drops by many orders of magnitude, and if antimatter can be safely stored for months or years, then the antimatter rocket might become the propulsion system of choice for many missions.

5.4 Resource Retrieval Via Solar Sail

After accessible solar system resources are surveyed and mining techniques developed, methods must be developed to economically ship them across the solar system in a manner analogous to freight railways. Drexler was one of the first researchers to engineer the solar sail for this application.[35]

Current-generation solar sails for Earth-launch typically have an areal mass thickness of ≈ 0.01 kg/m^2. These sail films are typically tri-layered, with the sunward side being a reflective metal (typically aluminum), the back (antisunward) side is an emissive material (such as chromium) and a plastic substrate is in between.[31]

To create a solar-sail in-space analog to a freight railroad, it will be necessary to reduce the areal mass thickness by about an order of magnitude. There are several possible ways to do this. Drexler proposed vapor-phase deposition as a method of creating thin metallic films in space.[35] A second possibility is to launch a metal/plastic bilayer sail from Earth with the plastic substrate constructed of UV-sensitive material that would evaporate in space.[36] Another option is the application of superstrong, thin, and hyperthin Earth-launched fabric-type sails such as the ESLI carbon microtruss.[37] As proposed by Forward and further developed by Matloff, an additional possibility is a perforated nanomesh sail.[38,39]

Much further research is required to ascertain which of these, or perhaps another technique, is superior for this application. But, it is not unreasonable to expect 22nd-century clipper ships with multi-kilometer sails crisscrossing the “prairies” of the solar system with their cargoes of asteroidal and cometary material (fig. 17).

The “parachute” sail shown in figure 17 is, of course, not the only sail configuration that might be chosen for this application. Various other sail configurations are discussed by McIness and Matloff.[5,31] As well as the development of ultrathin sail materials that are very long lived in the space environment, it will be necessary to utilize low-mass cables of the highest possible tensile strength. Various approaches, such as the hydrostatic beams of Genta and Brusca, that may reduce the mass of the supporting structure for a large solar sail have been suggested.[40]

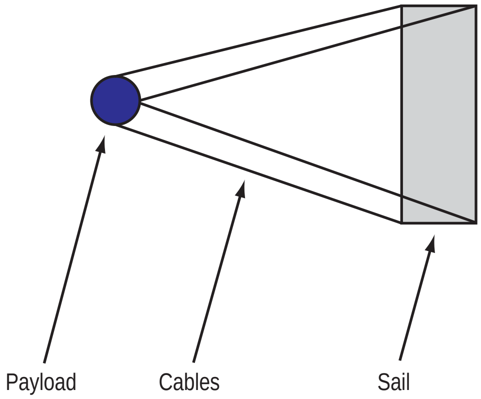


Figure 17. A future solar-sail freighter—the Sun is to the left.

6. PROPULSION SYSTEM FABRICATION USING IN-SPACE RESOURCES

Another possible connection between space manufacturing and in-space propulsion is the possible in situ fabrication of components for propulsion systems at SMFs. Drexler's aforementioned proposal to produce ultrathin solar sails in space using vapor-phase deposition is an example of this concept.[35]

With the application of rapid prototyping (RP) technology, many additional propulsion-system fabrication possibilities emerge. Rapid prototyping, as described by Doyle, is the three-dimensional equivalent of a Fax.[41] A prototype of a machine part or tool is first designed using a computer-aided design (CAD) package. The RP machine then quickly constructs the prototype layer by layer using powder, liquid, or sheets of material. After the prototype is constructed and approved, a cast is produced from which final products and parts can be constructed in quantity.

After early experimental and artistic applications in the 1980s, RP was utilized in the 1990s by Rocketdyne (Canoga Park, CA) to design and construct precision parts of rocket engines. This new technology reduces prototyping cost and time considerably.

An SMF could exploit this technology as follows. Lunar regolith or raw asteroidal/comet-nucleus material would first be gathered and then separated by element or compound. This material would serve as the feed-stock for the RP machine, which would construct precision propulsion-system components using onboard CAD equipment. Repair and replacement engine parts could thereby be constructed using in-space resources, reducing the need for resupply from Earth.

7. CONCLUSIONS: THE FAR FUTURE

After the connection of in-space propulsion, fabrication, and repair has opened the frontier of the solar system, the enhanced human in-space infrastructure may be applied to more ambitious goals. Two of these goals are the robotic exploration of interstellar space and the expansion of human civilization beyond the solar system.

The first institutional study of the feasibility of interstellar travel was Project Daedalus, which was conducted by the British Interplanetary Society between 1974 and 1978.[42] The Journal of the British Interplanetary Society continued to publish issues devoted to interstellar studies until 1990 and remains a major outlet for papers in this field.

After the conclusion of Project Daedalus, study coordinators Alan Bond and Anthony Martin published several papers concluding that the only ultimately feasible approach to interstellar travel by humans was the worldship.[43] A worldship would be a mobile version of the self-sufficient, closed-ecology space habitats discussed by O'Neill and others and would be capable of transferring a small human population to the vicinity of a nearby star on a voyage with a duration approximating a millennium.[19,20]

It was also concluded by Martin that only two propulsion systems might ultimately be feasible for worldship acceleration: (1) The nuclear-pulse rocket and (2) the ultrathin solar sail.[43] Nuclear-pulse rockets, as discussed by Dyson, are propelled by the detonation of high-yield thermonuclear devices beyond a pusher plate coated with ablative material and/or protected by charged-particle-reflecting magnetic fields.[44] Although ultimately technically feasible, the nuclear-pulse rocket has obvious political and sociological acceptance issues.

The interstellar solar sail was investigated before 1980 by NASA Jet Propulsion Laboratory (JPL) researcher Chauncey Uphoff, who incorporated his results in the JPL Thousand Astronomical Units (TAU) study.[45] TAU was a study of a robotic probe to 1,000 au from the Sun that could be accomplished using projected early 21st-century technology. The concept of interstellar solar sailing was further elaborated by Matloff and Mallove and reviewed by Mallove and Matloff and by Matloff.[5,46–48]

Figure 18 presents the basic concept of the interstellar (or extrasolar) solar sail. After launch from Earth or construction in space, the sailcraft is maneuvered into an elliptical or parabolic solar orbit with a perihelion as close to the Sun as possible. At perihelion, the sail is unfurled and oriented towards the Sun, then the spacecraft is accelerated by solar-radiation pressure to a heliocentric velocity higher than the solar escape velocity.

In the original concept, the sail was oriented normal to the Sun during postperihelion acceleration. As Giovanni Vulpetti has argued, there are in some cases advantages to nonconstant, nonnormal Sun-sail aspect angles.[49]

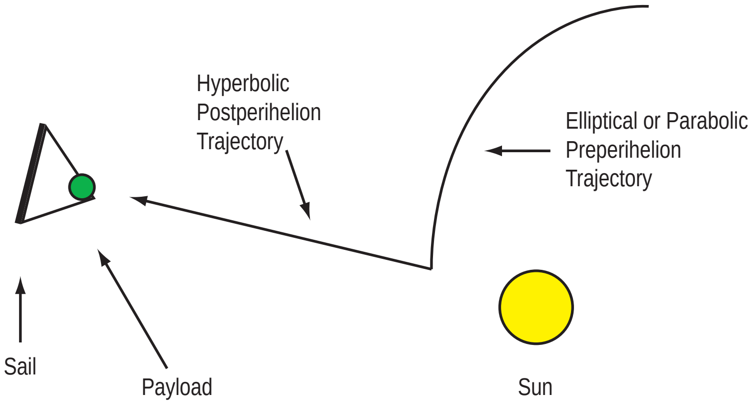


Figure 18. An interstellar solar sail.

If one assumes space-manufactured metallic monolayer sails with a thickness of ≈20 nm, thermally-limited approaches to the Sun within 0.01–0.04 au, and diamond-strength cables, modeling results reveal that interstellar travel times to the nearest extrasolar star system (Alpha Centauri, at 4.3 light years or 270,000 au) approximates to 1,000 yr, even for very large payloads.[47]

Peak accelerations exceed 1 g for many optimized trajectories. As demonstrated in a finite-element study by Cassenti et al., some sail configurations can withstand accelerations as high as 2.5 g.[50]

One advantage of this approach to interstellar travel is sail versatility. After acceleration, the sail and cables can be wrapped around the habitat section of the world ship to provide cosmic-ray shielding. If the target star is solar-type (as are both of the Alpha Centauri central stars), the sail can be unfurled again near the destination star and used for deceleration.[5]

Human capabilities are not yet up to the in-space manufacture of 100-km dimension, ultrathin metallic sails or the ultrastrong cables required to connect the worldship and the sail. Astronomy is not yet up to a survey of the planets (if any) that accompany the Alpha Centauri stars. Current knowledge of closed ecological systems and long-term sociological stability of small human populations is far from complete. Although a multigeneration mission to a nearby star cannot yet be planned, early extrasolar probes propelled by the solar sail have received increasing attention. This is perhaps because it is relatively easy to scale-down a worldship sail into an extrasolar probe sail.

During the 1990s, inspired in part by the NASA JPL TAU study and the ultimate prospects of sail-launched interstellar worldships, European researchers considered sail-launched extrasolar probes to the Sun's gravitational focus at 50 au and the heliopause at 100–200 au.[51,52] In the late 1990s, this work was incorporated into the NASA Interstellar Probe study.[53]

NASA should have the technological capability to launch early solar-photon-sail propelled interstellar precursor probes before 2020. If the areal mass thickness of the sail films approaches 0.001 kg/m^2, and the sail material can withstand a perihelion of about 0.2 au, a disc sail with a radius of ≈200 m should be able to project a 30-kg science payload (100-kg total payload) space craft on a voyage to the heliopause at 200 au from the Sun that requires no more than two decades. Such a craft could reach the inner-gravitational focus of the Sun, at 550 au, within a human lifetime.

Later in the 21st century, sail advances should allow NASA to explore the inner Oort Cloud, at 1,000–2,000 au from the Sun, on flights with durations approaching a human lifetime. This may be the best possible scenario with an Earth-launched solar-photon sail.

Advances in space manufacturing should eventually lead to the ability to construct solar photon sails in space that are close to the physically optimal film thickness. Experience with space-mining techniques as well as experience with many sail architectures should offer the opportunity to fabricate such sails using in-space resources.

Additional advances to be expected in the 21st century include maintenance of closed or nearly closed ecosystems in space. Experience with small space crews on long-duration explorations beyond LEO should offer data to sociologists regarding long-duration stability of small, isolated human communities.

There is no reason, therefore, that the capability to perform multigeneration interstellar voyages will not arise as a natural consequence of development of the solar system. Hopefully, new technologies such as beamed-energy sailing will greatly reduce interstellar-voyage durations before humans begin to expand towards the stars.[38,54]

APPENDIX

This Appendix consists of the Microsoft® PowerPoint™ slides of L. Johnson's presentation to the July 2003 Workshop.

In-Space Propulsion
Connectivity To In-Space Fabrication and Repair

July 8, 2003

Presented By

Les Johnson (NASA MSFC)

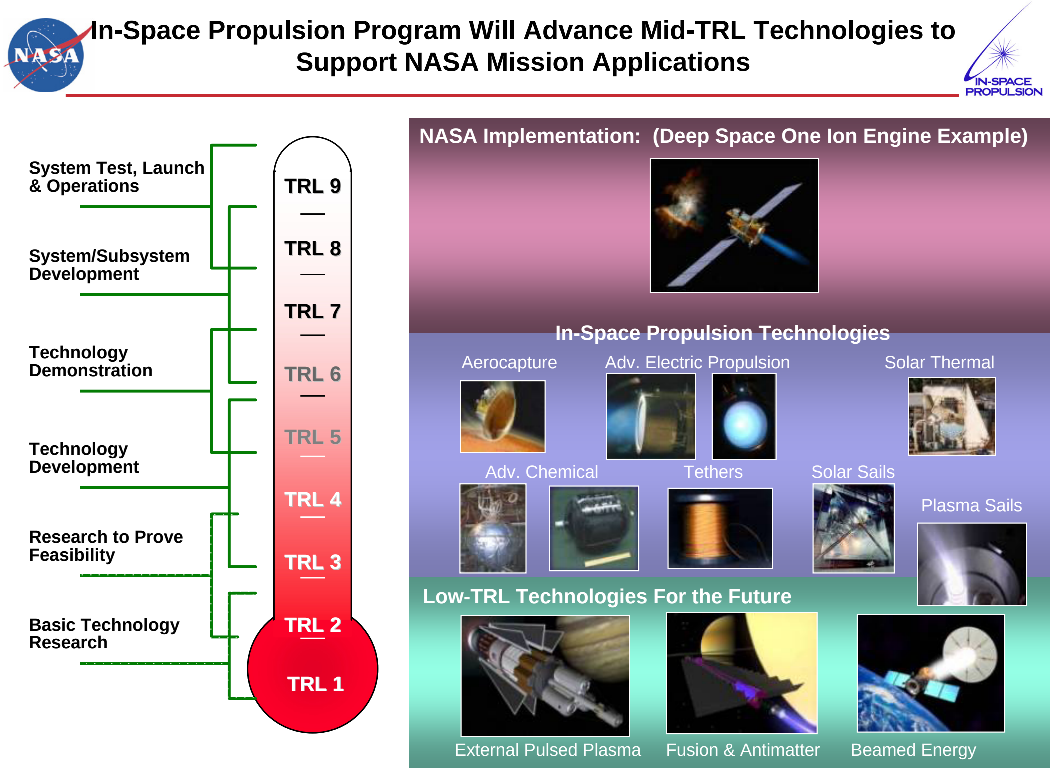
Co-Authors

David Harris & Ann Trausch (NASA MSFC)
Greg Matloff and Travis Taylor (Teledyne Brown Engineering)
Kathleen Cutting (Gray Research)

In Space Propulsion Program Overview

In-Space Propulsion Program Objective:

To develop in-space propulsion technologies that can enable and/or benefit near and mid-term NASA missions by significantly reducing cost, mass, and/or travel times.



In-Space Propulsion Program Will Advance Mid-TRL Technologies to Support NASA Mission Applications

System Test, Launch & Operations

System/Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

TRL 9

TRL 8

TRL 7

TRL 6

TRL 5

TRL 4

TRL 3

TRL 2

TRL 1

NASA Implementation: (Deep Space One Ion Engine Example)

In-Space Propulsion Technologies

Low-TRL Technologies For the Future

In-Space Propulsion
Technology Products

High Priority Technologies

- **Aerocapture**
  - Low-mass aeroshell with integrated TPS; Aerocapture flight-like instrumentation; Advanced Aerodynamic Decelerators (trailing ballutes, attached ballutes and inflatable aeroshells)
- **Next Generation Ion Thruster**
  - Next generation integrated ion engine thruster technology; NASA's Evolutionary Xenon Thruster; Carbon Based Ion Optics
- **Solar Sails**
  - Sail subsystem design and fabrication and ground demonstration; Structural testing of sail booms; Long term environmental evaluation of ultra-thin sail material

Medium Priority Technologies

- **Advanced Chemical**
  - Fuels development; Cryogenic Fluid Management; Lightweight components
- **kW Solar Electric Propulsion**
  - Laboratory demonstration of 50kW Hall thrusters; Competitively select thruster technology advancement based on application
- **Solar Thermal Propulsion**
  - Technology investments under further study; Directed tasks focused toward fundamental performance questions

High Risk/High Payoff & Lower Priority Technologies

- **Plasma Sails**
  - TBD
- **Momentum Exchange Tethers**
  - Model development and evaluation; Catch Mechanism concept; High strength tether
- **Solar Sails < 1g/m2**
  - Ultra-lightweight sail materials; Large area lightweight structures and mechanisms

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In Space Propulsion
In Space Fabrication and Repair

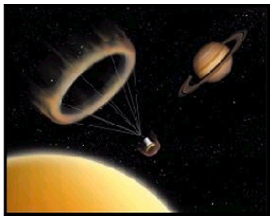
An Historical Perspective

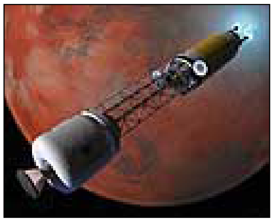
Historical Perspective

- **We are building canoes for Lewis and Clark**

Any study of the journey into the frontier of the West throughout the 1800's surely begins with the journey of Lewis and Clark and their Corps of Discovery at the beginning of that century. This journey, the first overland expedition to the Pacific Coast of this country and back, had many purposes: of commerce and transportation, as well as of exploration and scientific discovery.

<u>The In-Space Propulsion Program</u> seeks to provide enabling technologies to the expeditions of near- and mid-term NASA missions into the frontier of Solar System destinations.





Historical Perspective, Continued

- **The Next 50 years -- Conestoga wagons, Prairie Schooners . . .**

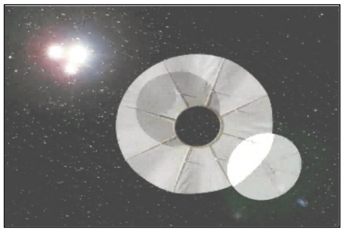
The Conestoga wagon was developed in the 1700's. Able to carry up to 5 tons, the bottom of the wagon curved up at both ends to prevent heavy loads from shifting. These wagons were the primary freight carriers before the introduction of the railroad.

They were adapted to the Sante Fe Trail with oxen or mules taking the place of horses, as better suited to the distance and environment.

The Conestoga was adapted once again for the journey west on the Oregon Trail. The Prairie Schooner was a smaller, lighter version, better suited for crossing streams and traveling over rough trails, as well as easier for a team to pull over long distances.

The Conestoga stands as a symbol not only of the pioneer spirit, but also of the necessity for methods of transportation to adapt to the frontier

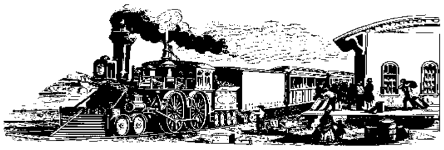
<u>Over the next 50 years</u>, In-Space Propulsion will continue to select the technologies for advancement that will be best suited for future destinations, and enhancing/enabling for In Space Manufacturing and Repair.



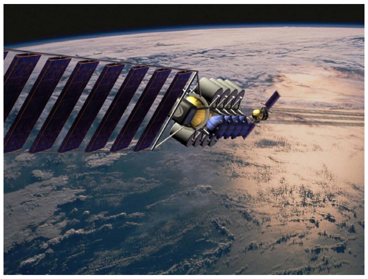
Historical Perspective, Continued

. . . and railroads

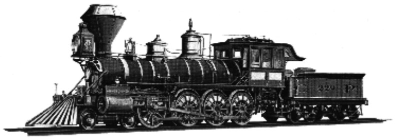
The expansion of the railroads increased the ease of travel and communication and encouraged even more westward expansion, both by settlers and industry. Throughout the West, many of the cities that thrive into the present began as settlements built where the railroad was expected to pass, and survived the difficult early stages of development because of the dependable influx of goods and people from the East.



Into the next half-century, putting in place the transportation nodes and manufacturing infrastructure to maintain In-Space Fabrication and Repair will be vital, and In-Space Propulsion technologies will be enabling for this task.

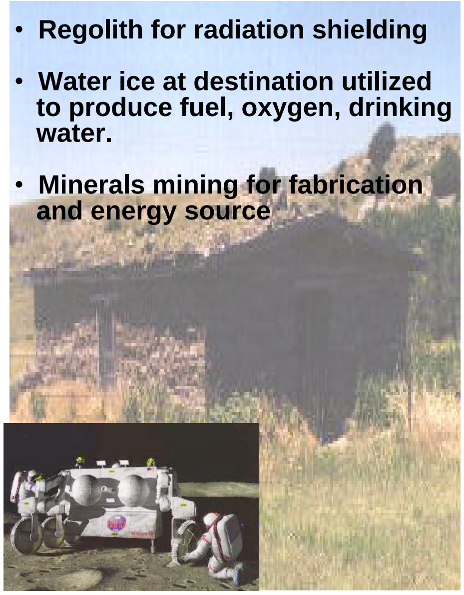


<u>In Space Propulsion</u> will lay the groundwork for reusable ‘railroads’ in space



History Provides Many Apt Analogies

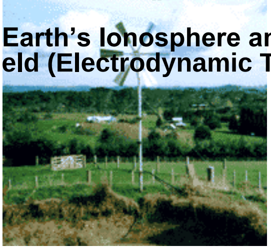
♦ Use Local Materials

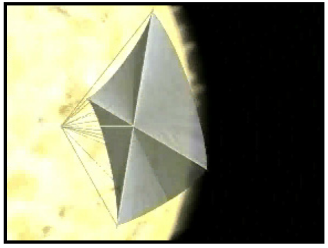


- **Regolith for radiation shielding**
- **Water ice at destination utilized to produce fuel, oxygen, drinking water.**
- **Minerals mining for fabrication and energy source**

♦ Live off the Land

- **Sunlight (solar power and sails)**
- **Solar Wind (plasma sails)**
- **Earth’s Ionosphere and Magnetic Field (Electrodynamic Tethers)**

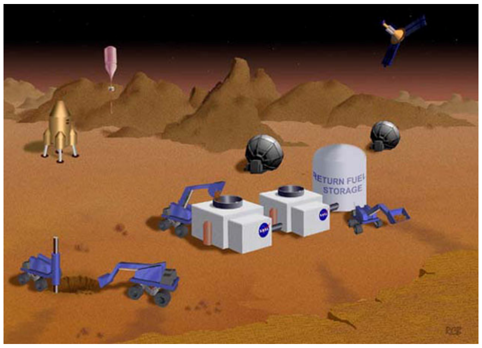




How In-Space Propulsion Can Support In-Space Fabrication and Repair
"Living Off The Land"

In Situ Resource Utilization

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid Term)

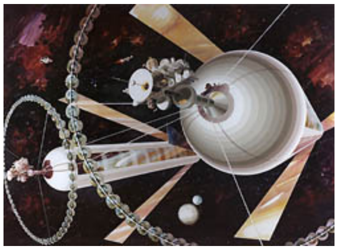


Using a portable laboratory, future robotic missions to Mars could breakdown gases from the atmosphere or process chemicals from the soil to manufacture fuel. This would be used as a propellant to return sample materials to Earth for analysis. A similar technology could derive oxygen and other gases from the atmosphere, to aid future missions by astronauts on visits to remote Martian outposts. Credit: NASA/JPL

- **Propellant can be manufactured in space (on another planet), reducing the need for resupply from Earth**
  - Reduced cost
  - Increased autonomy
- **Propellants that can be manufactured:**
  - **Mars** For immediate propellant needs, H_2 combined with the CO_2 from the Martian atmosphere (which is 95% CO_2) may be used to create an Oxygen-Methane bipropellant mixture.
  - **Moon** Hydrogen and Oxygen from lunar ice can be used for propellant.

Reboost / Drag Makeup of Orbital Manufacturing Facilities (Solar Electric Propulsion)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid Term)

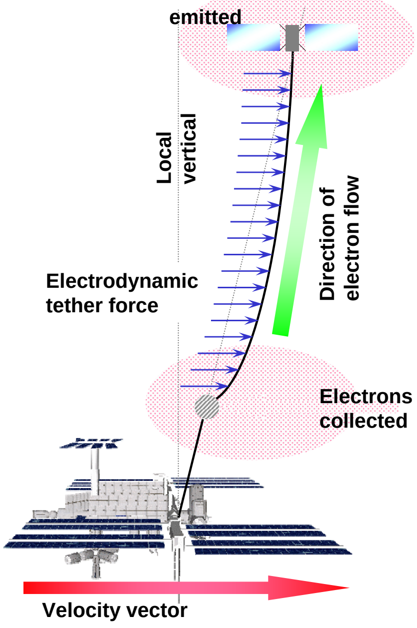


As envisioned by Gerald O'Neil, orbiting space habitats and fabrication facilities will require highly efficient propulsion that minimizes the need for re-supply from Earth.

- **Highly efficient solar electric thrusters can maintain spacecraft in LEO more cost effectively than with conventional chemical propulsion**

Reboost / Drag Makeup of Orbital Manufacturing Facilities (Electrodynamic Tethers)

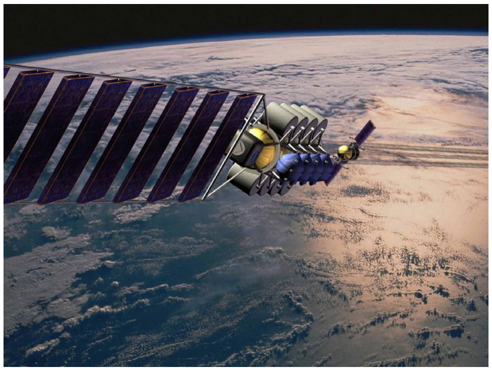
How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid Term)



- **Using the environment of LEO, large facilities can be reboosted electrodynamically, requiring no propellant or resupply**
  - F = I dL **X** B
    - F = Thrust Force
    - I = Current extracted from the ionosphere
    - L = Length of conducting tether
    - B = Earth's magnetic field

Highly Efficient Inter-Orbit Transfer (MXER Tethers)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid-Term)

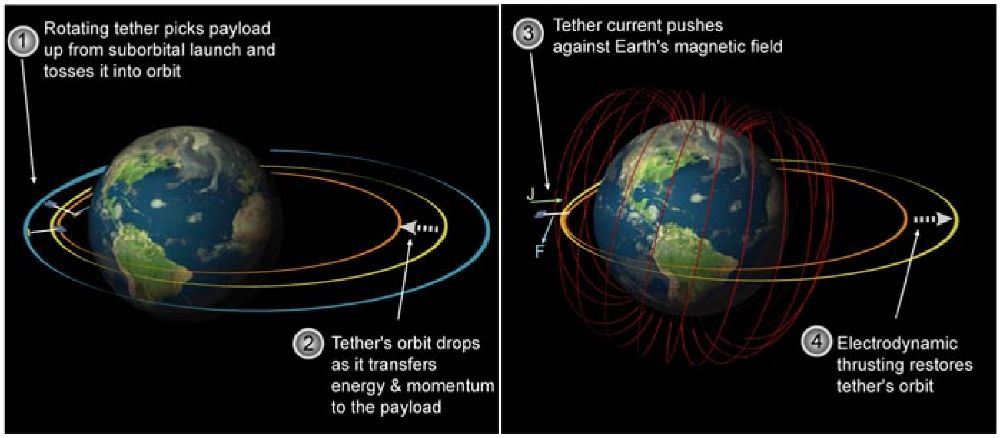


Momentum-Exchange/Electrodynamic-Reboost (MXER) tether systems can provide propellantless propulsion for a wide range of missions, including: orbital maneuvering and stationkeeping within Low Earth Orbit (LEO); orbital transfer of payloads from LEO to GEO, the Moon, and Mars; and eventually even Earth-to-Orbit (ETO) launch assist. By eliminating the need for propellant for in-space propulsion, MXER tethers can enable payloads to be launched on much smaller launch vehicles, resulting in order-of-magnitude reductions in launch costs.

- **Using a network of Momentum Exchange Tethers, large mass payload transfer within the Earth/Moon system may become practical**
  - A long, thin, high-strength cable is deployed in orbit and set into rotation around a central body.
  - The tether facility is placed in an elliptical orbit and its rotation is timed so that the tether is oriented vertically below the central body and swinging backwards when the facility reaches perigee
  - A grapple assembly located at the tether tip can rendezvous with and capture a payload moving in a lower orbit.
  - Half a rotation later, the tether can release the payload, tossing it into a higher energy orbit.

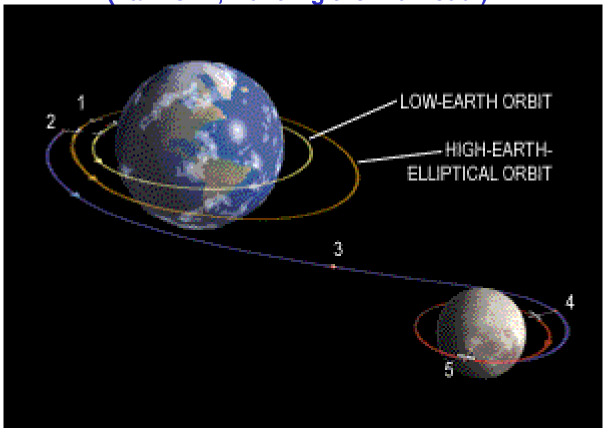
Highly Efficient Inter-Orbit Transfer (MXER Tethers, Continued)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid-Term)



Highly Efficient Inter-Orbit Transfer (MXER Tethers, Continued)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Far-Term; Building the 'Railroad')



LUNAR PAYLOADS could be delivered with a system of three tethers. The package is launched from Earth and is picked up by a tether in low orbit (*below*). This cartwheeling tether hands off the payload to another cartwheeling tether that is in higher orbit (*1*). Like a hunter hurling a rock with a sling, the second tether catapults the payload (*2*) toward the moon (*3*), where it is picked up by another tether in orbit there (*4*). This third cartwheeling tether then deposits the package onto the moon's surface or picks up a payload for the return trip (*5*).

Highly Efficient Inter-Orbit Transfer (Solar Thermal Propulsion)

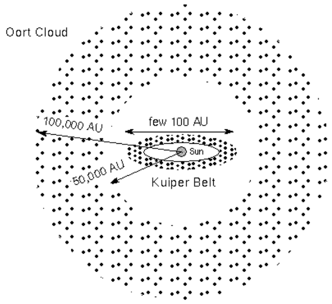
How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid Term)

In a solar/laser thermal rocket, solar or laser light is collected and focused to heat a propellant working fluid such as hydrogen. The collector mirrors are silvered balloon-like inflatable structures or thin sheets of silvered plastic supported by lightweight inflatable trusses. The light passes through a high temperature quartz window or into an open cavity on the side of the engine and focuses to a point to either directly heat the hydrogen propellant or heat a material such as graphite which then heats the hydrogen propellant.

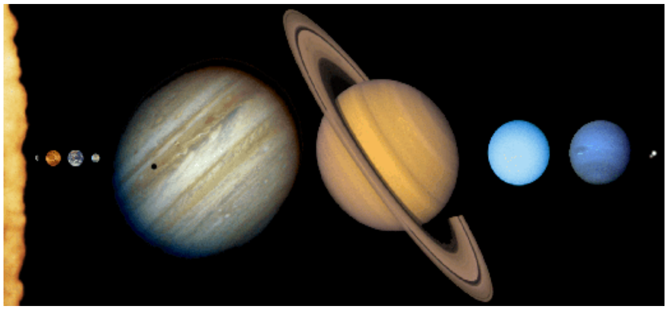
- **The energy of the sun can be focused to heat propellant for an in-space transportation system OR to drive an in-space furnace for large-scale manufacturing**

Deep Space Resource Surveys

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Far Term)



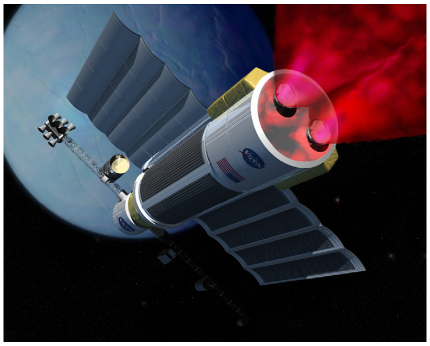
The Oort Cloud and Kuiper Belt (not to scale!). Extent of the two comet reservoirs are indicated. The nearest star is almost three times farther out than the Oort Cloud.



- ♦ **Highly energetic propulsion systems will be required to open the solar system economically**
  - We will need to move people and cargo across vast distances safely, quickly and efficiently
- ♦ **Potential destinations to be surveyed and utilized include:**
  - Asteroids and near-Earth objects
  - Kuiper Belt objects
  - Oort Cloud objects

Deep Space Resource Surveys (Antimatter Propulsion)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Far Term)



- ♦ **Harnessing the energy released when matter and antimatter meet is the key to being able to go "anywhere, anytime"**

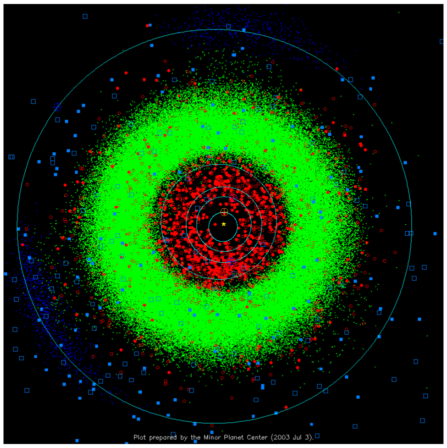
Propulsion Type	Specific Impulse [sec]	Thrust-to-Weight Ratio
Chemical Bipropellant	200 - 410	.1 - 10
Electromagnetic	1200 - 5000	10^{-4} - 10^{-3}
Nuclear Fission	500 - 3000	.01 - 10
Nuclear Fusion	10^{+4} - 10^{+5}	10^{-5} - 10^{-2}
Antimatter Annihilation	10^{+3} - 10^{+6}	10^{-3} - 1

Upon annihilation with matter, antimatter offers the highest energy density of any material currently found on Earth. Antimatter offers the greatest specific impulse of any propellant currently available or in development, and its thrust-to-weight ratio is still comparable with that of chemical propulsion. Simply put, it would take only 100 milligrams of antimatter to equal the propulsive energy of the Space Shuttle.

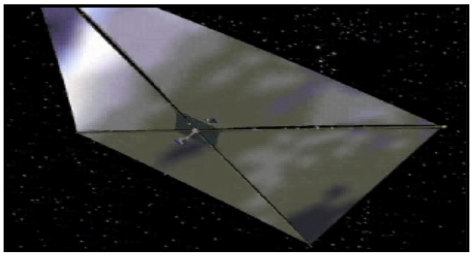
- ♦ **Unfortunately, though antimatter is real, we are far from being able to do this…**

Deep Space Resources
Bringing the Bounty Back Home

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Far Term)



- **Large, low-thrust solar sails could alter the orbit of resource-rich asteroids and divert them to near-Earth space for mining**

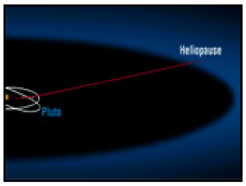


The orbits of the major planets are shown in light blue. The locations of the minor planets, including numbered and multiple-apparition/long-arc unnumbered objects, are indicated by green circles. Objects with perihelia within 1.3 AU are shown by red circles. Objects observed at more than one opposition are indicated by filled circles, objects seen at only one opposition are indicated by outline circles. The two "clouds" of objects 60° ahead and behind Jupiter (and at or near Jupiter's distance from the sun) are Jupiter Trojans, here colored deep blue. Numbered periodic comets are shown as filled light-blue squares. Other comets are shown as unfilled light-blue squares.

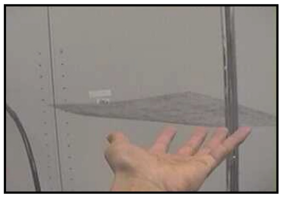
How In-Space Fabrication Can Support The Next Generation of In-Space Propulsion

Large Solar Sails for Interstellar Exploration

How In-Space Fabrication Can Support The Next Generation of In-Space Propulsion



The Heliopause is a barrier which charged particles from the sun cannot go beyond because cosmic rays from deep space force them back.

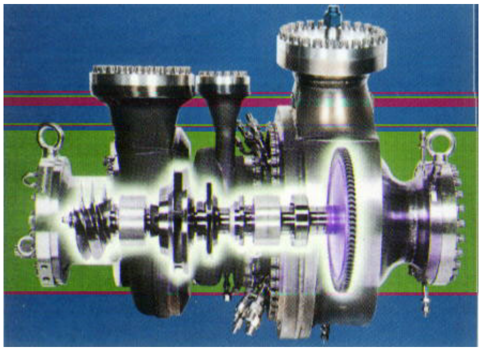


Carbon fiber µ-truss fabric
(1 gm/m², 2 mm thick)

- **Solar sails use solar photon "pressure" or force on a thin, lightweight reflective sheet to produce thrust**
- **Sails with diameters >200m are required to propel spacecraft beyond the edge of the solar system (with reasonable trip times!)**
- **Large (> 200m), light-weight sails (<<1 gm/m²) cannot be built and launched from Earth**
- **Manufacturing them in space provides an alternative**
  - Carbon spun sails
  - Chemical vapor deposition
  - Other???

Rapid Prototyping and Fabrication Using *In-Situ* Resources

How In-Space Fabrication Can Support The Next Generation of In-Space Propulsion



- **Using lunar regolith, it ought to be possible to rapidly cast high-temperature, high-strength components for propulsion systems**

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave Blank)*	**2. REPORT DATE** September 2005	**3. REPORT TYPE AND DATES COVERED** Technical Memorandum

4. TITLE AND SUBTITLE In-Space Propulsion: Connectivity to In-Space Fabrication and Repair	**5. FUNDING NUMBERS**
6. AUTHORS L. Johnson, D. Harris, A. Trausch, G.L. Matloff,* T. Taylor,** and K. Cutting***	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) George C. Marshall Space Flight Center Marshall Space Flight Center, AL 35812	**8. PERFORMING ORGANIZATION REPORT NUMBER** M–1146
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546–0001	**10. SPONSORING/MONITORING AGENCY REPO NUMBER** NASA/TM—2005–214184

11. SUPPLEMENTARY NOTES

Prepared by the In-Space Propulsion Technology Office, Space Transportation Programs/Projects Office
*New York City College of Technology, Brooklyn, NY, **BAE Systems, Huntsville, AL, ***Gray Research, Huntsville, AL

12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category 16 Availability: NASA CASI 301–621–0390	**12b. DISTRIBUTION CODE**

13. ABSTRACT *(Maximum 200 words)*

The connectivity between new in-space propulsion technologies and the ultimate development of an in-space fabrication and repair infrastructure are described in this Technical Memorandum. A number of advanced in-space propulsion technologies are being developed by NASA, many of which are directly relevant to the establishment of such an in-space infrastructure. These include aerocapture, advanced solar-electric propulsion, solar-thermal propulsion, advanced chemical propulsion, tethers, and solar photon sails. Other, further-term technologies have also been studied to assess their utility to the development of such an infrastructure.

14. SUBJECT TERMS in-space propulsion, in-space fabrication, solar sails tethers, aerocapture	**15. NUMBER OF PAGES** 60
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** Unlimited

National Aeronautics and
Space Administration
IS04
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812