



Space Technologies & Advancements

Angel Cathey

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Space Colonization



Artist Les Bossinas' 1989 concept of Mars mission

Space Colonization (space settlement, space humanization, space habitation) is autonomous (self-sufficient) human habitation outside of Earth. It is a long-term goal of national space programs.

The first space colony may be on the Moon, or on Mars. Ample quantities of all the necessary materials, such as solar energy and water, are on the Moon, Mars, or near Earth asteroids.

In 2005 NASA Administrator Michael Griffin identified space colonization as the ultimate goal of current spaceflight programs, saying:

... the goal isn't just scientific exploration ... it's also about extending the range of human habitat out from Earth into the solar system as we go forward in time ... In the long run a single-planet species will not survive ... If we humans want to survive for hundreds of thousands or millions of years, we must ultimately populate other planets. Now, today the technology is such that this is barely conceivable. We're in the infancy of it. ... I'm talking about that one day, I don't know when that day is, but there will be more human beings who live off the Earth than on it. We may well have people living on the moon. We may have people living on the moons of Jupiter and other planets. We may have people making habitats on asteroids ... I know that humans will colonize the solar system and one day go beyond.

– *Michael D. Griffin*

The NASA Lunar outpost, providing a permanent human presence on the moon, is at the planning stage. There is an ongoing development of technologies that may be used in future space colonization projects.

Method

Building colonies in space would require access to water, food, space, people, construction materials, energy, transportation, communications, life support, simulated gravity, and radiation protection. It is likely the colonies would be located by proximity to such resources. The practice of space architecture seeks to transform spaceflight from a heroic test of human endurance to a normality within the bounds of comfortable experience.

Materials

Colonies on the Moon, Mars, or asteroids could extract local materials. The moon is deficient in volatiles such as argon, helium and compounds of carbon, hydrogen and nitrogen. The LCROSS impactor was targeted at the Cabeus crater which was chosen as having a high concentration of water for the moon. A plume of material erupted in which some water was detected. Anthony Colaprete estimated that the Cabeus crater contains material with 1% water or possibly more. Water ice should also be in other permanently shadowed craters near the lunar poles. Although helium is present only in low concentrations on the moon, where it is deposited into regolith by the solar wind, an estimated million tons of He3 exists over all. It also has industrially significant oxygen, silicon, and metals such as iron, aluminum, and titanium. Launching materials from Earth is expensive, so bulk materials could come from the Moon, a Near-Earth Object (NEO— an asteroid or comet with an orbit near Earth), Phobos, or Deimos, where gravitational forces are much smaller, there is no atmosphere, and there is no biosphere to damage. Many NEOs contain substantial amounts of metals, oxygen, hydrogen, and carbon. Certain NEOs may contain nitrogen.

Farther out, Jupiter's Trojan asteroids are thought to be high in water ice and probably other volatiles.

Energy

Solar energy in orbit is abundant, reliable, and is commonly used to power satellites today. There is no night in space, and no clouds or atmosphere to block sunlight. The solar energy available at any distance, d , from the Sun can be calculated by the formula $E = 1367/d^2$ watts per square meter, where d is measured in astronomical units.

Particularly in the weightless conditions of space, sunlight can be used directly, using large solar ovens made of lightweight metallic foil so as to generate thousands of degrees of heat; or reflected onto crops to enable photosynthesis to proceed.

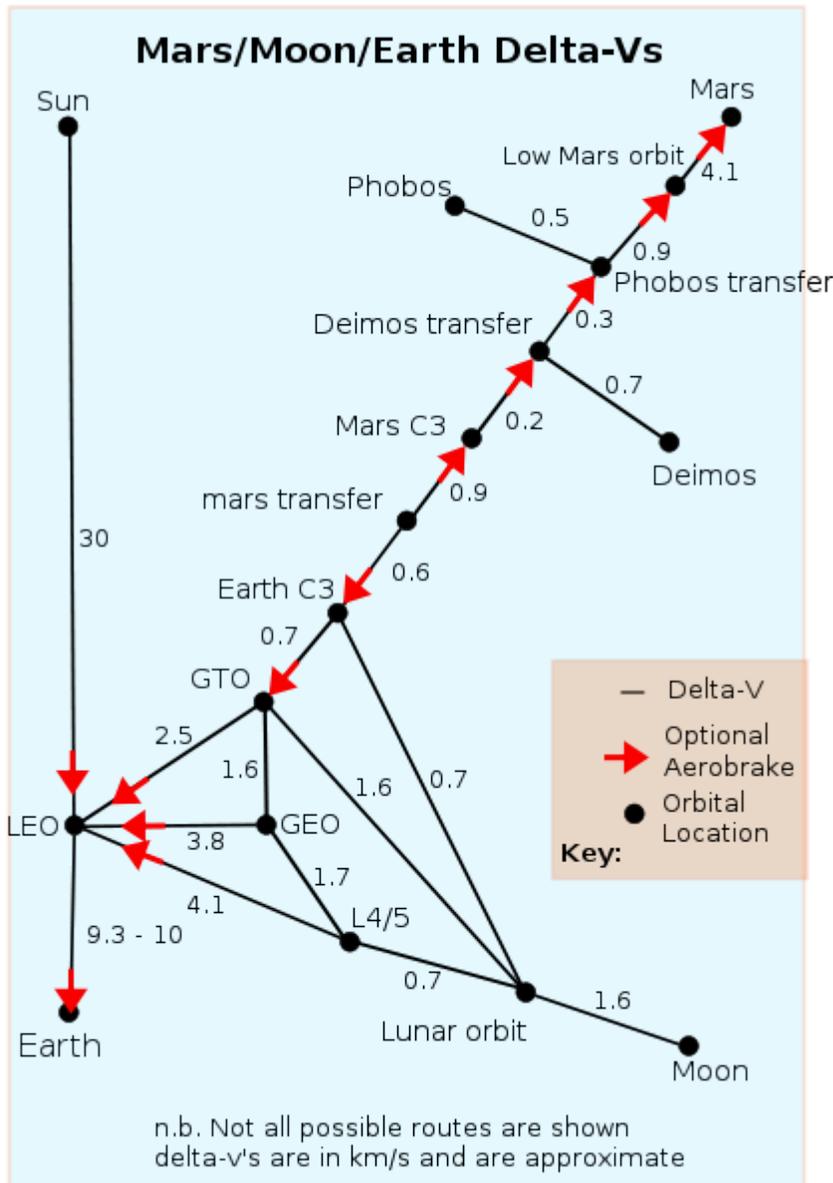
Large structures would be needed to convert sunlight into significant amounts of electrical power for settlers' use. In highly electrified nations on Earth, electrical consumption can average 1 kilowatt/person (or roughly 10 megawatt-hours per person per year.)

Energy may be an eventual export item for space settlements, perhaps using wireless power transmission e.g. via microwave beams to send power to Earth or the Moon. This method has zero emissions, so would have significant benefits such as elimination of greenhouse gases and nuclear waste. Ground area required per watt would be less than conventional solar panels.

The Moon has nights of two Earth weeks in duration and Mars has night, dust, and is farther from the Sun, reducing solar energy available by a factor of about $\frac{1}{2}$ - $\frac{2}{3}$, and possibly making nuclear power more attractive on these bodies. Alternatively, energy could be transmitted to the lunar and martian surfaces from solar power satellites.

For both solar thermal and nuclear power generation in airless environments, such as the Moon and space, and to a lesser extent the very thin Martian atmosphere, one of the main difficulties is dispersing the inevitable heat generated. This requires fairly large radiator areas.

Transportation



Delta-v's in km/s for various orbital maneuvers using conventional rockets. Red arrows show where optional aerobraking can be performed in that particular direction, black numbers give delta-v in km/s that apply in either direction.

Space access

Transportation to orbit is often the limiting factor in space endeavours. To settle space, much cheaper launch vehicles are required, as well as a way to avoid serious damage to the atmosphere from the thousands, perhaps millions, of launches required. One possibility is the air-breathing hypersonic spaceplane under development by NASA and

other organizations, both public and private. There are also proposed projects such as building a space elevator or a mass driver; or launch loops.

Cislunar and solar system travel

Transportation of large quantities of materials from the Moon, Phobos, Deimos, and Near Earth asteroids to orbital settlement construction sites is likely to be necessary.

Transportation using off-Earth resources for propellant in conventional rockets would be expected to massively reduce in-space transportation costs compared to the present day. Propellant launched from the Earth is likely to be prohibitively expensive for space colonization, even with improved space access costs.

Other technologies such as tether propulsion, VASIMR, ion drives, solar thermal rockets, solar sails, magnetic sails, and nuclear thermal propulsion can all potentially help solve the problems of high transport cost once in space.

For lunar materials, one well-studied possibility is to build mass drivers to launch bulk materials to waiting settlements. Alternatively, lunar space elevators might be employed.

Communication

Compared to the other requirements, communication is easy for orbit and the Moon. A great proportion of current terrestrial communications already passes through satellites. Yet, as colonies further from the earth are considered, communication becomes more of a burden. Transmissions to and from Mars suffer from significant delays due to the speed of light and the greatly varying distance between conjunction and opposition — the lag will range between 7 and 44 minutes — making real-time communication impractical. Other means of communication that do not require live interaction such as e-mail and voice mail systems should pose no problem.

Life support

In space settlements, a closed ecological system must recycle or import all the nutrients without "crashing." The closest terrestrial analogue to space life support is possibly that of the nuclear submarine. Nuclear submarines use mechanical life support systems to support humans for months without surfacing, and this same basic technology could presumably be employed for space use. However, nuclear submarines run "open loop"— extracting oxygen from seawater, and typically dumping carbon dioxide overboard, although they recycle existing oxygen. Recycling of the carbon dioxide has been approached in the literature using the Sabatier process or the Bosch reaction.

The Biosphere 2 project in Arizona has shown that a complex, small, enclosed, man-made biosphere can support eight people for at least a year, although there were many problems. A year or so into the two-year mission oxygen had to be replenished, which strongly suggests that they achieved atmospheric closure.

The relationship between organisms, their habitat and the non-Earth environment can be:

- Organisms and their habitat fully isolated from the environment (examples include artificial biosphere, Biosphere 2, life support system)
- Changing the environment to become a life-friendly habitat, a process called terraforming.
- Changing organisms to become more compatible with the environment

A combination of the above technologies is also possible.

97–99% of the light energy provided to the plant ends up as heat and needs to be dissipated somehow to avoid overheating the habitat.

Radiation protection

Cosmic rays and solar flares create a lethal radiation environment in space. In Earth orbit, the Van Allen belts make living above the Earth's atmosphere difficult. To protect life, settlements must be surrounded by sufficient mass to absorb most incoming radiation. About five to ten tons of material per square meter of surface area is required. This can be leftover material (slag) from processing lunar soil and asteroids into oxygen, metals, and other useful materials, however it represents a significant obstacle to maneuvering vessels with such massive bulk. Inertia would necessitate powerful thrusters to start or stop rotation, or electric motors to spin two massive portions of a vessel in opposite senses. Shielding material can be stationary around a rotating interior. Hull-metals can also be magnetized to provide additional protection without adding mass.

Self-replication

Self-replication is an optional attribute, but some think it the ultimate goal because it allows a much more rapid increase in colonies, while eliminating costs to and dependence on Earth. It could be argued that the establishment of such a colony would be Earth's first act of self-replication. Intermediate goals include colonies that expect only information from Earth (science, engineering, entertainment) and colonies that just require periodic supply of light weight objects, such as integrated circuits, medicines, genetic material and tools.

Population size

In 2002, the anthropologist John H. Moore estimated that a population of 150–180 would allow normal reproduction for 60 to 80 generations — equivalent to 2000 years.

A much smaller initial population of as little as two female humans should be viable as long as human embryos are available from Earth. Use of a sperm bank from Earth also allows a smaller starting base with negligible inbreeding.

Researchers in conservation biology have tended to adopt the "50/500" rule of thumb initially advanced by Franklin and Soule. This rule says a short-term effective population size (N_e) of 50 is needed to prevent an unacceptable rate of inbreeding, while a long-term N_e of 500 is required to maintain overall genetic variability. The $N_e = 50$ prescription corresponds to an inbreeding rate of 1% per generation, approximately half the maximum rate tolerated by domestic animal breeders. The $N_e = 500$ value attempts to balance the rate of gain in genetic variation due to mutation with the rate of loss due to genetic drift.

Location

Location is a frequent point of contention between space colonization advocates.

The location of colonization can be on a physical body or free-flying:

- On a planet, natural satellite, or asteroid
- In orbit around the Earth, Sun, Lagrangian point or other object

Planetary locations

Some planetary colonization advocates cite the following potential locations:

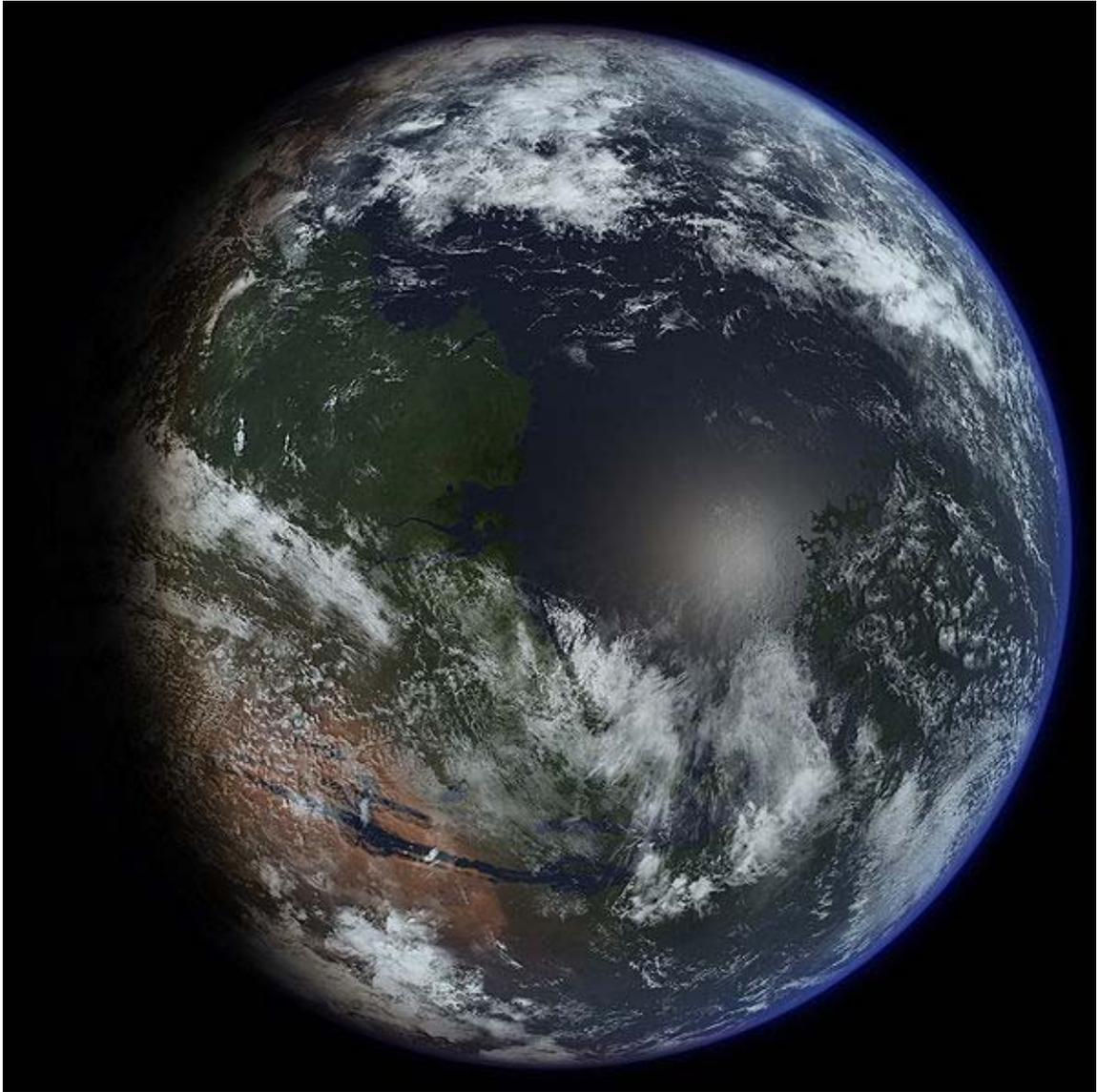
Mars

The surface of Mars is about the same size as the dry land surface of Earth. The ice in Mars' south polar cap, if spread over the planet, would be a layer 12 meters (39 feet) thick and there is carbon (locked as carbon dioxide in the atmosphere).

Mars may have gone through similar geological and hydrological processes as Earth and therefore contain valuable mineral ores. Equipment is available to extract *in situ* resources (e.g., water, air) from the Martian ground and atmosphere. There is interest in colonizing Mars in part because life could have existed on Mars at some point in its history, and may even still exist in some parts of the planet.

However, its atmosphere is very thin (averaging 800 Pa or about 0.8% of Earth sea-level atmospheric pressure); so the pressure vessels necessary to support life are very similar to deep space structures. The climate of Mars is colder than Earth's. Its gravity is only around a third that of Earth's; it is unknown whether this is sufficient to support human beings for extended periods (all long-term human experience to date has been at around Earth gravity or one g).

The atmosphere is thin enough, when coupled with Mars' lack of magnetic field, that radiation is more intense on the surface, and protection from solar storms would require radiation shielding.



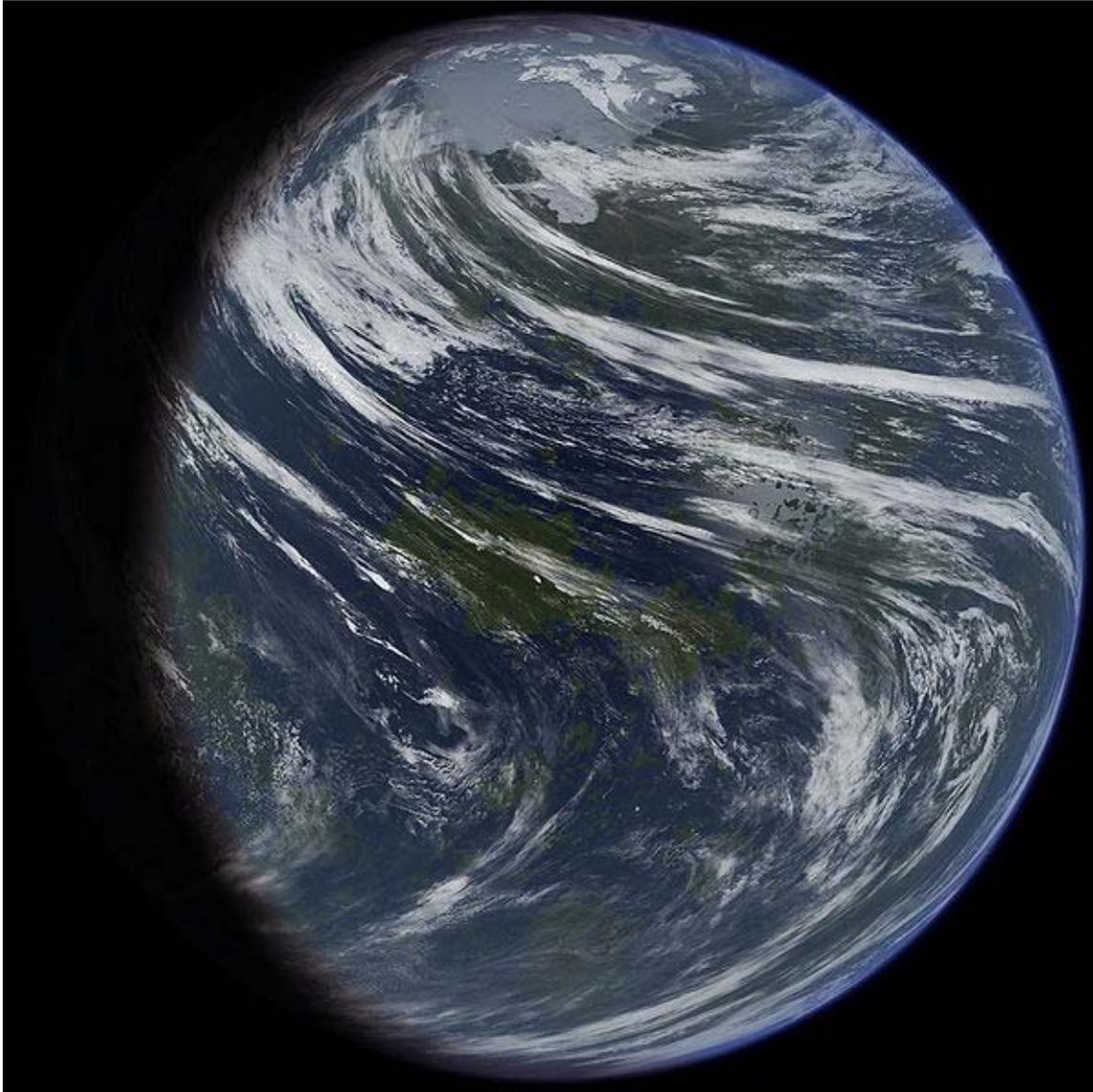
An artist's conception of a terraformed Mars (2009)

Terraforming Mars would make life outside of pressure vessels on the surface possible. There is some discussion of it actually being done.

Mercury

There is a suggestion that Mercury could be colonized using the same technology, approach and equipment that is used in colonization of the Moon. Such colonies would almost certainly be restricted to the polar regions due to the extreme daytime temperatures elsewhere on the planet. The recent discovery of ionized water has astounded scientists. This discovery significantly improves the small planet's prospects as a future colony.

Venus



Artist's impression of a terraformed Venus

While the surface of Venus is far too hot and features atmospheric pressure at least 90 times that at sea level on Earth, its massive atmosphere offers a possible alternate location for colonization. At an altitude of approximately 50 km, the pressure is reduced to a few atmospheres, and the temperature would be between 40–100 °C, depending on the altitude. This part of the atmosphere is probably within dense clouds which contain some sulfuric acid. Even these may have a certain benefit to colonization, as they present a possible source for the extraction of water.

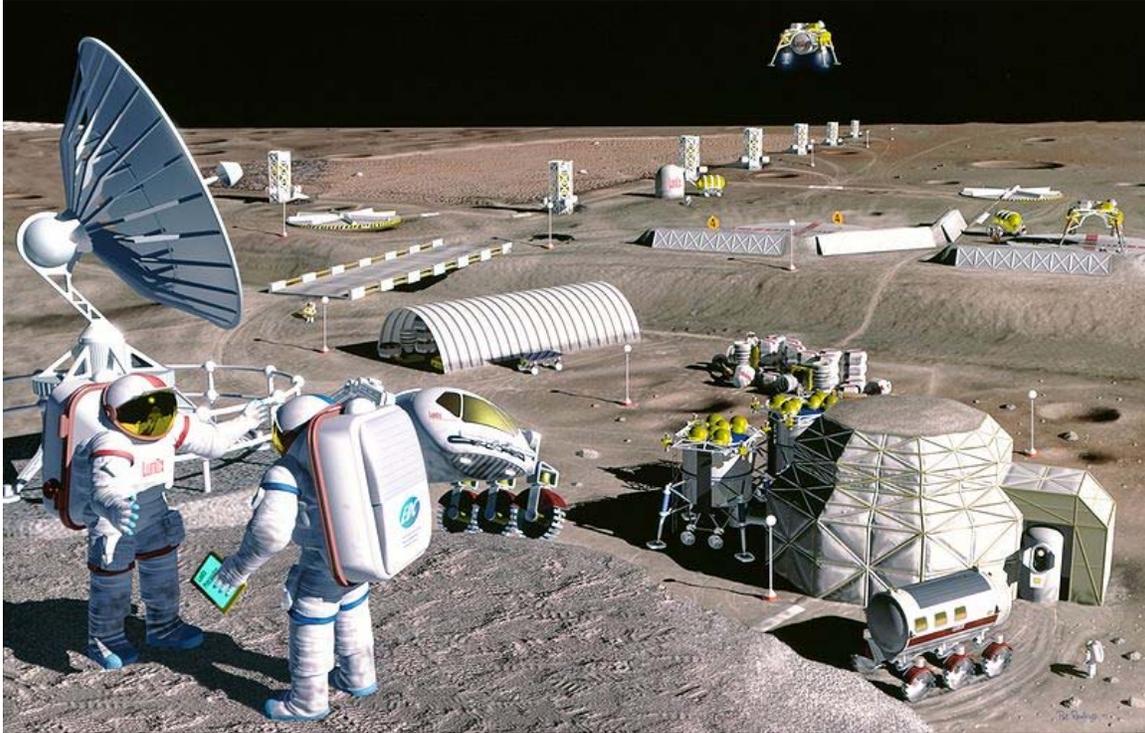
Gas giants

It may be possible to colonize the three farthest gas giants with floating cities in their atmospheres. By heating hydrogen balloons, large masses can be suspended underneath at roughly Earth gravity. A human colony on Jupiter would be less practical due to its high gravity, escape velocity and radiation. Such colonies could export Helium-3 for use in fusion reactors if they ever become practical. Escape from the gas giant planets (especially Jupiter) seems well beyond current or near-term foreseeable chemical rocket technology however, due to the combination of large velocity and high acceleration needed even to achieve low orbit.

Paul Birch suggested a method of colonizing the gas giants that did not use buoyancy to support the colony in the atmosphere. He suggested a strip colony extending completely around the planet. It would rotate at the same speed as the planetary atmosphere at the equator and be held above the atmosphere by rotating mass internal to the strip and connected to the strip by only magnetic force. This rotating mass would be isolated from the strip colony by a vacuum. The extent of the strip colony could be such that the bottom edge is within the atmosphere for communication with the planet and extraction of raw materials. In the vacuum environment outside the top edge of the strip, electromagnetic acceleration to or from orbital velocity would provide communication with interplanetary space. This sort of colony would be especially suitable for Saturn, Uranus and Neptune for which the gravitational attraction at the altitude of the visible atmosphere is near one Earth gravity. A robotic levitated equatorial strip colony at Jupiter could allow the extraction of raw materials from that planet.

Satellite locations

The Moon



Moon colony (1995)

Due to its proximity and familiarity, Earth's Moon is discussed as a target for colonization. It has the benefits of proximity to Earth and lower escape velocity, allowing for easier exchange of goods and services. A drawback of the Moon is its low abundance of volatiles necessary for life such as hydrogen, nitrogen, and carbon. Water ice deposits that exist in some polar craters could serve as a source for these elements. An alternative solution is to bring hydrogen from near earth asteroids and combine it with oxygen extracted from lunar rock.

The moon's low surface gravity is also a concern (it is unknown whether $1/6g$ is sufficient to support human habitation for long periods).

Jovian moons - Europa, Callisto and Ganymede

The Artemis Project designed a plan to colonize Europa, one of Jupiter's moons. Scientists were to inhabit igloos and drill down into the European ice crust, exploring any sub-surface ocean. This plan discusses possible use of "air pockets" for human habitation. Europa is considered one of the more habitable bodies in the solar system and so merits investigation as a possible abode for life.

Ganymede is the largest moon in the Solar System. It may be attractive as Ganymede is the only moon with a magnetosphere and so is less irradiated at the surface. The presence of magnetosphere, likely indicates a convecting molten core within Ganymede, which may in turn indicate a rich geologic history for the moon.

NASA performed a study called *HOPE* (Revolutionary Concepts for **H**uman **O**uter **P**lanet **E**xploration) regarding the future exploration of the solar system. The target chosen was Callisto. It could be possible to build a surface base that would produce fuel for further exploration of the solar system.

The three out of four largest moons of Jupiter (Europa, Ganymede and Callisto) have an abundance of volatiles making future colonization possible.

Phobos and Deimos

The moons of Mars may be a target for space colonization. Low delta-v is needed to reach the Earth from Phobos and Deimos, allowing delivery of material to cislunar space, as well as transport around the Martian system. The moons themselves may be suitable for habitation, with methods similar to those for asteroids.

Titan, Enceladus and other Saturnian moons

Titan is suggested as a target for colonization, because it is the only moon in our solar system to have a dense atmosphere and is rich in carbon-bearing compounds. Robert Zubrin identified Titan as possessing an abundance of all the elements necessary to support life, making Titan perhaps the most advantageous locale in the outer Solar System for colonisation, and saying "In certain ways, Titan is the most hospitable extraterrestrial world within our solar system for human colonisation".

Enceladus is a small, icy moon orbiting close to Saturn, notable for its extremely bright surface and the geyser-like plumes of ice and water vapor that erupt from its southern polar region. If Enceladus has liquid water, it joins Mars and Jupiter's moon Europa as one of the prime places in the solar system to look for extraterrestrial life and possible future settlements.

Other large satellites: Rhea, Iapetus, Dione, Tethys and Mimas, all have large quantities of volatiles, which can be used to support settlement.

Moons of Uranus, Neptune's Triton and beyond

The five large moons of Uranus (Miranda, Ariel, Umbriel, Titania and Oberon) and Triton - Neptune's moon, although very cold, have large amounts of frozen water and other volatiles and could potentially be settled, only they would require a lot of nuclear power to sustain the habitats. Triton's thin atmosphere also contains some nitrogen and even some frozen nitrogen on the surface (the surface temperature is 38 K or about -391° Fahrenheit). Pluto is estimated to have a very similar structure to Triton.

Asteroids

Near Earth Asteroids

Many small asteroids in orbit around the Sun have the advantage that they pass closer than Earth's moon several times per decade. In between these close approaches to home, the asteroid may travel out to a furthest distance of some 350,000,000 kilometers from the Sun (its aphelion) and 500,000,000 kilometers from Earth.

Main Belt Asteroids

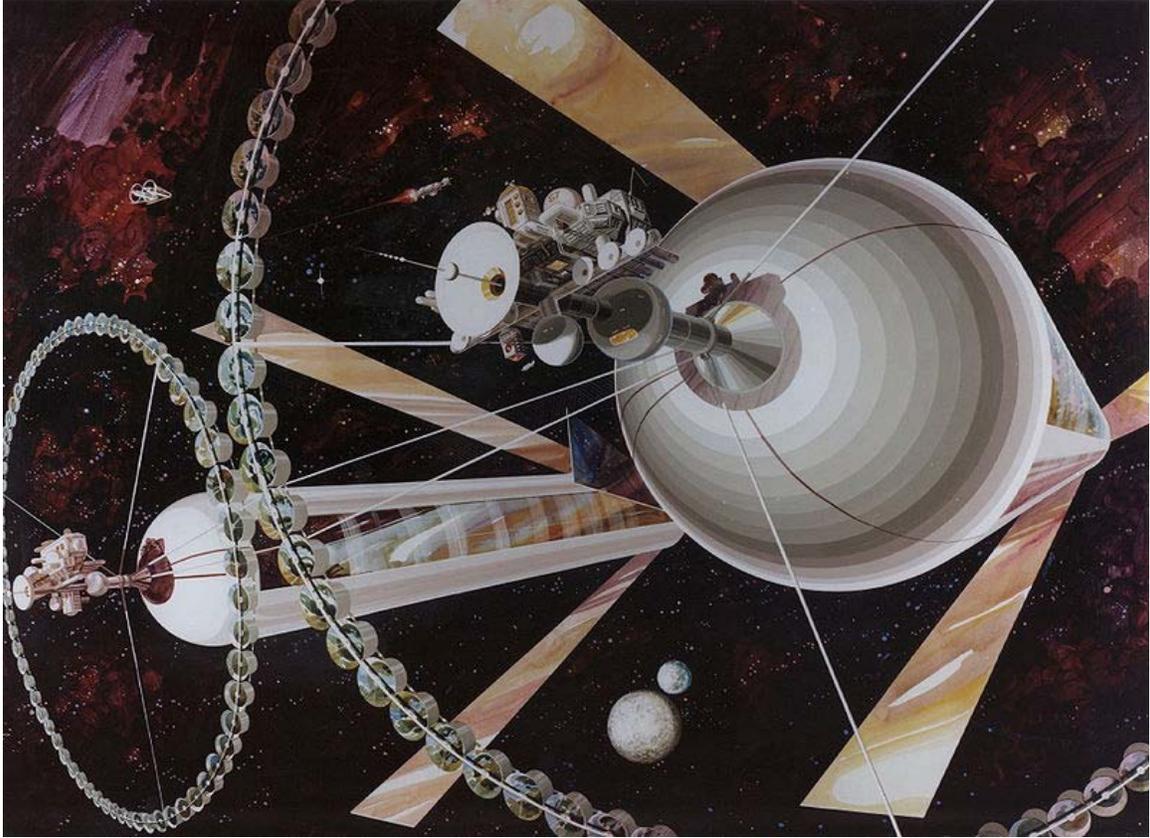
Colonization of asteroids would require space habitats. The asteroid belt has significant overall material available, the largest object being Ceres, although it is thinly distributed as it covers a vast region of space. Unmanned supply craft should be practical with little technological advance, even crossing 1/2 billion kilometers of cold vacuum. The colonists would have a strong interest in assuring that their asteroid did not hit Earth or any other body of significant mass, but would have extreme difficulty in moving an asteroid of any size. The orbits of the Earth and most asteroids are very distant from each other in terms of delta-v and the asteroidal bodies have enormous momentum. Rockets or mass drivers can perhaps be installed on asteroids to direct their path into a safe course.

Ceres

Ceres is a dwarf planet in the main asteroid belt, comprising about one third the mass of the whole belt and being the sixth largest body in the inner Solar System by mass and volume. Being the largest body in the asteroid belt, Ceres could become the main base and transport hub for future asteroid mining infrastructure, allowing mineral resources to be transported further to Mars, the Moon and Earth.

Free space

Space habitats



O'Neill cylinders space colony (Island Three design from the 1970s)



Artist's conception of a space habitat called the Stanford torus, by Don Davis (1976).

Locations in space would necessitate a space habitat, also called space colony and orbital colony, or a space station which would be intended as a permanent settlement rather than as a simple waystation or other specialized facility. They would be literal "cities" in space, where people would live and work and raise families. Many designs have been proposed with varying degrees of realism by both science fiction authors and scientists.

A space habitat would serve as a proving ground for a generation ship which could function as a long-term home for hundreds or thousands of people. Such a space habitat could be isolated from the rest of humanity but near enough to Earth for help. This would test if thousands of humans can survive on their own before sending them beyond the reach of help.

Earth orbit

Compared to other locations, Earth orbit has substantial advantages and one major, but solvable, problem. Orbits close to Earth can be reached in hours, whereas the Moon is days away and trips to Mars take months. There is ample continuous solar power in high Earth orbits, whereas all planets lose sunlight at least half the time. Weightlessness makes construction of large colonies considerably easier than in a gravity environment.

Astronauts have demonstrated moving multi-ton satellites by hand. 0g recreation is available on orbital colonies, but not on the Moon or Mars. Finally, the level of (pseudo-) gravity is controlled at any desired level by rotating an orbital colony. Thus, the main living areas can be kept at 1 g, whereas the Moon has 1/6 g and Mars 1/3 g. It's not known what the minimum g-force is for ongoing health but 1 g is known to ensure that children grow up with strong bones and muscles.

The main disadvantage of orbital colonies is lack of materials. These may be expensively imported from the Earth, or more cheaply from extraterrestrial sources, such as the Moon (which has ample metals, silicon, and oxygen), Near Earth Asteroids, comets, or elsewhere. Other disadvantages of orbital colonies are orbital decay, and atmospheric pollution in the case of Earth.

As of 2009, the International Space Station provides a temporary, yet still non-autonomous, human presence in Low Earth orbit.

Lagrange points

Lagrange point colonization is the colonization of the five equilibrium points in the orbit of a planet or its primary moon, called Lagrange points. The most obvious points for colonization are the points in the Earth-Moon system and the points in the Sun-Earth system. Although it would generally take days or even months to reach with current technology, many of these points would have near-continuous solar power capability since their distance from Earth would result in only brief and infrequent eclipses of light from the Sun.

Earth-Moon

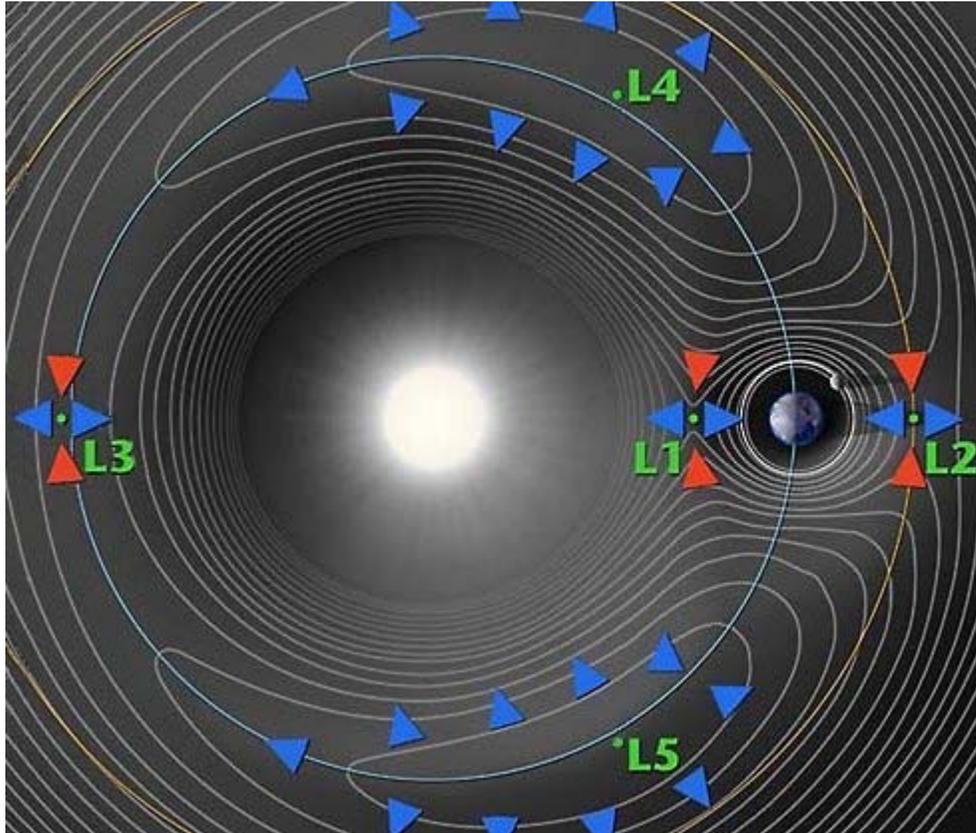
An L_1 station would have a number of important functions due to its stationary position between the Earth and Moon. One, it is in a perfect location to monitor and coordinate communications among various missions on the nearside of the Moon. A vessel launched from L_1 could reach any place on the Moon within a few hours to a day. This would make it ideal for crisis management if an emergency occurred on the Moon. Furthermore, it could serve as a way station, especially once built up, and would probably be used to handle tourists and casual visitors to the Moon. A station like this could also serve as a repair center for ships moving throughout the Solar System.

The L_2 point, on the far side of the Moon, is completely shielded from the Earth by the Moon so radio telescopes placed there would receive much less interference than existing telescopes. Of course, since the moon is tide locked, any colony on the far side of the moon has this same benefit; a lunar facility, however, would suffer from "moonquakes".

Both L_1 and L_2 require active stationkeeping since neither is fully stable. Colonies at the L_4 and L_5 positions would have the advantage of being stable without any need for stationkeeping, and could be used as a waypoint for travel to and from cislunar space.

In addition, they would significantly reduce the delta-V (velocity change) needed to move from one to another, or to enter or leave Earth orbit, an important drawback of any Lunar surface station, which demands high energy expenditure to escape and comparable or greater amount to soft-land.

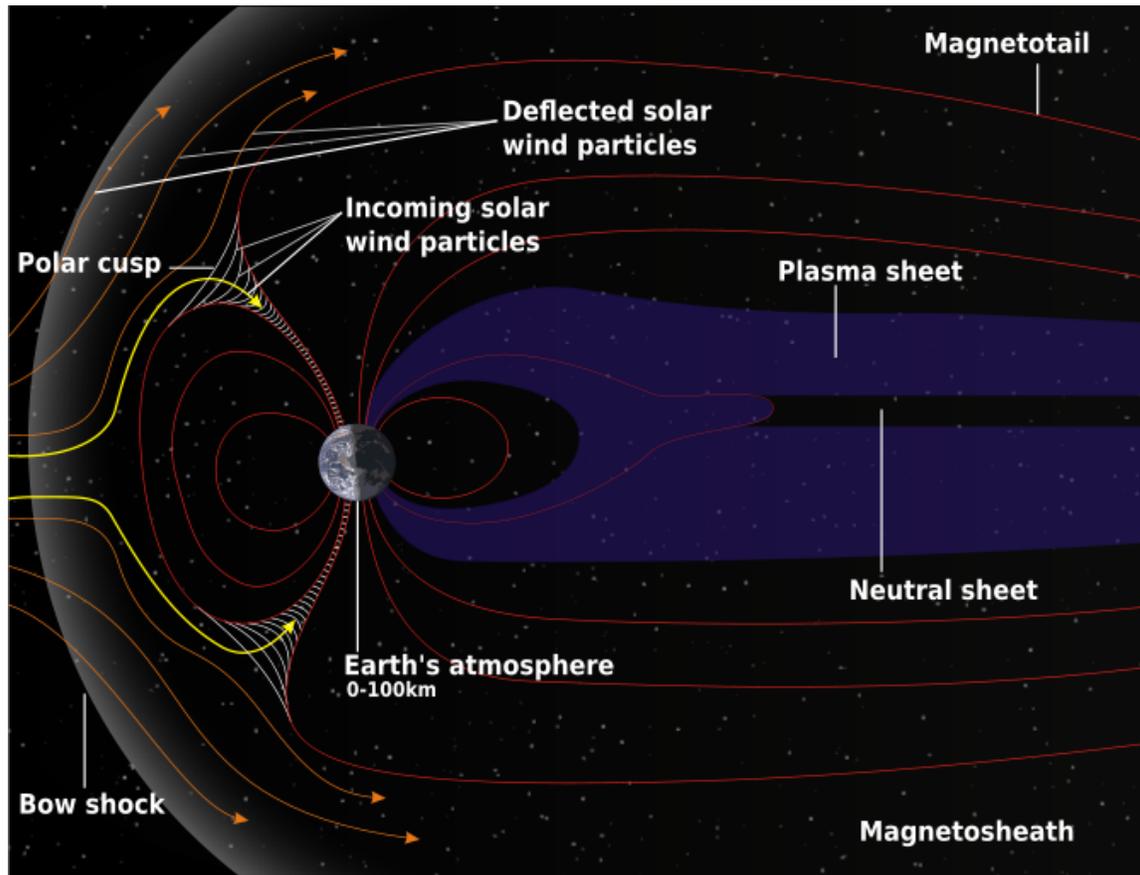
Sun-Earth



Contour lines of the effective potential illustrate the 5 Lagrange points of the Sun-Earth system.

The L_1 position is useful for solar observations since it is near the Earth but in constant sunlight. It could also be useful for collecting solar power. Conversely, the L_2 point is perpetually in the shadow of the Earth, and as such offers a prime location for observing the outer planets or deep space. L_4 and L_5 colonies could be used as waypoints in space travel, to expand the practical launch window for travel to and from the Earth and other planets. These positions are useful for colonies as they are stable without any need for stationkeeping.

Disadvantages



Schematic of Earth's magnetosphere. The solar wind flows from left to right.

The risk of proton exposure from the solar wind as well as the health threat from cosmic rays is significant. In the Earth-Moon system, the orbit of colonies at L_1 - L_5 will take them outside of the protection of the Earth's magnetosphere for approximately two-thirds of the time (as occurs with the Moon). Colonies at L_1 (located between the Earth and Moon) will experience this to a lesser degree while L_2 (located beyond the Moon) will experience this to a greater degree and all of them will be exposed to the little understood plasma sheet of the magnetotail.

In the Sun-Earth system, L_1 and L_3 - L_5 are all outside of the protection of the Earth's magnetosphere. L_2 periodically transfers from within the magnetotail, plasma sheet, and solar wind depending on the intensity and direction of the solar wind.

Statites

Statites or "static satellites" employ solar sails to position themselves in orbits that gravity alone could not accomplish. Such a solar sail colony would be free to ride solar radiation pressure and travel off the ecliptic plane. Navigational computers with an advanced understanding of flocking behavior could organize several statite colonies into the beginnings of the true "swarm" concept of a Dyson sphere.

Outside the solar system

Looking beyond our solar system, there are billions of potential suns with possible colonization targets.

The long-term survival of the human race is at risk as long as it is confined to a single planet. Sooner or later, disasters such as an asteroid collision or nuclear war could wipe us all out. But once we spread out into space and establish independent colonies, our future should be safe. There isn't anywhere like the Earth in the solar system, so we would have to go to another star.

– *Stephen Hawking, Physicist*

Interstellar travel

Many scientific papers have been published about interstellar travel. Given sufficient travel time and engineering work, both unmanned and generational voyages seem possible, though representing a very considerable technological and economic challenge unlikely to be met for some time, particularly for manned probes.

The main difficulty is the vast distances that have to be covered. This means that a very high speed is needed. Otherwise, the time involved, with most realistic propulsion methods, would be from decades to millennia. Hence an interstellar ship would be much more severely exposed to the hazards found in interplanetary travel, including hard vacuum, radiation, weightlessness, and micrometeoroids.

Intergalactic travel

Intergalactic travel, as it pertains to humans, is impractical by modern engineering ability and is considered highly speculative. It would require the available means of propulsion to become advanced far beyond what is currently thought possible to engineer in order to bring a large craft close to the speed of light. Unless the craft were capable of reaching extreme relativistic speeds, another obstacle would be to navigate the spacecraft between galaxies and succeed in reaching any chosen galaxy, star, planet or other body, as this would need an improvement over current understanding of galactic movements and their coordination. The craft would have to be of considerable size, without reaching speeds with noteworthy relativistic effect as mentioned above it would also need a life support system and structural design able to support human life through thousands of generations

and last the millions of years required, including the propulsion system—which would have to work perfectly the millions of years after it was built to slow down the machine for its final approach. Even for unmanned probes which would be much lighter in mass, the problem exists that the information they send can only travel at light speed, which would mean millions of years just to receive the data they send.

Current physics states that an object within space-time cannot exceed the speed of light, which seemingly limits any object to the millions of years it would at best take for a craft traveling near the speed of light to reach any remote galaxy. Science fiction frequently employs speculative concepts such as wormholes and hyperspace as more practical means of intergalactic travel to work around this issue. However, some scientists are optimistic in regard to future research into techniques considered even in concept sheer science fiction in the past.

Starship

Space colonization technology could in principle allow human expansion at high, but sub-relativistic speeds, substantially less than the speed of light, c . An interstellar colony ship would be similar to a space habitat, with the addition of major propulsion capabilities and independent energy generation. Hypothetical starship concepts proposed both by scientists and in hard science fiction include:

- A generation ship would travel much slower than light, with consequent interstellar trip times of many decades or centuries. The crew would go through generations before the journey is complete, so that none of the initial crew would be expected to survive to arrive at the destination, assuming current human lifespans.
- A sleeper ship, in which most or all of the crew spend the journey in some form of hibernation or suspended animation, allowing some or all who undertake the journey to survive to the end.
- An Embryo-carrying Interstellar Starship (EIS), much smaller than a generation ship or sleeper ship, transporting human embryos or DNA in a frozen or dormant state to the destination. (Obvious biological and psychological problems in birthing, raising, and educating such voyagers, neglected here, may not be fundamental.)
- A nuclear fusion or fission powered ship (e.g., ion drive) of some kind, achieving velocities of up to perhaps 10% c permitting one-way trips to nearby stars with durations comparable to a human lifetime.
- A Project Orion-ship, a nuclear-powered concept proposed by Freeman Dyson which would use nuclear explosions to propel a starship. A special case of the preceding nuclear rocket concepts, with similar potential velocity capability, but possibly easier technology.
- Laser propulsion concepts, using some form of beaming of power from the Solar System might allow a light-sail or other ship to reach high speeds, comparable to those theoretically attainable by the fusion-powered electric rocket, above. These methods would need some means, such as supplementary nuclear propulsion, to

stop at the destination, but a hybrid (light-sail for acceleration, fusion-electric for deceleration) system might be possible.

The above concepts all appear limited to high, but still sub-relativistic speeds, due to fundamental energy and reaction mass considerations, and all would entail trip times which might be enabled by space colonization technology, permitting self-contained habitats with lifetimes of decades to centuries. Yet human interstellar expansion at average speeds of even 0.1% of c would permit settlement of the entire Galaxy in less than one half of a galactic rotation period of $\sim 250,000,000$ years, which is comparable to the timescale of other galactic processes. Thus, even if interstellar travel at near relativistic speeds is never feasible (which cannot be clearly determined at this time), the development of space colonization could allow human expansion beyond the Solar System without requiring technological advances that cannot yet be reasonably foreseen. This could greatly improve the chances for the survival of intelligent life over cosmic timescales, given the many natural and human-related hazards that have been widely noted.

The star Tau Ceti, about twelve light years away, has an abundance of cometary and asteroidal material in orbit around it. These materials could be used for the construction of space habitats for human settlement.

Terrestrial analogues to space colonies

The most famous attempt to build an analogue to a self-sufficient colony is Biosphere 2, which attempted to duplicate Earth's biosphere.

Many space agencies build testbeds for advanced life support systems, but these are designed for long duration human spaceflight, not permanent colonization.

Remote research stations in inhospitable climates, such as the Amundsen-Scott South Pole Station or Devon Island Mars Arctic Research Station, can also provide some practice for off-world outpost construction and operation. The Mars Desert Research Station has a habitat for similar reasons, but the surrounding climate is not strictly inhospitable.

Nuclear Submarines provide an example of conditions encountered in artificial space environment. Crews of these vessels often spend long periods (6 months or more) submerged during their deployments. However, the submarine environment provides a somewhat open life support system since the vessel can replenish supplies of fresh water and oxygen from seawater.

Other examples of small groups in isolated living conditions are record long-distance flights, long-distance (single-handed) sails, oil platforms, prisons, bunkers, small islands and underground bases.

The study of terrestrial analogues is also a central focus in space architecture.

Literature

The literature for space colonization began in 1869 when Edward Everett Hale wrote about an inhabited artificial satellite.

The Russian schoolmaster and physicist Konstantin Tsiolkovsky foresaw elements of the space community in his book *Beyond Planet Earth* written about 1900. Tsiolkovsky had his space travelers building greenhouses and raising crops in space.

Others have also written about space colonies as Lasswitz in 1897 and Bernal, Oberth, Von Pirquet and Noordung in the 1920s. Wernher von Braun contributed his ideas in a 1952 *Colliers* article. In the 1950s and 1960s, Dandridge M. Cole published his ideas.

Another seminal book on the subject was the book *The High Frontier: Human Colonies in Space* by Gerard K. O'Neill in 1977 which was followed the same year by *Colonies in Space* by T. A. Heppenheimer.

M. Dyson wrote *Home on the Moon; Living on a Space Frontier* in 2003; Peter Eckart wrote *Lunar Base Handbook* in 2006 and then Harrison Schmitt's *Return to the Moon* written in 2007.

Debate

Justification

In 2001, the space news website asked Freeman Dyson, J. Richard Gott and Sid Goldstein for reasons why some humans should live in space. Their answers were:

- Spread life and beauty throughout the Universe
- Ensure the survival of our species
- Make money through new forms of space commercialization such as solar power satellites, asteroid mining, and space manufacturing
- Save the environment of Earth by moving people and industry into space
- Provide entertainment value in order to distract from immediate surroundings, space tourism
- Ensure sufficient supply of rare materials, including from the Outer Solar System – natural gas (in connection with expected worldwide hydrocarbons peak) and drinking water (in connection with expected worldwide water shortage)

Nick Bostrom argued that from a utilitarian perspective space colonization should be a chief goal as it would enable a very large population living for a very long period of time (possibly billions of years) which would produce an enormous amount of utility (or happiness). He claims that it is more important to reduce existential risks to increase the probability of eventual colonization rather than to accelerate technological development so that space colonization could happen sooner.

Louis J. Halle, formerly of the United States Department of State, wrote in *Foreign Affairs* (Summer 1980) that the colonization of space will protect humanity in the event of global nuclear warfare.

The scientist Paul Davies also supports the view that if a planetary catastrophe threatens the survival of the human species on Earth, a self-sufficient colony could "reverse-colonize" the Earth and restore human civilization.

The author and journalist William E. Burrows and the biochemist Robert Shapiro proposed a private project, the Alliance to Rescue Civilization, with the goal of establishing an off-Earth backup of human civilization.

Objections

Colonizing space would require massive amounts of financial, physical and human capital devoted to research, development, production, and deployment.

The fundamental problem of public things, needed for survival, such as space programs, is the free rider problem. Convincing the public to fund such programs would require additional self-interest arguments: If the objective of space colonization is to provide a "backup" in case everyone on Earth is killed, then why should someone on Earth pay for something that is only useful after they're dead? This assumes that space colonization is not widely acknowledged as a sufficiently valuable social goal.

Other objections include concern about creating a culture in which humans are no longer seen as human, but rather as material assets. The issues of human dignity, morality, philosophy, culture, bioethics, and the threat of megalomaniac leaders in these new "societies" would all have to be addressed in order for space colonization to meet the psychological and social needs of people living in isolated colonies or generation ships.

As an alternative or addendum for the future of the human race, many science fiction writers have focused on the realm of the 'inner-space', that is the computer aided exploration of the human mind and human consciousness.

Counter arguments

The argument of need

The population of Earth continues to increase, while its carrying capacity and available resources do not. If the resources of space are opened to use and viable life-supporting habitats can be built, the Earth will no longer define the limitations of growth. On the other hand, extrapolations made using available figures for population growth, shows that the population of Earth will stop growing around 2070.

Furthermore, even if humanity manages to avoid devastating Earth through war, pestilence, pollution, global cooling, global warming, and even cometary impacts, the

Earth will ultimately become uninhabitable by the heating from the Sun as it ages. If humanity has not made permanent habitations in space by the time any one of these incidents occurs, it may very well go extinct.

“ Maybe the reason civilizations don't get around to colonizing other planets is that there's a narrow window when they have the tools, population and will to do so, and the window usually closes on them.”

--John Tierney

"If it's true that civilizations normally go extinct because they get stuck on their home planets, then the odds are against us"

”

--John Tierney

The argument of benefits

Detractors of the development of permanent space colonies and infrastructure often cite the very high initial investment costs of space colonies and permanent space infrastructure yet they ignore all potential returns on that investment. The long-term vision of developing space infrastructure is that it will provide long-term benefits far in excess of the initial start-up costs. Therefore, such a development program should be viewed more as a long-term investment and not like current social spending programs that incur spending commitments but provide little or no return on that investment.

Because current space launch costs are so high (on the order of \$4,000 to \$40,000 / kg launched into orbit) any serious plan to develop space infrastructure at a reasonable cost must include developing the ability of that infrastructure to manufacture most or all of its requirements plus those for permanent human habitation in space. Therefore, the initial investments must be made in the development of the initial capacity to provide these necessities: Materials, Energy, Transportation, Communication, Life support, Radiation protection, Self-replication, and Population.

Once the needs of the permanent settlements have been met, any additional production capacity could be used to either extend that initial infrastructure (a concept commonly called "bootstrapping") or traded back to Earth in payment of the initial investment or in exchange for goods more easily manufactured on the Earth.

Although some items of the infrastructure requirements above can already be easily produced on the Earth and would therefore not be very valuable as trade items (oxygen, water, base metal ores, silicates, etc.), other high value items are more abundant, more easily produced, of higher quality, or can only be produced in space. These would provide (over the long-term) a very high return on the initial investment in space infrastructure.

Some of these high trade value goods include precious metals, gem stones, power, solar cells, ball bearings, semi-conductors, and pharmaceuticals.

“ ... the smallest Earth-crossing asteroid 3554 Amun is a mile-wide (2 km) lump of iron, nickel, cobalt, platinum, and other metals; it contains 30 times as much metal as Humans have mined throughout history, although it is only the smallest of dozens of known metallic asteroids and worth perhaps US\$ 20 trillion if mined slowly to meet demand at 2001 market prices. ”

“ In the 2,900 km³ of Eros, there is more aluminium, gold, silver, zinc and other base and precious metals than have ever been excavated in history or indeed, could ever be excavated from the upper layers of the Earth's crust. ”

The main impediments to commercial exploitation of these resources are the very high cost of initial investment, the very long period required for the expected return on those investments (estimated to be 50 years or more by some), and because it has never been done before - the high-risk nature of the investment.

The argument of nationalism

Space proponents counter this argument by pointing out that humanity as a whole has been exploring and expanding into new territory since long before Europe's colonial period, going back into prehistory (the nationalist argument also ignores multinational cooperative space efforts); that seeing the Earth as a single, discrete object instills a powerful sense of the unity, connectedness of the human environment, and of the immateriality of political borders; and that in practice, international collaboration in space has shown its value as a unifying and cooperative endeavor.

Advocacy

Space advocacy organizations include

- The Alliance to Rescue Civilization plans to establish backups of human civilization on the Moon and other locations away from Earth.
- The Colonize the Cosmos site advocates orbital colonies.
- The Artemis Project plans to set up a private lunar surface station.
- The British Interplanetary Society, founded in 1933, is the world's longest established space society.
- The Living Universe Foundation has a detailed plan in which the entire galaxy is colonized.
- The Mars Society promotes Robert Zubrin's Mars Direct plan and the settlement of Mars.

- The National Space Society is an organization with the vision of "people living and working in thriving communities beyond the Earth."
- The Planetary Society is the largest space interest group, but has an emphasis on robotic exploration and the search for extraterrestrial life.
- The Space Frontier Foundation promotes strong free market, capitalist views about space development.
- The Space Settlement Institute is searching for ways to make space colonization happen in our lifetimes.
- The Space Studies Institute was founded by Gerard K. O'Neill to fund the study of space habitats.
- Students for the Exploration and Development of Space (SEDS) is a student organization founded in 1980 at MIT and Princeton.
- Foresight Nanotechnology Institute – The space challenge.

Chapter-2

Space Technologies



Teddy bears lifted to 30,085 metres above sea level on a helium balloon in a materials experiment by CU Spaceflight and SPARKS science club. Each of the bears wore a different space suit designed by 11-13 year olds from SPARKS.

Space technology is technology that is related to entering, and retrieving objects or life forms from space.

"Every day" technologies such as weather forecasting, remote sensing, GPS systems, satellite television, and some long distance communications systems critically rely on

space infrastructure. Of sciences astronomy and Earth sciences (via remote sensing) most notably benefit from space technology.

Computers and telemetry were once leading edge technologies that might have been considered "space technology" because of their criticality to boosters and spacecraft. They existed prior to the Space Race of the Cold War (between the USSR and the USA.) but their development was vastly accelerated to meet the needs of the two major superpowers' space programs. While still used today in spacecraft and missiles, the more prosaic applications such as remote monitoring (via telemetry) of patients, water plants, highway conditions, etc. and the widespread use of computers far surpasses their space applications in quantity and variety of application.

Space is such an alien environment that attempting to work in it requires new techniques and knowledge. New technologies originating with or accelerated by space-related endeavors are often subsequently exploited in other economic activities. This has been widely pointed to as beneficial by space advocates and enthusiasts favoring the investment of public funds in space activities and programs. Political opponents counter that it would be far cheaper to develop specific technologies directly if they are beneficial and scoff at this justification for public expenditures on space-related research.

Specific space technologies

Aerobot

An **aerobot** is an aerial robot, usually used in the context of an unmanned space probe or unmanned aerial vehicle.

While work has been done since the 1960s on robot "rovers" to explore the Moon and other worlds in the Solar system, such machines have limitations. They tend to be expensive and have limited range, and due to the communications time lags over interplanetary distances, they have to be smart enough to navigate without disabling themselves.

For planets with atmospheres of any substance, however, there is an alternative: an autonomous flying robot, or "aerobot" Most aerobot concepts are based on aerostats, primarily balloons, but occasionally airships. Flying above obstructions in the winds, a balloon could explore large regions of a planet in great detail for relatively low cost. Airplanes for planetary exploration have also been proposed.

Basics of balloons

While the notion of sending a balloon to another planet sounds strange at first, balloons have a number of advantages for planetary exploration. They can be made light in weight and are potentially relatively inexpensive. They can cover a great deal of ground, and their view from a height gives them the ability to examine wide swathes of terrain with

far more detail than would be available from an orbiting satellite. For exploratory missions, their relative lack of directional control is not a major obstacle as there is generally no need to direct them to a specific location.

Balloon designs for possible planetary missions have involved a few unusual concepts. One is the solar, or infrared (IR) Montgolfiere. This is a hot-air balloon where the envelope is made from a material that traps heat from sunlight, or from heat radiated from a planetary surface. Black is the best color for absorbing heat, but other factors are involved and the material may not necessarily be black.

Solar Montgolfieres have several advantages for planetary exploration, as they can be easier to deploy than a light gas balloon, do not necessarily require a tank of light gas for inflation, and are relatively forgiving of small leaks. They do have the disadvantage that they are only aloft during daylight hours.

The other is a "reversible fluid" balloon. This type of balloon consists of an envelope connected to a reservoir, with the reservoir containing a fluid that is easily vaporized. The balloon can be made to rise by vaporizing the fluid into gas, and can be made to sink by condensing the gas back into fluid. There are a number of different ways of implementing this scheme, but the physical principle is the same in all cases.

A balloon designed for planetary exploration will carry a small gondola containing an instrument payload. The gondola will also carry power, control, and communications subsystems. Due to weight and power supply constraints, the communications subsystem will generally be small and low power, and interplanetary communications will be performed through an orbiting planetary probe acting as a relay.

A solar Montgolfiere will sink at night, and will have a guide rope attached to the bottom of the gondola that will curl up on the ground and anchor the balloon during the darkness hours. The guide rope will be made of low friction materials to keep it from catching or tangling on ground features.

Alternatively, a balloon may carry a thicker instrumented "snake" in place of the gondola and guiderope, combining the functions of the two. This is a convenient scheme for making direct surface measurements.

A balloon could also be anchored to stay in one place to make atmospheric observations. Such a static balloon is known as an "aerostat".

One of the trickier aspects of planetary balloon operations is inserting them into operation. Typically, the balloon enters the planetary atmosphere in an "aeroshell", a heat shield in the shape of a flattened cone. After atmospheric entry, a parachute will extract the balloon assembly from the aeroshell, which falls away. The balloon assembly then deploys and inflates.

Once operational, the aerobot will be largely on its own and will have to conduct its mission autonomously, accepting only general commands over its long link to Earth. The aerobot will have to navigate in three dimensions, acquire and store science data, perform flight control by varying its altitude, and possibly make landings at specific sites to provide close-up investigation.

The Venus Vega balloons

The first, and so far only, planetary balloon mission was performed by the Space Research Institute of Soviet Academy of Sciences in cooperation with the French space agency CNES in 1985. A small balloon, similar in appearance to terrestrial weather balloons, was carried on each of the two Soviet Vega Venus probes, launched in 1984.

The first balloon was inserted into the atmosphere of Venus on 11 June 1985, followed by the second balloon on 15 June 1985. The first balloon failed after only 56 minutes, but the second operated for a little under two Earth days until its batteries ran down.

The Venus Vega balloons were the idea of Jacques Blamont, chief scientist for CNES and the father of planetary balloon exploration. He energetically promoted the concept and enlisted international support for the small project.

The scientific results of the Venus VEGA probes were modest. More importantly, the clever and simple experiment demonstrated the validity of using balloons for planetary exploration.

The Mars aerobot effort

After the success of the Venus VEGA balloons, Blamont focused on a more ambitious balloon mission to Mars, to be carried on a Soviet space probe.

The atmospheric pressure on Mars is about 150 times less than that of Earth. In such a thin atmosphere, a balloon with a volume of 5,000 to 10,000 cubic meters (178,500 to 357,000 cubic feet) could carry a payload of 20 kilograms (44 pounds), while a balloon with a volume of 100,000 cubic meters (3,600,000 cubic feet) could carry 200 kilograms (440 pounds).

The French had already conducted extensive experiments with solar Montgolfieres, performing over 30 flights from the late 1970s into the early 1990s. The Montgolfieres flew at an altitude of 35 kilometers, where the atmosphere was as thin and cold as it would be on Mars, and one spent 69 days aloft, circling the Earth twice.

Early concepts for the Mars balloon featured a "dual balloon" system, with a sealed hydrogen or helium-filled balloon tethered to a solar Montgolfiere. The light-gas balloon was designed to keep the Montgolfiere off the ground at night. During the day, the Sun would heat up the Montgolfiere, causing the balloon assembly to rise.

Eventually, the group decided on a cylindrical sealed helium balloon made of aluminized PET film, and with a volume of 5,500 cubic meters (196,000 cubic feet). The balloon would rise when heated during the day and sink as it cooled at night.

Total mass of the balloon assembly was 65 kilograms (143 pounds), with a 15 kilogram (33 pound) gondola and a 13.5 kilogram (30 pound) instrumented guiderope. The balloon was expected to operate for ten days. Unfortunately, although considerable development work was performed on the balloon and its subsystems, Russian financial difficulties pushed the Mars probe out from 1992, then to 1994, and then to 1996. The Mars balloon was dropped from the project due to cost, and the probe was lost on launch in 1996 anyway.

JPL aerobot experiments

By this time, the Jet Propulsion Laboratory (JPL) of the US National Aeronautics and Space Administration (NASA) had become interested in the idea of planetary aerobots, and in fact a team under Jim Cutts of JPL had been working on concepts for planetary aerobots for several years, as well as performing experiments to validate aerobot technology.

The first such experiments focused on a series of reversible-fluid balloons, under the project name ALICE, for "Altitude Control Experiment". The first such balloon, ALICE 1, flew in 1993, with other flights through ALICE 8 in 1997.

Related work included the characterization of materials for a Venus balloon envelope, and two balloon flights in 1996 to test instrument payloads under the name BARBE, for "Balloon Assisted Radiation Budget Equipment".

By 1996, JPL was working on a full-fledged aerobot experiment named PAT, for "Planetary Aerobot Testbed", which was intended to demonstrate a complete planetary aerobot through flights into Earth's atmosphere. PAT concepts envisioned a reversible-fluid balloon with a 10-kilogram payload that would include navigation and camera systems, and eventually would operate under autonomous control. The project turned out to be too ambitious, and was cancelled in 1997.

JPL continued to work on a more focused, low-cost experiments to lead to a Mars aerobot, under the name MABVAP, for "Mars Aerobot Validation Program". MABVAP experiments included drops of balloon systems from hot-air balloons and helicopters to validate the tricky deployment phase of a planetary aerobot mission, and development of envelopes for superpressure balloons with materials and structures suited to a long-duration Mars mission.

JPL also provided a set of atmospheric and navigation sensors for the Solo Spirit round-the-world manned balloon flights, both to support the balloon missions and to validate technologies for planetary aerobots.

JPL aerobot mission concepts

While these tests and experiments were going on, JPL performed a number of speculative studies for planetary aerobot missions to Mars, Venus, Saturn's moon Titan, and the outer planets.

Mars

JPL's MABVAP technology experiments are intended to lead to an actual Mars aerobot mission, named MABTEX, for "Mars Aerobot Technology Experiment". As its name implies, MABTEX is primarily intended to be an operational technology experiment as a precursor to a more ambitious efforts. MABTEX is currently envisioned as a small superpressure balloon, carried to Mars on a "microprobe" weighing no more than 40 kilograms (88 lb). Once inserted, the operational balloon would have a total mass of no more than 10 kilograms (22 lb) and would remain operational for a week. The small gondola would have navigational and control electronics, along with a stereo imaging system, as well as a spectrometer and magnetometer.

Current plans envision a follow-on to MABTEX as a much more sophisticated aerobot named MGA, for "Mars Geoscience Aerobot". Current design concepts for MGA envision a superpressure balloon system very much like that of MABTEX, but much larger. MGA would carry a payload ten times larger than that of MABTEX, and would remain aloft for up to three months, circling Mars more than 25 times and covering over 500,000 kilometres (310,000 mi). The payload would include sophisticated equipment, such as an ultrahigh resolution stereo imager, along with oblique imaging capabilities; a radar sounder to search for subsurface water; an infrared spectroscopy system to search for important minerals; a magnetometer; and weather and atmospheric instruments. MABTEX might be followed in turn by a small solar-powered blimp named MASEPA, for "Mars Solar Electric Propelled Aerobot".

Venus

JPL has also pursued similar studies on Venus aerobots. A Venus Aerobot Technology Experiment (VEBTEX) has been considered as a technology validation experiment, but the focus appears to have been more on full operational missions. One mission concept, the Venus Aerobot Multisonde (VAMS), envisions an aerobot operating at altitudes above 50 kilometres (31 mi) that would drop surface probes, or "sondes", onto specific surface targets. The balloon would then relay information from the sondes directly to Earth, and would also collect planetary magnetic field data and other information. VAMS would require no fundamentally new technology, and may be appropriate for a NASA low-cost Discovery planetary science mission.

Significant work has been performed on a more ambitious concept, the Venus Geoscience Aerobot (VGA). Designs for the VGA envision a relatively large reversible-fluid balloon, filled with helium and water, that could descend to the surface of Venus to sample surface sites, and then rise again to high altitudes and cool off.

Developing an aerobot that can withstand the high pressures and temperatures (up to 480 degrees Celsius, or almost 900 degrees Fahrenheit) on the surface of Venus, as well as passage through sulfuric acid clouds, will require new technologies. VGA is not expected to be ready until late in the next decade. Prototype balloon envelopes have been fabricated from polybenzoxazole, a polymer that exhibits high strength, resistance to heat, and low leakage for light gases. A gold coating is applied to allow the polymer film to resist corrosion from acid clouds.

Work has also been done on a VGA gondola weighing about 30 kilograms (66 lb). In this design, most instruments are contained in a spherical pressure vessel with an outer shell of titanium and an inner shell of stainless steel. The vessel contains a solid-state camera and other instruments, as well as communications and flight control systems. The vessel is designed to tolerate pressures of up to a hundred atmospheres and maintain internal temperatures below 30 °C (86 °F) even on the surface of Venus. The vessel is set at the bottom of a hexagonal "basket" of solar panels that in turn provide tether connections to the balloon system above, and is surrounded by a ring of pipes acting as a heat exchanger. An S-band communications antenna is mounted on the rim of the basket, and a radar antenna for surface studies extends out of the vessel on a mast.

Titan

Titan, the largest moon of Saturn, is an attractive target for aerobot exploration, as it has a nitrogen atmosphere twice as dense as that of Earth's that contains a smog of organic photochemicals, hiding the moon's surface from view by visual sensors. An aerobot would be able to penetrate this haze to study the moon's mysterious surface and search for complex organic molecules. NASA has outlined a number of different aerobot mission concepts for Titan, under the general name of Titan Biologic Explorer.

One concept, known as the Titan Aerobot Multisite mission, involves a reversible-fluid balloon filled with argon that could descend from high altitude to the surface of the moon, perform measurements, and then rise again to high altitude to perform measurements and move to a different site. Another concept, the Titan Aerobot Singlesite mission, would use a superpressure balloon that would select a single site, vent much of its gas, and then survey that site in detail.

An ingenious variation on this scheme, the Titan Aeroover, combines aerobot and rover. This vehicle features a triangular frame that connects three balloons, each about two meters (6.6 ft) in diameter. After entry into Titan's atmosphere, the aeroover would float until it found an interesting site, then vent helium to descend to the surface. The three balloons would then serve as floats or wheels as necessary. JPL has built a simple prototype that looks three beachballs on a tubular frame.

No matter what form the Titan Biologic Explorer mission takes, the system would likely require an atomic-powered radioisotope thermoelectric generator module for power. Solar power would not be possible at Saturn's distance and under Titan's smog, and

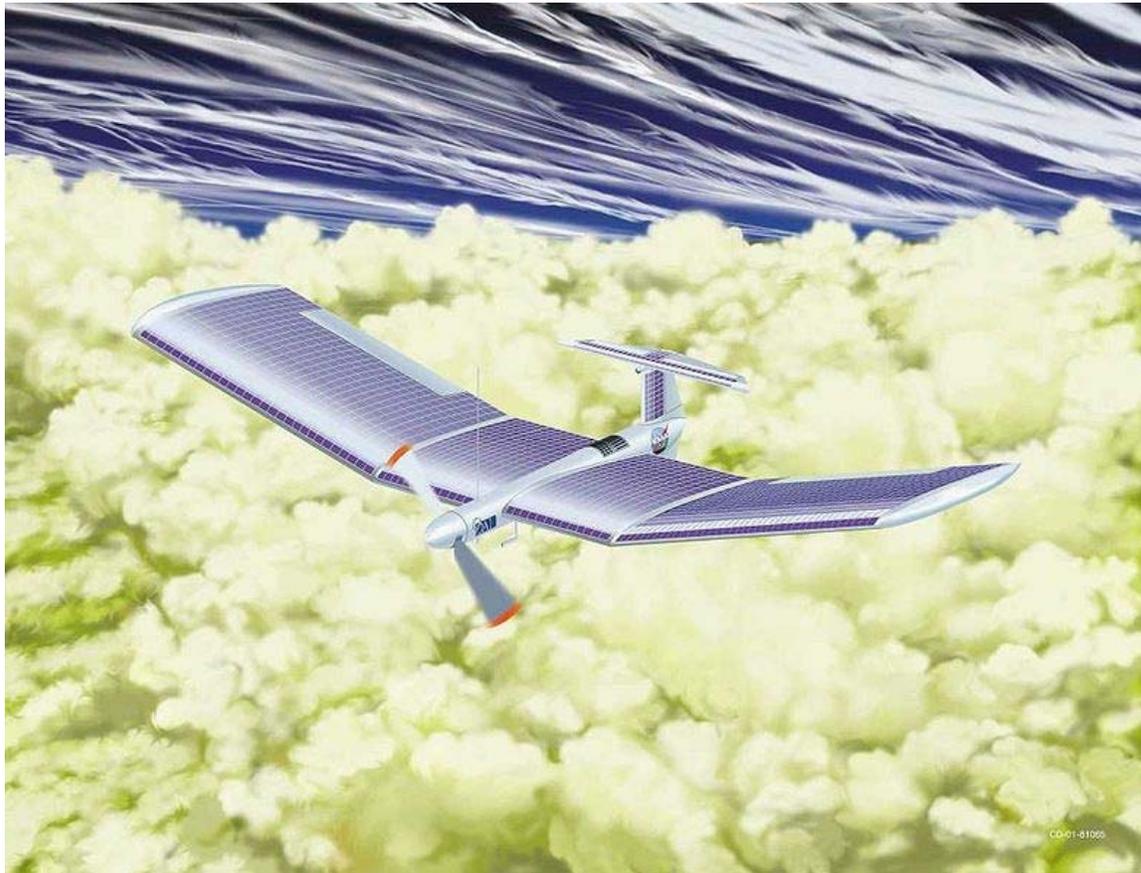
batteries would not give adequate mission endurance. The aerobot would also carry a miniaturized chemical lab to search for complicated organic chemicals.

Jupiter

Finally, aerobots might be used to explore the atmosphere of Jupiter and possibly the other gaseous outer planets. As the atmospheres of these planets are largely composed of hydrogen, and since there is no lighter gas than hydrogen, such an aerobot would have to be a Montgolfiere. As sunlight is weak at such distances, the aerobot would obtain most of its heating from infrared energy radiated by the planet below.

A Jupiter aerobot might operate at altitudes where the air pressure ranges from one to ten atmospheres, occasionally dropping lower for detailed studies. It would make atmospheric measurements and return imagery and remote sensing of weather phenomena, such as Jupiter's Great Red Spot. A Jupiter aerobot might also drop sondes deep into the atmosphere and relay their data back to an orbiter until the sondes are destroyed by temperature and pressure.

Planetary Aircraft



Artist's conception for a Venus airplane

Winged airplane concepts have been proposed for robotic exploration in the atmosphere of Mars, Venus, and even Jupiter.

The main technical challenges of flying on Mars include

1. Understanding and modeling the low Reynolds number, high subsonic Mach Number aerodynamics
2. Building appropriate, often unconventional airframe designs and aerostructures
3. Mastering the dynamics of deployment from a descending entry vehicle aeroshell

4 Integrating a non-air breathing propulsion subsystem into the system.

An aircraft concept, ARES was selected for a detailed design study as one of the four finalists for the 2007 Mars Scout Program opportunity, but was eventually not selected in favor of the Phoenix mission. In the design study, both half-scale and full-scale aircraft were tested under Mars-atmospheric conditions.

Booster (rocketry)



A GEM-40 strap-on booster for a Delta II launch vehicle.

In spaceflight, a **booster** may be:

- An entire launch vehicle or "launcher" used to lift a spacecraft. Initially all boosters used for human spaceflight and most unmanned boosters used liquid propellant, at least for the core launch vehicle
- A strap-on rocket, (either a solid rocket booster or liquid rocket booster) used to augment the lift capability of a core launch vehicle

Examples

As examples of the first meaning, the booster for most of the Mercury manned program was the Atlas, for Gemini it was a Titan II, and for Apollo it was usually the Saturn V. As an example of the second meaning, the Titan III used strap-on boosters.

The Space Shuttle program was the first time solid rockets were used in U.S. manned space launches. "Booster" can refer to either the Space Shuttle Solid Rocket Boosters, or to the entire vehicle as it ascends under powered flight, even after the solid rocket boosters are jettisoned.

When using strap-on boosters, the core vehicle is sometimes ignited concurrently at liftoff (as in the Space Shuttle), or sometimes the vehicle lifts off solely using strap-on boosters, and core is ignited at altitude (Titan III).

Other uses

Another use of the term "booster" in spaceflight is the Booster Systems Engineer, whose call sign is **Booster**. This is a support position at NASA's Mission Control Center.

In aviation, boosters are often called JATO rockets. Solid rocket boosters were planned for some Air Force programs such as the X-20 Dyna-Soar, but were ultimately never used.

Various missiles also use solid rocket boosters. Examples are;

- 2K11 (SA-4) which uses SRBs as a first stage, and then a ramjet.
- S-200 (SA-5) which uses SRBs as the first stage, followed by a solid fuel rocket.
- Surface launched versions of the turbojet powered Boeing Harpoon use an SRB.

Human spaceflight



Edward White on a spacewalk during the Gemini 4 mission

Human spaceflight is spaceflight with a human crew and possibly passengers. This makes it unlike robotic space probes or remotely-controlled satellites. Human spaceflight is sometimes called **manned spaceflight**, a term now deprecated by major space agencies in favor of its gender-neutral alternative.

The first human spaceflight was accomplished on April 12, 1961 by Soviet cosmonaut Yuri Gagarin. The only countries to have independent human spaceflight capability are Russia, United States and China. As of 2010, human spaceflights are being actively launched by the Soyuz programme conducted by the Russian Federal Space Agency, the Space Shuttle program conducted by NASA, and the Shenzhou program conducted by the China National Space Administration.

The US will lose governmental human spaceflight launch capability upon retirement of the Space Shuttle, expected in 2011. Under the Bush administration, the Constellation program included plans for canceling the Shuttle and replacing it with the capability for spaceflight beyond low Earth orbit. In the 2011 United States federal budget, the Obama administration proposed canceling Constellation. Under the new plan, NASA would rely on transportation services provided by the private sector, such as Space X's Falcon 9. The period between the retirement of the Shuttle and the initial operational capability of new

systems (either Constellation or the new commercial proposals), similar to the gap between the cancellation of Apollo and the first Space Shuttle flight, is often referred to as the human spaceflight gap.

In recent years there has been a gradual movement towards more commercial forms of spaceflight. A number of non-governmental startup companies have sprung up in recent years, hoping to create a space tourism industry. NASA has also tried to stimulate private spaceflight through programs such as Commercial Crew Development (CCDev) and Commercial Orbital Transportation Services (COTS). With its 2011 budget proposals released in early February 2010, the Obama administration is moving towards a model where commercial companies would supply NASA with transportation services of both crew and cargo to low Earth orbit. The vehicles used for these services would then serve both NASA and potential commercial customers. NASA intends to spend \$6 billion in the coming years to develop commercial crew vehicles, using a model similar to that used under COTS.

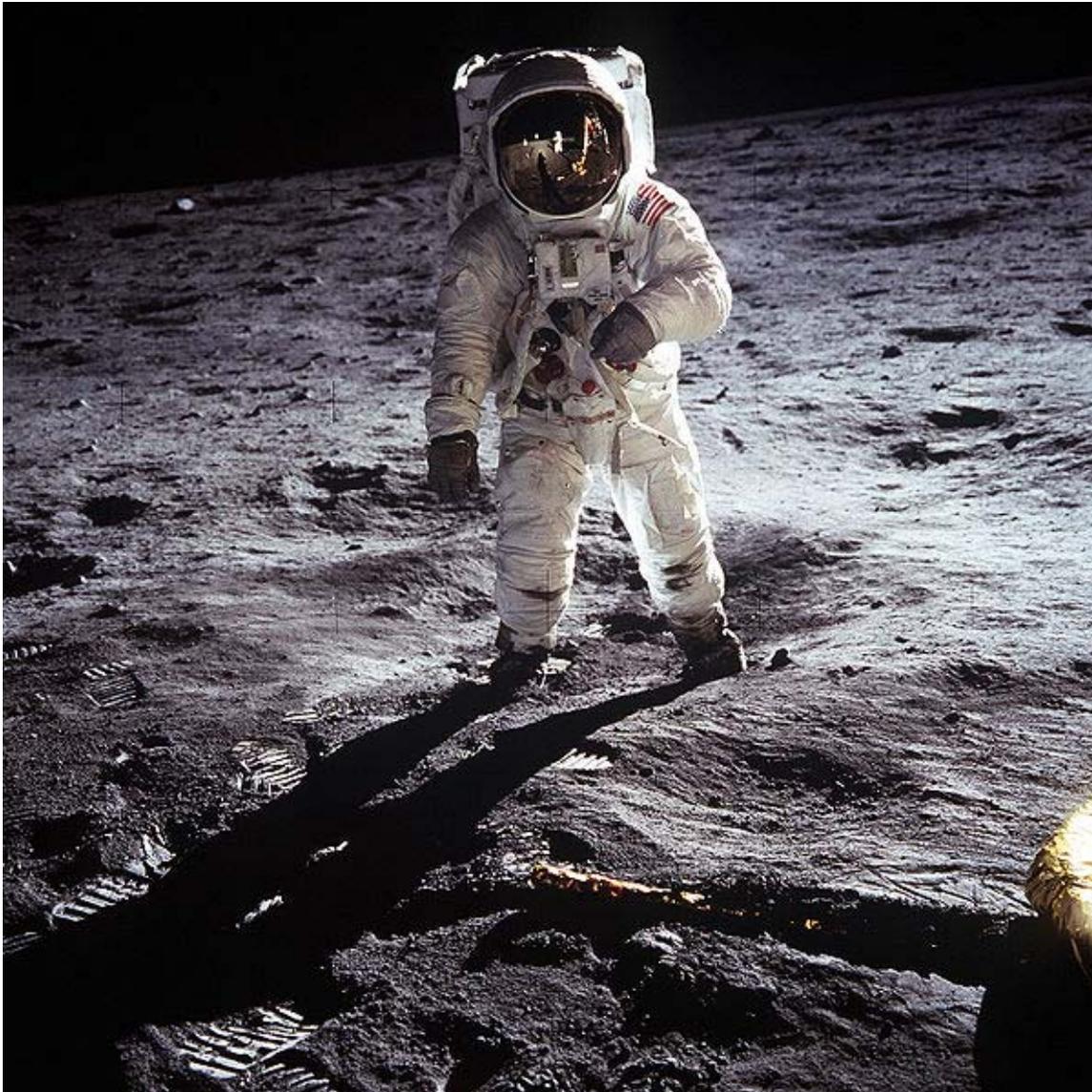
History

First human spaceflights



Yuri Gagarin, the first man in space, in his space suit during the Vostok 1 mission

The first human spaceflight took place on April 12, 1961, when cosmonaut Yuri Gagarin made one orbit around the Earth aboard the Vostok 1 spacecraft, launched by the Soviet space program and designed by the rocket scientist Sergey Korolyov. Valentina Tereshkova became the first woman in space on board Vostok 6 on June 16, 1963. Both spacecraft were launched by Vostok 3KA launch vehicles. Alexei Leonov made the first spacewalk when he left the Voskhod 2 on March 8, 1965. Svetlana Savitskaya became the first woman to do so on July 25, 1984.



Buzz Aldrin on the surface of the Moon during Apollo 11

The United States became the second nation to achieve manned spaceflight, with the suborbital flight of astronaut Alan Shepard aboard *Freedom 7*, carried out as part of Project Mercury. The spacecraft was launched on May 5, 1961 on a Redstone rocket. The

first U.S. orbital flight was that of John Glenn aboard *Friendship 7*, which was launched February 20, 1962 on an Atlas rocket. Since 1981 the U.S. has conducted all its human spaceflight missions with reusable Space Shuttles. Sally Ride became the first American woman in space in 1983. Eileen Collins was the first female Shuttle pilot, and with Shuttle mission STS-93 in July 1999 she became the first woman to command a U.S. spacecraft.

The People's Republic of China became the third nation to achieve human spaceflight when Yang Liwei launched into space on a Chinese-made vehicle, the Shenzhou 5, on October 15, 2003. The flight made China the third nation to have launched its own manned spacecraft using its own launcher. Previous European (Hermes) and Japanese (HOPE-X) domestic manned programs were abandoned after years of development, as was the first Chinese attempt, the Shuguang spacecraft.

The farthest destination for a human spaceflight mission has been the Moon. The only missions to the Moon have been those conducted by NASA as part of the Apollo program. The first such mission, Apollo 8, orbited the Moon but did not land. The first Moon landing mission was Apollo 11, during which—on July 20, 1969—Neil Armstrong and Buzz Aldrin became the first people to set foot on the Moon. Six missions landed in total, numbered Apollo 11–17, excluding Apollo 13. Altogether twelve men walked on the Moon, the only humans to have been on an extraterrestrial body. The Soviet Union discontinued its program for lunar orbiting and landing of human spaceflight missions on June 24, 1974 when Valentin Glushko became General Designer of NPO Energiya.

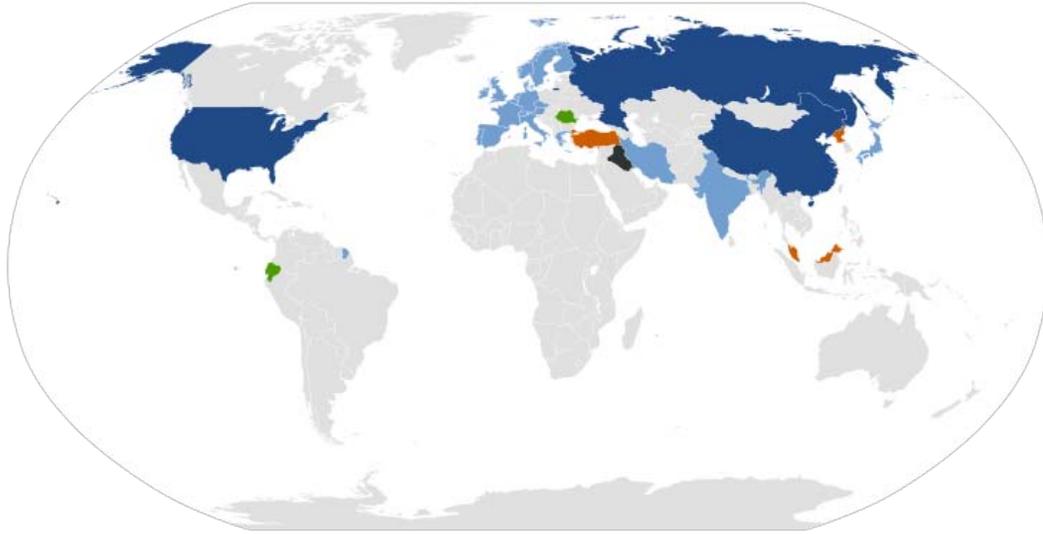
The longest single human spaceflight is that of Valeriy Polyakov, who left earth on January 8, 1994, and didn't return until March 22, 1995 (a total of 437 days 17 hr. 58 min. 16 sec. aboard). Sergei Krikalyov has spent the most time of anyone in space, 803 days, 9 hours, and 39 seconds altogether. The longest period of continuous human presence in space lasted as long as 3,644 days, eight days short of 10 years, spanning the launch of Soyuz TM-8 on September 5, 1989 to the landing of Soyuz TM-29 on August 28, 1999.

For many years beginning in 1961, only two countries, the USSR (later Russia) and United States, had their own astronauts. Citizens of other nations flew in space, beginning with the flight of Vladimir Remek, a Czech, on a Soviet spacecraft on March 2, 1978. As of 2010, citizens from 38 nations (including space tourists) have flown in space aboard Soviet, American, Russian, and Chinese spacecraft.

Space programs

As of 2010, human spaceflight missions have been conducted by the former Soviet Union/(Russia), the United States, the People's Republic of China and by the private spaceflight company Scaled Composites.

Several other countries and space agencies have announced and begun human spaceflight programs by their own technology, including India (ISRO), Ecuador (EXA), Japan (JAXA), Iran (ISA) and Malaysia (MNSA).



Countries which have human spaceflight agendas.

Currently the following spacecraft and spaceports are used for launching human spaceflights:

- Soyuz with Soyuz rocket—Baikonur Cosmodrome
- Space Shuttle—Kennedy Space Center
- International Space Station (ISS)—Assembled in orbit; crews transported by the previous two spacecraft
- Shenzhou spacecraft with Long March rocket—Jiuquan Satellite Launch Center

Historically, the following spacecraft and spaceports have also been used for human spaceflight launches:

- Vostok—Baikonur Cosmodrome
- Mercury—Cape Canaveral Air Force Station
- Voskhod—Baikonur Cosmodrome
- X-15—Edwards Air Force Base, (two internationally recognized suborbital flights in program)
- Gemini—Cape Canaveral Air Force Station
- Apollo—Kennedy Space Center (Apollo 7 at Cape Canaveral Air Force Station)
- Salyut space station—Baikonur Cosmodrome
- Almaz space station—Baikonur Cosmodrome (Almaz was a series of military space stations under cover of the civilian name Salyut)
- Skylab space station—Kennedy Space Center
- Mir space station—Baikonur Cosmodrome
- SpaceShipOne with White Knight—Mojave Spaceport

Numerous private companies attempted human spaceflight programs in an effort to win the \$10 million Ansari X Prize. The first private human spaceflight took place on June 21, 2004, when SpaceShipOne conducted a suborbital flight. SpaceShipOne captured the prize on October 4, 2004, when it accomplished two consecutive flights within one week. SpaceShipTwo, launching from the carrier aircraft White Knight Two, is planned to conduct regular suborbital space tourism.

Most of the time, the only humans in space are those aboard the ISS, whose crew of six spends up to six months at a time in low Earth orbit.

NASA and ESA now use the term "human spaceflight" to refer to their programs of launching people into space. Traditionally, these endeavors have been referred to as "manned space missions."

National spacefaring attempts

Safety concerns

Life support

The immediate needs for breathable air and drinkable water are addressed by the life support system of the spacecraft.

Medical issues

Effects of microgravity

Medical data from astronauts in low earth orbits for long periods, dating back to the 1970s, show several adverse effects of a microgravity environment: loss of bone density, decreased muscle strength and endurance, postural instability, and reductions in aerobic capacity. Over time these deconditioning effects can impair astronauts' performance or increase their risk of injury.

In a weightless environment, astronauts put almost no weight on the back muscles or leg muscles used for standing up. Those muscles then start to weaken and eventually get smaller. If there is an emergency at landing, the loss of muscles, and consequently the loss of strength can be a serious problem. Sometimes, astronauts can lose up to 25% of their muscle mass on long term flights. When they get back to ground, they will be considerably weakened and will be out of action for a while.

Astronauts experiencing weightlessness will often lose their orientation, get motion sickness, and lose their sense of direction as their bodies try to get used to a weightless environment. When they get back to Earth, or any other mass with gravity, they have to readjust to the gravity and may have problems standing up, focusing their gaze, walking and turning. Importantly, those body motor disturbances after changing from different

gravities only get worse the longer the exposure to little gravity. These changes will affect operational activities including approach and landing, docking, remote manipulation, and emergencies that may happen while landing. This can be a major roadblock to mission success.

Radiation

Without proper shielding the crews of missions beyond low Earth orbit (LEO) might be at risk from high-energy protons emitted by solar flares. Lawrence Townsend of the University of Tennessee and others have studied the most powerful solar flare ever recorded. That flare was seen by the British astronomer Richard Carrington in September 1859. Radiation doses astronauts would receive from a Carrington-type flare could cause acute radiation sickness and possibly even death.

Another type of radiation, galactic cosmic rays, present further challenges to human spaceflight beyond LEO.

Radiation damage to the immune system

There is also some scientific concern that extended space flight might slow down the body's ability to protect itself against diseases. Some of the problems are a weakened immune system and the activation of dormant viruses in the body. Radiation can cause both short and long term consequences to the bone marrow stem cells which create the blood and immune systems. Because the interior of a spacecraft is so small, a weakened immune system and more active viruses in the body can lead to a fast spread of infection.

Isolation

During long missions, astronauts are isolated and confined into small spaces. Depression, cabin fever and other psychological problems may result that impact crew safety and mission success.

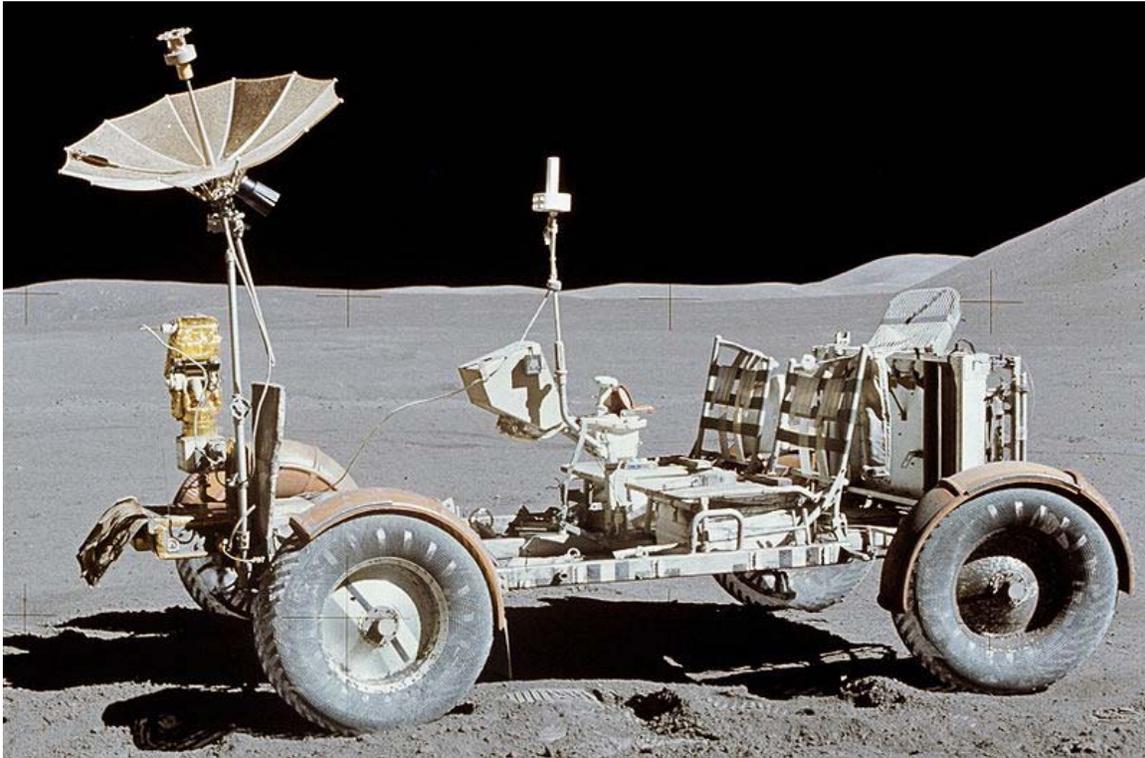
Astronauts may not be able to quickly return to Earth or receive medical supplies, equipment or personnel if a medical emergency occurs. The astronauts may have to rely for long periods on their limited existing resources and medical advice from the ground.

Fatality risk

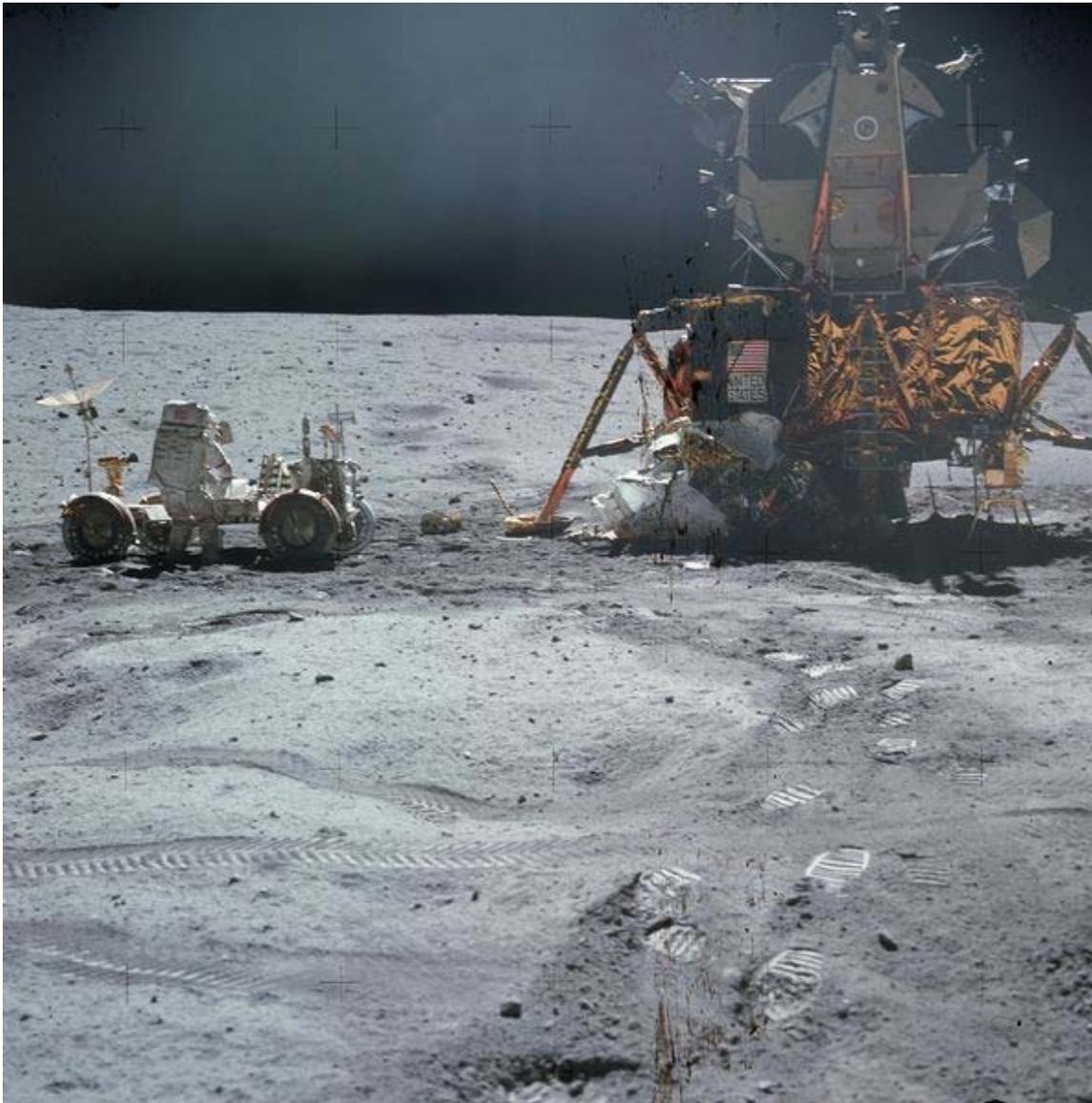
As of 2009, 18 crew members have died during actual spaceflight missions (see table). Over 100 others have died in accidents during activity directly related to spaceflight missions or testing.

Year	#of Deaths	Mission	Known or likely cause
1967	1	Soyuz 1	
1971	3	Soyuz 11	
1986	7	Space Shuttle Challenger	(mission never reached space)
2003	7	Space Shuttle Columbia	Asphyxia from cabin breach, trauma from object impact, or burns from re-entry heat

Lunar rover (Apollo)



The U.S. Apollo Lunar Roving Vehicle from Apollo 15 on the moon in 1971

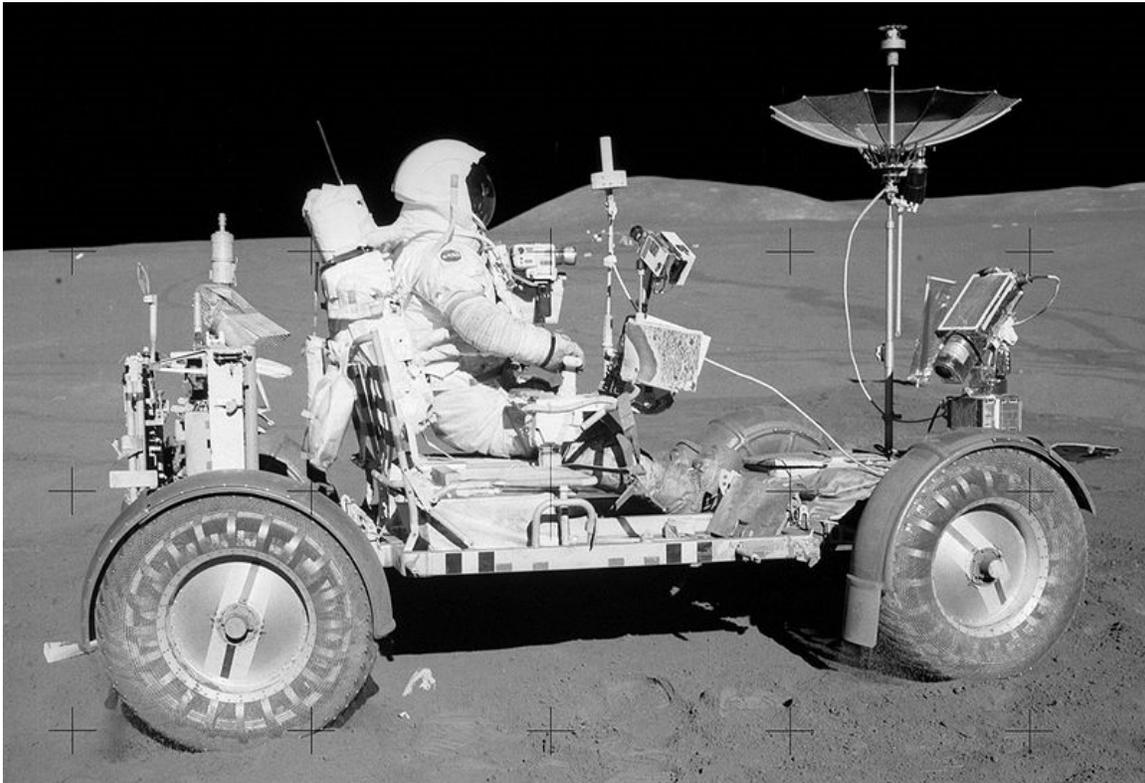


John Young works at the LRV near the LM *Orion* on Apollo 16 in April 1972.

The **Lunar Roving Vehicle (LRV)** or **lunar rover** was a battery-powered four-wheeled rover used on the Moon during the last three missions of the American Apollo program (15, 16, and 17) during 1971 and 72. It was popularly known as the **moon buggy**, which was a play-on-words of dune buggy.

The LRV could carry one or two astronauts, their equipment, and lunar samples.

History



Apollo 15 LRV

The concept of a lunar rover predated Apollo, with a 1950s series in *Collier's Weekly* magazine by Wernher Von Braun and others, "Man Will Conquer Space Soon!", describing a six week stay on the moon, featuring ten-ton tractor trailers for moving supplies. In the February 1964 issue of *Popular Science*, Von Braun, then director of NASA's Marshall Space Flight Center, discussed the need for a lunar surface vehicle. In anticipation of this as-yet unfunded project, NASA officially changed the name of the lunar lander from Lunar Excursion Module to simply Lunar Module in an effort to make clear that the capability for powered lunar surface mobility ("excursions" away from the lunar lander base) did not yet exist.

The author of the general idea, design and form of the LRV was engineer Mieczyslaw G. Bekker. The final lightweight design, the new tires, and the folding mechanism of the assembly were the inventions of engineer Ferenc Pavlics.

The first cost-plus-incentive-fee contract to Boeing (with Delco Electronics as a major sub-contractor) was for \$19,000,000 and called for delivery of the first LRV by April 1, 1971, but cost overruns led to a final cost of \$38,000,000. Four lunar rovers were built, one each for Apollo missions 15, 16, and 17; and one used for spare parts after the cancellation of further Apollo missions. There were other LRV models built: a static

model to assist with human factors design, an engineering model to design and integrate the subsystems, two one-sixth gravity models for testing the deployment mechanism, a one-gravity trainer to give the astronauts instruction in the operation of the rover and allow them to practice driving it, a mass model to test the effect of the rover on the Apollo Lunar Module (LM) structure, balance and handling, a vibration test unit to study the LRV's durability and handling of launch stresses, and a qualification test unit to study integration of all LRV subsystems.

LRVs were used for greater surface mobility during the Apollo J-class missions (*Apollo 15*, *Apollo 16*, and *Apollo 17*). The rover was first used on July 31, 1971, during the *Apollo 15* mission. This greatly expanded the range of the lunar explorers. Previous teams of astronauts were restricted to short walking distances around the landing site due to the bulky space suit equipment required to sustain life in the lunar environment. The range, however, was operationally restricted to remain within walking distance of the lunar module, in case the rover broke down at any point. The rovers had a top speed of about 8 mph (13 km/h), although Gene Cernan recorded a maximum speed of 11.2 mph (18.0 km/h), giving him the (unofficial) lunar land speed record.

The LRV was developed in only 17 months and yet performed all its functions on the Moon with no major anomalies. Harrison Schmitt of Apollo 17 said, "...the Lunar Rover proved to be the reliable, safe and flexible lunar exploration vehicle we expected it to be. Without it, the major scientific discoveries of Apollo 15, 16, and 17 would not have been possible; and our current understanding of lunar evolution would not have been possible."

The LRVs did experience some minor problems. The rear fender extension on the Apollo 16 LRV was lost during the mission's second EVA (extra-vehicular activity) at station 8 when Young bumped into it while going to assist Duke. The dust thrown up from the wheel covered the crew, the console and the communications equipment. High battery temperatures and resulting high power consumption ensued. No repair attempt was mentioned. The fender extension on the Apollo 17 LRV broke when accidentally bumped by Eugene Cernan with a hammer handle. The crew taped the extension back in place, but due to the dusty surfaces, the tape did not adhere and the extension was lost after about one hour of driving, causing the astronauts to be covered with dust. For the second EVA, a replacement "fender" was made with some EVA maps, duct tape, and a pair of clamps from inside the Lunar Module - nominally intended for the moveable overhead light. This repair was later undone so that the clamps could be brought back inside for launch. The maps were brought back and are now on display at the National Air and Space Museum. The abrasion from the dust is evident on some portions of the makeshift fender.



Lunar rover on Space Achievement Decade Issue of 1971

The color television camera mounted on the front of the LRV could be remotely operated by Mission Control in two axes: pan and tilt. This allowed far better television coverage of the EVA than the earlier missions. On each mission, at the conclusion of the astronauts' stay on the surface, the commander drove the LRV to a position away from the Lunar Module so that the camera could record the ascent stage launch. The camera operator in Mission Control experienced difficulty in timing the various delays so that the LM ascent stage was in frame through the launch. On the third and final attempt (Apollo 17), the launch and ascent were successfully tracked.

NASA's rovers, left behind, are among the artificial objects on the Moon; as are the Soviet Union's unmanned rovers, Lunokhod 1 and Lunokhod 2.

Features and specifications



Eugene Cernan test drives the Apollo 17 lunar rover shortly after unloading it from the LM

The Apollo Lunar Roving Vehicle was an electric vehicle designed to operate in the low-gravity vacuum of the Moon and to be capable of traversing the lunar surface, allowing the Apollo astronauts to extend the range of their surface extravehicular activities. Three LRVs were used on the Moon, one on Apollo 15 by astronauts David Scott and Jim Irwin, one on Apollo 16 by John Young and Charles Duke, and one on Apollo 17 by Gene Cernan and Harrison Schmitt. The mission Commanders served as the drivers, occupying the left-hand seats of LRVs.

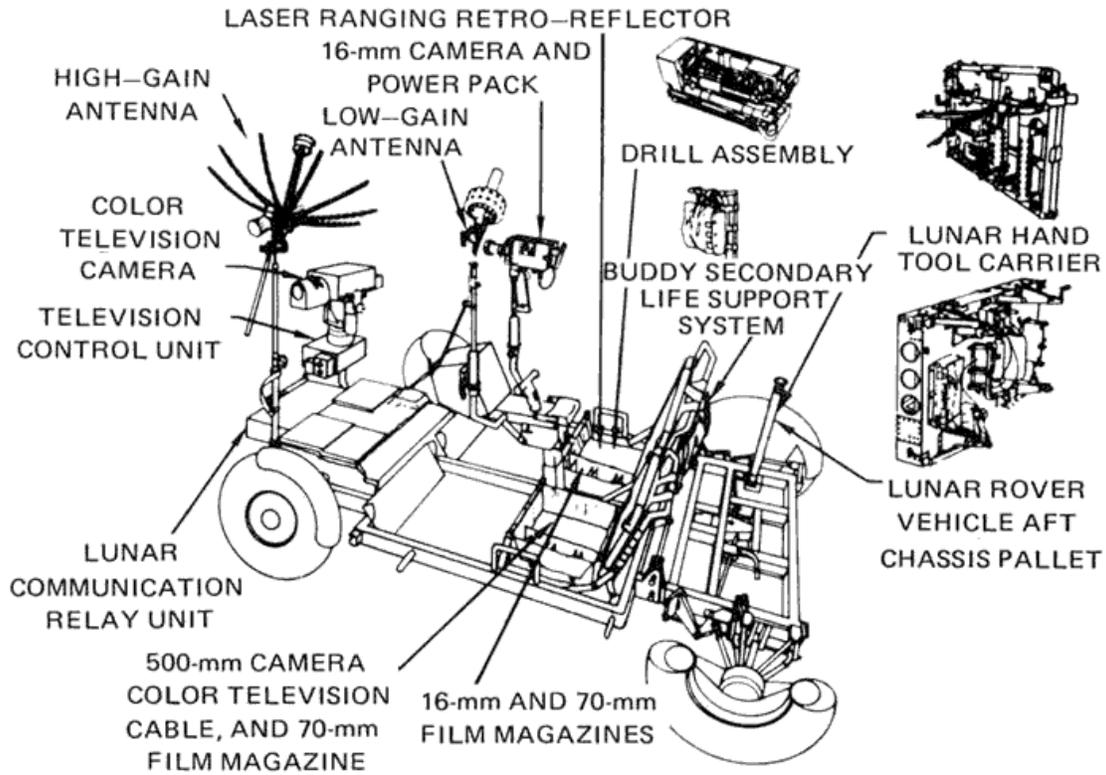
Mass and payload

The Lunar Roving Vehicle had a mass of 463 lbs (210 kg) and was designed to hold a payload of an additional 1,080 lbs (490 kg) on the lunar surface. The frame was 10 feet (3 m) long with a wheelbase of 7.5 feet (2.3 m). The height of the vehicle was 3.6 ft (1.1 m). The frame was made of aluminum alloy 2219 tubing welded assemblies and consisted of a three-part chassis which was hinged in the center so it could be folded up and hung in the Lunar Module quad 1 bay. It had two side-by-side foldable seats made of tubular aluminum with nylon webbing and aluminum floor panels. An armrest was mounted between the seats, and each seat had adjustable footrests and a Velcro seat belt. A large mesh dish antenna was mounted on a mast on the front center of the rover. The suspension consisted of a double horizontal wishbone with upper and lower torsion bars and a damper unit between the chassis and upper wishbone. Fully loaded the LAV had a ground clearance of 14 inches (35 cm).

Wheels and power

The wheels were manufactured by General Motors Defense Research Laboratories. They consisted of a spun aluminum hub and a 32 inches (81 cm) diameter, 9 inches (23 cm) wide tire made of zinc coated woven 0.033 inches (0.84 mm) diameter steel strands attached to the rim and discs of formed aluminum. Titanium chevrons covered 50 percent of the contact area to provide traction. Inside the tire was a 25.5 inches (65 cm) diameter bump stop frame to protect the hub. Dust guards were mounted above the wheels. Each wheel had its own electric drive made by Delco, DC series wound motor capable of 0.25 horsepower (190 W) @ 10,000 rpm, attached to the wheel via an 80:1 harmonic drive, and a mechanical brake unit. Maneuvering capability was provided through the use of front and rear steering motors. Each series wound DC steering motor was capable of 0.1 horsepower (75 W). Both sets of wheels would turn in opposite directions, giving a steering radius of 10 feet (3 m), or could be decoupled so only one set would be used for steering. They could also free-wheel in case of drive failure. Power was provided by two 36-volt silver-zinc potassium hydroxide non-rechargeable batteries with a capacity of 121 A·h each (a total of 242 A·h), translating into a range of 57 mi (92 km). These were used to power the drive and steering motors and also a 36 volt utility outlet mounted on front of the LRV to power the communications relay unit or the TV camera. LRV batteries and electronics were passively cooled, using reflective, upward-facing radiating surfaces mounted atop each battery unit. While driving, radiators were covered with mylar blankets to minimize dust accumulation. When stopped, the astronauts would open the blankets, and manually removed dust from the cooling surfaces with hand brushes.

Control and navigation



Lunar Rover diagram. (NASA)

A T-shaped hand controller situated between the two seats controlled the four drive motors, two steering motors and brakes. Moving the stick forward powered the LRV forward, left and right turned the vehicle left or right, pulling backwards activated the brakes. Activating a switch on the handle before pulling back would put the LRV into reverse. Pulling the handle all the way back activated a parking brake. The control and display modules were situated in front of the handle and gave information on the speed, heading, pitch, and power and temperature levels.

Navigation was based on continuously recording direction and distance through use of a directional gyro and odometer and feeding this data to a computer which would keep track of the overall direction and distance back to the LM. There was also a Sun-shadow device which could give a manual heading based on the direction of the Sun, using the fact that the Sun moved very slowly in the sky.

Usage

Each rover was used on three traverses, one per day over the three day course of each mission, with the individual performances logged as follows:

mission	total distance	total time	longest single traverse	maximum range from the LM
Apollo 15 (LRV-001)	17.25 miles (27.76 km)	3h 02 m	7.75 miles (12.47 km)	3.1 miles (5.0 km)
Apollo 16 (LRV-002)	16.50 miles (26.55 km)	3h 26 m	7.20 miles (11.59 km)	2.8 miles (4.5 km)
Apollo 17 (LRV-003)	22.30 miles (35.89 km)	4h 26 m	12.50 miles (20.12 km)	4.7 miles (7.6 km)

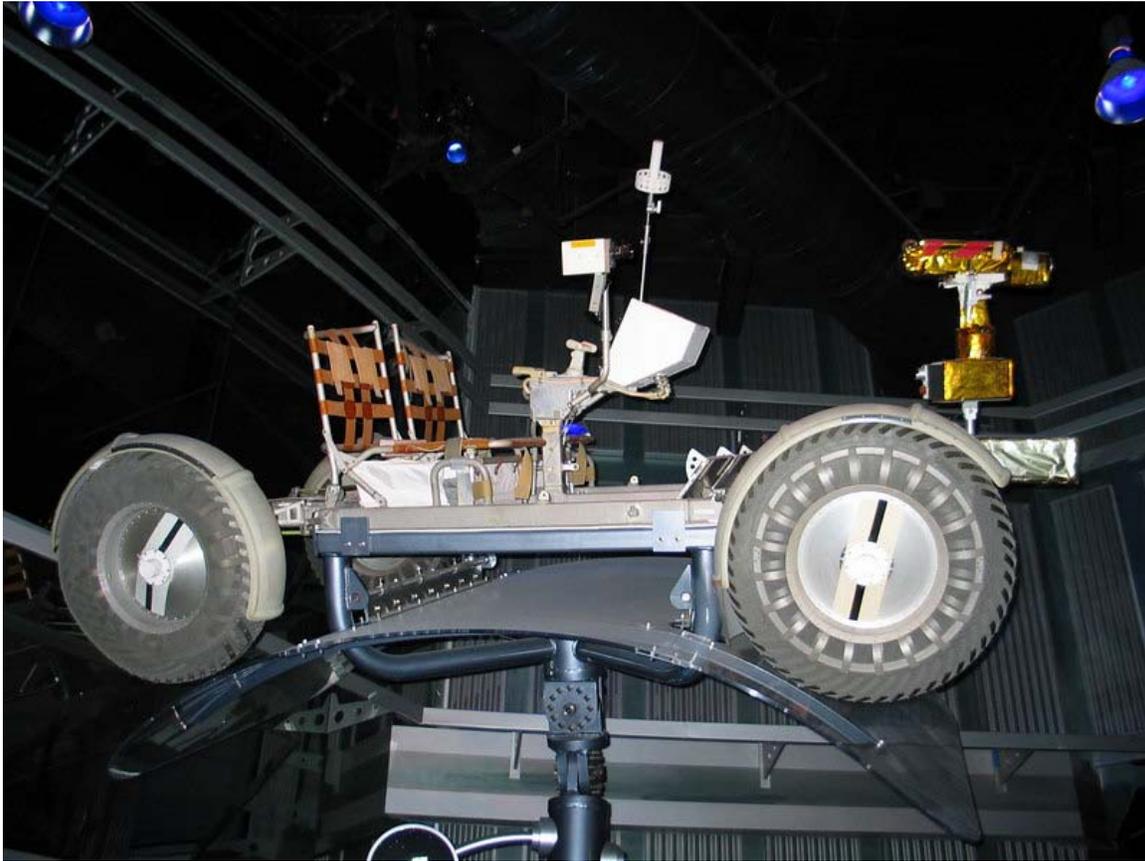
An operational constraint on the use of the LRV was that the astronauts must be able to walk back to the LM if the LRV were to fail at any time during the EVA (called the "Walkback Limit"). Thus, the traverses were limited in the distance they could go at the start and at any time later in the EVA. Therefore, they went to the farthest point away from the LM and worked their way back to it so that, as the life support consumables were depleted, their remaining walk back distance was equally diminished. This constraint was relaxed during the longest traverse on Apollo 17, based on the demonstrated reliability of the LRV and spacesuits on previous missions.

Deployment

Deployment of the LRV from the LM quad 1 by the astronauts was achieved with a system of pulleys and braked reels using ropes and cloth tapes. The rover was folded and stored in quad 1 with the underside of the chassis facing out. One astronaut would climb the egress ladder on the LM and release the rover, which would then be slowly tilted out by the second astronaut on the ground through the use of reels and tapes. As the rover was let down from the bay most of the deployment was automatic. The rear wheels folded out and locked in place and when they touched the ground the front of the rover could be unfolded, the wheels deployed, and the entire frame let down to the surface by pulleys.

The rover components locked into place upon opening. Cabling, pins and tripods would then be removed and the seats and footrests raised. After switching on all the electronics the vehicle was ready to back away from the LM.

Current locations



Rover replica on display at Epcot

Several rovers were created for testing, training or validation purposes. The engineering mockup is on display at the Museum of Flight in Seattle, Washington. The Qualification Test Unit is on display at the National Air and Space Museum in Washington D.C. The rover used for vibration testing is on display in the Davidson Saturn V Center at the Marshall Space Flight Center in Huntsville, Alabama. Additional test units are on display at the Johnson Space Center in Houston, Texas and the Kennedy Space Center Visitors Complex in Cape Canaveral, Florida.

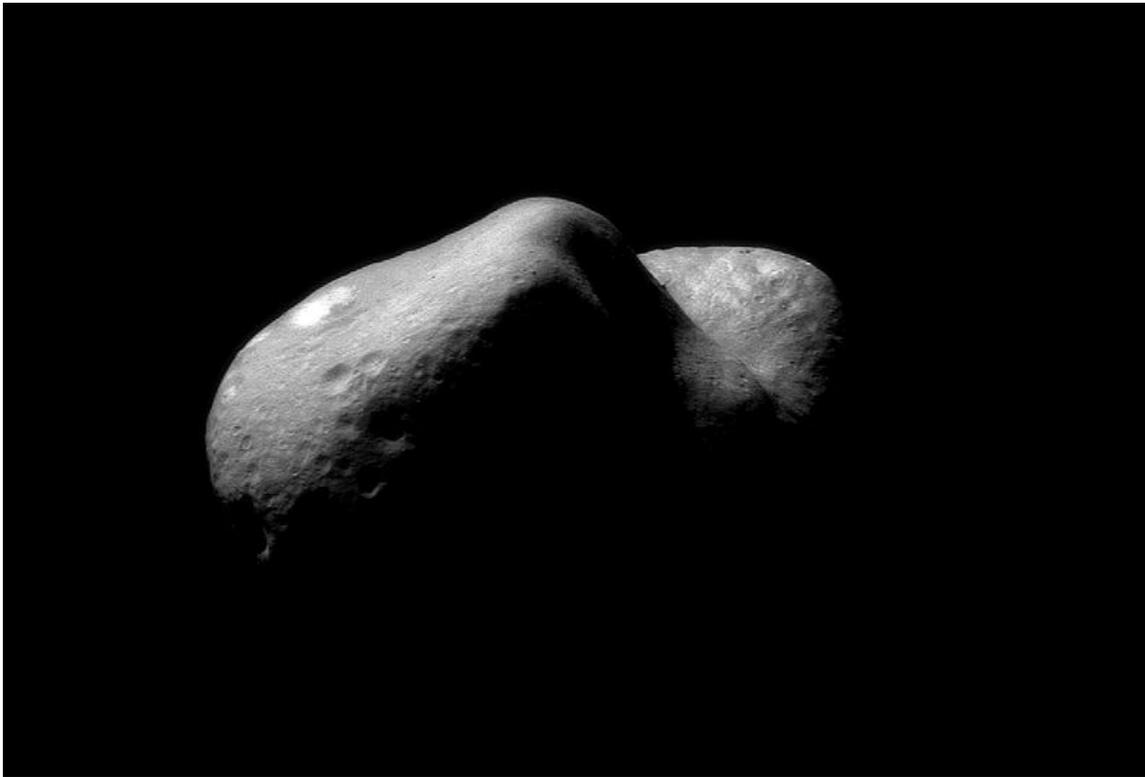
Replicas of rovers are on display at the National Museum of Naval Aviation in Pensacola, Florida and Kansas Cosmosphere and Space Center in Hutchinson, Kansas. A replica on loan from the Smithsonian Institution is on display at the Mission: Space attraction at Epcot at the Walt Disney World Resort near Orlando, Florida.

Four flight-ready rovers were manufactured. Three of them were carried to the Moon on Apollo 15, 16, and 17, and left there. After Apollo 18 was canceled, the other lunar rover was used for spare parts for the Apollo 15 to 17 missions. The only lunar rovers on display are test vehicles, trainers, and models. The rover used on Apollo 15 was left on

the lunar surface at Hadley-Apennine (26.10 N, 3.65 E). The rover used on Apollo 16 was left on the lunar surface at Descartes (8.99 S, 15.51 E). The rover used on Apollo 17 was left on the lunar surface at Taurus-Littrow (20.16 N, 30.76 E).

Future space technologies

Asteroid mining



433 Eros is a stony asteroid in a near-Earth orbit

Asteroid mining refers to the possibility of exploiting raw materials from asteroids and planetoids in space, especially near-Earth objects. Minerals and volatiles could be mined from an asteroid or spent comet to provide space construction material (e.g., iron, nickel, titanium), to extract water and oxygen to sustain the lives of prospector-astronauts on site, as well as hydrogen and oxygen for use as rocket fuel. In space exploration, these activities are referred to as in-situ resource utilization.

Some day, the platinum, cobalt and other valuable elements from asteroids may even be returned to Earth for profit. At 1997 prices, a relatively small metallic asteroid with a diameter of 1 mile contains more than \$20 trillion US dollars worth of industrial and precious metals. In fact, all the gold, cobalt, iron, manganese, molybdenum, nickel, osmium, palladium, platinum, rhenium, rhodium and ruthenium that we now mine from

the Earth's crust, and that are essential for our economic and technological development, came originally from the rain of asteroids that hit the Earth after the crust cooled. This is because, while asteroids and the Earth congealed from the same starting materials, Earth's massive gravity pulled all such siderophilic (iron loving) elements into the planet's core during its molten youth more than four billion years ago. Initially, this left the crust utterly depleted of such valuable elements. Asteroid impacts re-infused the depleted crust with metals.

In 2004, the world production of iron ore exceeded a billion metric tons. In comparison, a comparatively small M-type asteroid with a mean diameter of 1 km could contain more than two billion metric tons of iron-nickel ore, or two to three times the annual production for 2004. The asteroid 16 Psyche is believed to contain 1.7×10^{19} kg of nickel-iron, which could supply the 2004 world production requirement for several million years. A small portion of the extracted material would also contain precious metals.

In 2006, the Keck Observatory announced that the binary Trojan asteroid 617 Patroclus, and possibly large numbers of other Jupiter Trojan asteroids, are likely extinct comets and consist largely of water ice. Similarly, Jupiter-family comets, and possible near-Earth asteroids which are defunct comets, might also economically provide water. The process of bootstrapping—using materials native to space for propellant, tankage, radiation shielding, and other high-mass components of space infrastructure—could lead to radical reductions in its cost.

Asteroid selection

An important factor to consider in target selection is orbital economics, in particular the delta- v (Δv) and travel time to and from the target. More of the extracted native material must be expended as propellant in higher Δv trajectories, thus less returned as payload. Direct Hohmann trajectories are faster than Hohmann trajectories assisted by planetary and/or lunar flybys, which in turn are faster than those of the Interplanetary Transport Network, but the latter have lower Δv than the former.

Currently, the quality of the ore and the consequent cost and mass of equipment required to extract it are unknown. However, potential markets for materials can be identified and profit estimated. For example, the delivery of multiple tonnes of water to low earth orbit (LEO) in a space tourism economy could generate a significant profit.

Near-Earth asteroids are considered likely candidates for early mining activity. Their low Δv location makes them suitable for use in extracting construction materials for near-Earth space-based facilities, greatly reducing the economic cost of transporting supplies into Earth orbit.

The table at right shows a comparison of Δv requirements for various missions. In terms of propulsion energy requirements, a mission to a near-earth asteroid compares favorably to alternative mining missions.

An example of a potential target for an early asteroid mining expedition is 4660 Nereus. This body has a very low Δv compared to lifting materials from the surface of the Moon. However it would require a much longer round-trip to return the material.

Mining Considerations

There are three options for mining:

1. Bring back raw asteroidal material.
2. Process it on-site to bring back only processed materials, and perhaps produce fuel propellant for the return trip.
3. Transport the asteroid to a safe orbit around the Moon or Earth. This can hypothetically allow for most materials to be used and not wasted.

Processing *in situ* for the purpose of extracting high-value minerals will reduce the energy requirements for transporting the materials, although the processing facilities must first be transported to the mining site.

Mining operations require special equipment to handle the extraction and processing of ore in outer space. The machinery will need to be anchored to the body, but once in place, the ore can be moved about more readily due to the lack of gravity. Docking with an asteroid can be performed using a harpoon-like process, where a projectile penetrates the surface to serve as an anchor then an attached cable is used to winch the vehicle to the surface, if the asteroid is rigid enough for a harpoon to be effective.

Due to the distance from Earth to an asteroid selected for mining, the round-trip time for communications will be several minutes or more, except during occasional close approaches to Earth by near-Earth asteroids. Thus any mining equipment will either need to be highly automated, or a human presence will be needed nearby. Humans would also be useful for troubleshooting problems and for maintaining the equipment. On the other hand, multi-minute communications delays have not prevented the success of robotic exploration of Mars, and automated systems would be much less expensive to build and deploy.

Material Extraction

There are several options for material extraction:

Strip Mining

Material is successively scraped off the surface in a process comparable to strip mining. There is strong evidence that many asteroids consist of rubble piles, making this approach feasible.

Shaft Mining

A mine can be dug into the asteroid, and the material extracted through the shaft. This requires a transportation system to carry the ore to the processing facility.

Magnetic Rakes

Asteroids with a high metal content may be covered in loose grains that can be gathered by means of a magnet.

Heating

For volatile materials in extinct comets, heat can be used to melt and vaporize the matrix.

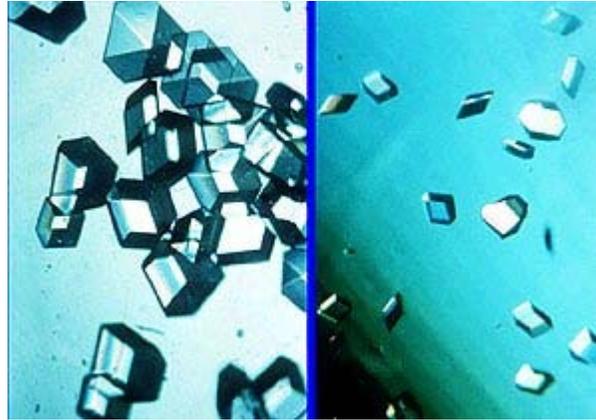
Harvest Self-Replicating Machines

A self-replicating machine could be sent to an asteroid or other body in the solar system. For example, imagine a one kilogram solar powered device that is able to extract materials from the surface of an asteroid to assemble an exact copy of itself over the course of one month. One month after arrival there will be two such devices. After 10 months there will be 1,024; after 20 months more than a million; 30 months more than a billion; 40 months more than a trillion; 50 months more than a quadrillion; 60 months (five years) more than a quintillion, and so on. Thus, in five years, with no human intervention, such a device could refine more than half the mass of 16 Psyche, the most massive metallic M-type asteroid and one of the ten largest in the asteroid belt. The devices could then be harvested (they are, presumably, made of metals as well as silicon and other elements for their solar panels).

Space manufacturing

Space manufacturing is the production of manufactured goods in an environment outside a planetary atmosphere. Typically this includes conditions of microgravity and hard vacuum. Manufacturing in space has several potential advantages over Earth-based industry.

1. The unique environment can allow for industrial processes that cannot be readily reproduced on Earth.
2. Raw materials can be collected and processed from other bodies within the solar system at a low expense compared to the cost of lifting materials into orbit.
3. Potentially hazardous processes can be performed in space with minimal risk to the environment of the Earth or other planets.
4. Items too large to launch on a rocket can be assembled in orbit for use in orbit.



Comparison of insulin crystal growth in outer space (left) and on Earth (right). NASA image.

The space environment is expected to be beneficial for production of a variety of products. Once the heavy capitalization costs of assembling the mining and manufacturing facilities is paid, the production will need to be economically profitable in order to become self-sustaining and beneficial to society. The most significant cost is overcoming the energy hurdle for boosting materials into orbit. Once this barrier is significantly reduced in cost per kilogram, the entry price for space manufacturing can make it much more attractive to entrepreneurs.

Economic requirements of space manufacturing imply a need to collect the requisite raw materials at a minimum energy cost. The economical movement of material in space is directly related to the delta-v, or change in velocity required to move from the mining sites to the manufacturing plants. Near-earth asteroids, Phobos, Deimos and the lunar surface have a much lower delta-v compared to launching the materials from the surface of the Earth to Earth orbit.

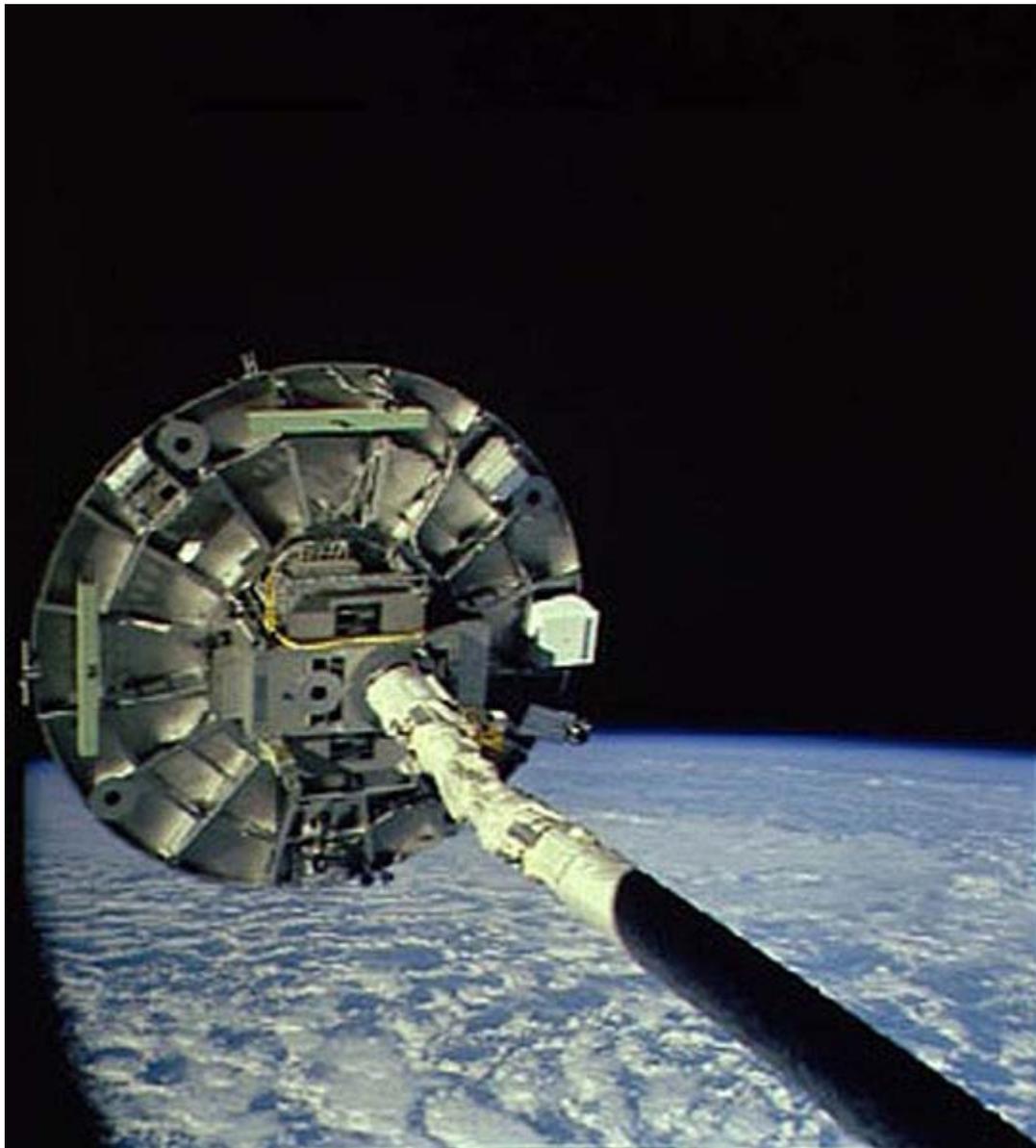
History

During the Soyuz 6 mission, Russian astronauts performed the first welding experiments in space. Three different welding processes were tested using a hardware unit called Vulkan. The tests included welding aluminum, titanium, and stainless steel.

The Skylab mission, launched in May, 1973, served as a laboratory to perform various space manufacturing experiments. The station was equipped with a materials processing facility that included a multi-purpose electric furnace, a crystal growth chamber, and an electron beam gun. Among the experiments to be performed was research on molten metal processing; photographing the behavior of ignited materials in zero-gravity; crystal growth; processing of immiscible alloys; brazing of stainless steel tubes, electron beam welding, and the formation of spheres from molten metal. The crew spent a total of 32 man-hours on materials science and space manufacturing investigation during the mission.

The Space Studies Institute began hosting a bi-annual *Space Manufacturing Conference* in 1977.

Microgravity research in materials processing continued in 1983 using the Spacelab facility. This module has been carried into orbit 26 times aboard the Space Shuttle, as of 2002. In this role the shuttle has served as an interim, short-duration research platform in lieu of the upcoming International Space Station.



The Wake Shield Facility is deployed by the Space Shuttle's robotic arm. *NASA image.*

In February 1994 and September 1995, the Wake Shield Facility was carried into orbit by the Space Shuttle. This demonstration platform used the vacuum created in the orbital wake to manufacture thin films of gallium arsenide and aluminum gallium arsenide.

On May 31, 2005, the recoverable, unmanned Foton-M2 laboratory was launched into orbit. Among the experiments were crystal growth and the behavior of molten-metal in weightlessness.

ISS

The completion of the International Space Station is expected to provide expanded and improved facilities for performing industrial research. These will lead to improvements in our knowledge of materials sciences, new manufacturing techniques on Earth, and potentially some important discoveries in space manufacturing methods. The completion of this facility has been delayed due to safety problems with the Space Shuttle.

The Material Science Laboratory Electromagnetic Levitator (MSL-EML) on board the Columbus Laboratory is a science facility that can be used to study the melting and solidification properties of various materials. The Fluid Science Laboratory (FSL) will be used to study the behavior of liquids in microgravity.

Environment

There are several unique differences between the properties of materials in space compared to the same materials on the Earth. These differences can be exploited to produce unique or improved manufacturing techniques.

- The microgravity environment allows control of convection in liquids or gasses, and the elimination of sedimentation. Diffusion becomes the primary means of material mixing, allowing otherwise immiscible materials to be intermixed. The environment allows enhanced growth of larger, higher-quality crystals in solution.
- The ultraclean vacuum of space allows the creation of very pure materials and objects. The use of vapor deposition can be used to build up materials layer by layer, free from defects.
- Surface tension causes liquids in microgravity to form perfectly round spheres. This can cause problems when trying to pump liquids through a conduit, but it is very useful when perfect spheres of consistent size are needed for an application.
- Space can provide readily available extremes of heat and cold. Sunlight can be focused to concentrate enough heat to melt the materials, while objects kept in perpetual shade are exposed to temperatures close to absolute zero. The temperature gradient can be exploited to produce strong, glassy materials.

Materials processing

For most manufacturing applications, specific material requirements must be satisfied. Mineral ores need to be refined to extract specific metals, and volatile organic compounds will need to be purified. Ideally these raw materials are delivered to the processing site in an economical manner, where time to arrival, propulsion energy expenditure, and extraction costs are factored into the planning process. Minerals can be

obtained from asteroids, the lunar surface, or a planetary body. Volatiles could potentially be obtained from a comet or the moons of Mars or other planets. It may also prove possible to extract hydrogen from the cold traps at the poles of the Moon.

Another potential source of raw materials, at least in the short term, is recycled orbiting satellites and other man-made objects in space. Some consideration was given to the use of the Space Shuttle external fuel tanks for this purpose, but NASA determined that the potential benefits were outweighed by the increased risk to crew and vehicle.

Unless the materials processing and the manufacturing sites are co-located with the resource extraction facilities, the raw materials will need to be moved about the solar system. There are several proposed means of providing propulsion for this material, including solar sails, magnetic sails, mini-magnetospheric plasma propulsion (which uses a cloud of ionized gas as a magnetic sail), electric ion thrusters, or mass drivers (this last method uses a sequence of electromagnets mounted in a line to accelerate a conducting material).

At the materials processing facility, the incoming materials will need to be captured by some means. Maneuvering rockets attached to the load can park the content in a matching orbit. Alternatively, if the load is moving at a low delta-v relative to the destination, then it can be captured by means of a mass-catcher. This could consist of a large, flexible net or inflatable structure that would transfer the momentum of the mass to the larger facility. Once in place, the materials can be moved into place by mechanical means or by means of small thrusters.

Materials can be used for manufacturing either in their raw form, or by processing them to extract the constituent elements. Processing techniques include various chemical, thermal, electrolytic, and magnetic methods for separation. In the near term, relatively straightforward methods can be used to extract aluminum, iron, oxygen, and silicon from lunar and asteroidal sources. Less concentrated elements will likely require more advanced processing facilities, which may have to wait until a space manufacturing infrastructure is fully developed.

Some of the chemical processes will require a source of hydrogen for the production of water and acid mixtures. Hydrogen gas can also be used to extract oxygen from the lunar regolith, although the process is not very efficient. So a readily available source of useful volatiles is a positive factor in the development of space manufacturing. Alternatively, oxygen can be liberated from the lunar regolith without reusing any imported materials. Just heat the regolith to 2,500 C in a vacuum. This was tested on Earth with lunar simulant in a vacuum chamber. As much as 20% of the sample was released as free oxygen. Eric Cardiff calls the remainder slag. This process is highly efficient in terms of imported materials used up per batch, but is not the most efficient process in energy per kilogram of oxygen.

One proposed method of purifying asteroid materials is through the use of carbon monoxide (CO). Heating the material to 500 °F (260 °C) and exposing it to CO causes

the metals to form gaseous carbonyls. This vapor can then be distilled to separate out the metal components, and the CO can then be recovered by another heating cycle. Thus an automated ship can scrape up loose surface materials from, say, the relatively nearby 4660 Nereus (in delta-v terms), process the ore using solar heating and CO, and eventually return with a load of almost pure metal. The economics of this process can potentially allow the material to be extracted at one-twentieth the cost of launching from Earth, but it would require a two-year round trip to return any mined ore.

Manufacturing

Due to speed of light constraints on communication, manufacturing in space at a distant point of resource acquisition will either require completely autonomous robotics to perform the labor, or a human crew with all the accompanying habitat and safety requirements. If the plant is built in orbit around the Earth, or near a manned space habitat, however, telecheric devices can be used for certain tasks that require human intelligence and flexibility.

Solar power provides a readily available power source for thermal processing. Even with heat alone, simple thermally-fused materials can be used for basic construction of stable structures. Bulk soil from the Moon or asteroids has a very low water content, and when melted to form glassy materials is very durable. These simple, glassy solids can be used for the assembly of habitats on the surface of the Moon or elsewhere. The solar energy can be concentrated in the manufacturing area using an array of steerable mirrors.

The availability and favorable physical properties of metals will make them a major component of space manufacturing. Most of the metal handling techniques used on Earth can also be adopted for space manufacturing, but a few will need significant modifications. The microgravity environment of space will necessitate modifications to some metal handling techniques.

The production of hardened steel in space will introduce some new factors. Carbon only appears in small proportions in lunar surface materials and will need to be delivered from elsewhere. Waste materials carried by humans from the Earth is one possible source, as are comets. The water normally used to quench steel will also be in short supply, and require strong agitation.

Casting steel can be a difficult process in microgravity, requiring special heating and injection processes, or spin forming. Heating can be performed using sunlight combined with electrical heaters. The casting process would also need to be managed to avoid the formation of voids as the steel cools and shrinks.

Various metal-working techniques can be used to shape the metal into the desired form. The standard methods are casting, drawing, forging, machining, rolling, and welding. Both rolling and drawing metals require heating and subsequent cooling. Forging and extrusion can require powered presses, as gravity is not available. Electron beam welding has already been demonstrated on board the Skylab, and will probably be the method of

choice in space. Machining operations can require precision tools which will need to be imported from the Earth for some duration.

New space manufacturing technologies are being studied at places such as Marshall's *National Center for Advanced Manufacturing*. The methods being investigated include coatings that can be sprayed on surfaces in space using a combination of heat and kinetic energy, and electron beam free form fabrication of parts. Approaches such as these, as well as examination of material properties that can be investigated in an orbiting laboratory, will be studied on the International Space Station.

Products

There are thought to be a number of useful products that can potentially be manufactured in space and result in an economic benefit. Research and development is required to determine the best commodities to be produced, and to find efficient production methods. The following products are considered prospective early candidates:

- Growth of protein crystals
- Improved semiconductor wafers
- Micro-encapsulation

As the infrastructure is developed and the cost of assembly drops, some of the manufacturing capacity can be directed toward the development of expanded facilities in space, including larger scale manufacturing plants. These will likely require the use of lunar and asteroid materials, and so follow the development of mining bases.

Rock is the simplest product, and at minimum is useful for radiation shielding. It can also be subsequently processed to extract elements for various uses.

Water from lunar sources, Near Earth Asteroids or Martian moons is thought to be relatively cheap and simple to extract, and gives adequate performance for many manufacturing and material shipping purposes. Separation of water into hydrogen and oxygen can be easily performed in small scale, but some scientists believe that this will not be performed on any large scale initially due to the large quantity of equipment and electrical energy needed to split water and liquify the resultant gases. Water used in steam rockets gives a specific impulse of about 190 seconds; less than half that of hydrogen/oxygen, but this is adequate for delta-v's that are found between Mars and Earth. Water is useful as a radiation shield and in many chemical processes.

Ceramics made from lunar or asteroid soil can be employed for a variety of manufacturing purposes. These uses include various thermal and electrical insulators, such as heat shields for payloads being delivered to the Earth's surface.

Metals can be used to assemble a variety of useful products, including sealed containers (such as tanks and pipes), mirrors for focusing sunlight, and thermal radiators. The use of

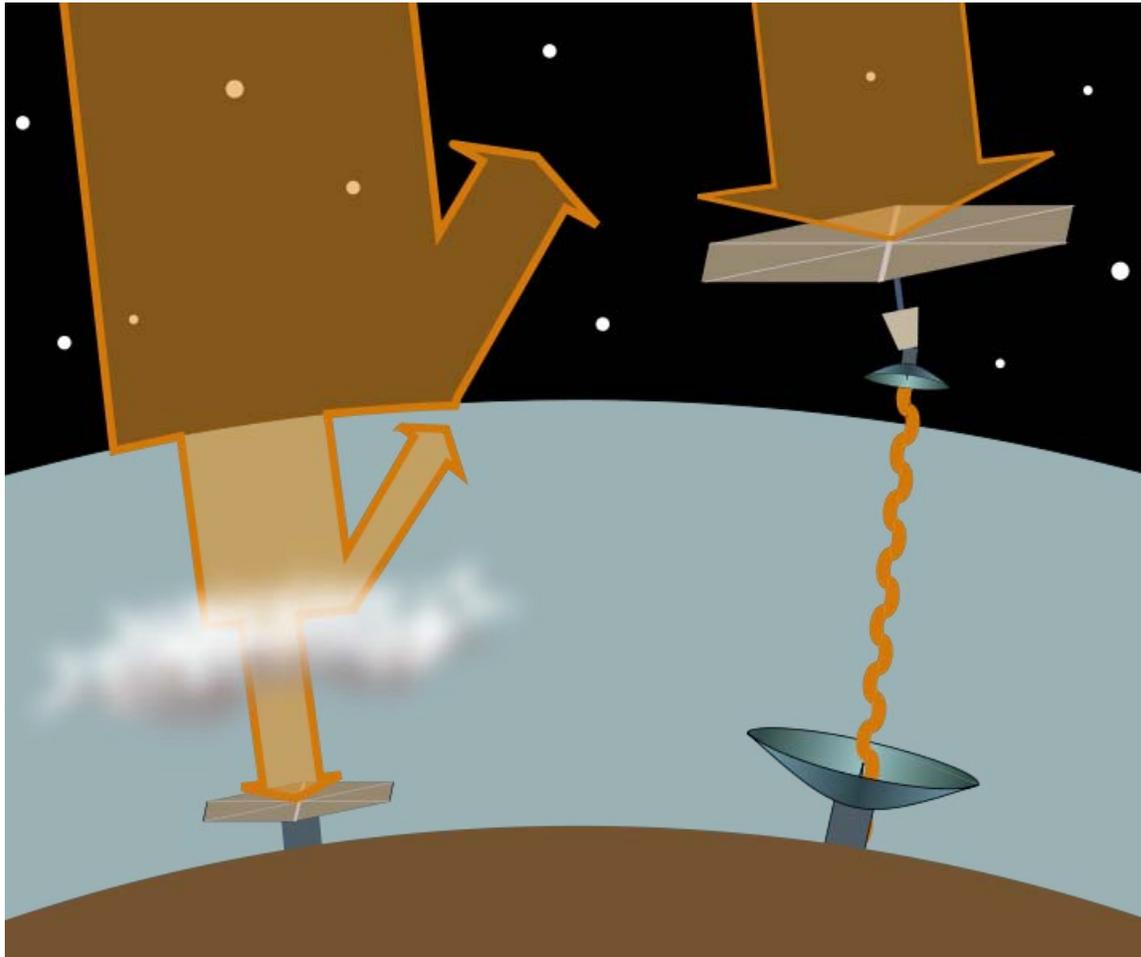
metals for electrical devices would require insulators for the wires, so a flexible insulating material such as plastic or fiberglass will be needed.

A notable output of space manufacturing is expected to be **solar panels**. Expansive solar energy arrays can be constructed and assembled in space. As the structure does not need to support the loads that would be experienced on Earth, huge arrays can be assembled out of proportionately smaller amounts of material. The generated energy can then be used to power manufacturing facilities, habitats, spacecraft, lunar bases, and even beamed down to collectors on the Earth with microwaves.

Other possibilities for space manufacturing include propellants for spacecraft, some repair parts for spacecraft and space habitats, and, of course, larger factories. Ultimately, space manufacturing facilities can hypothetically become nearly self-sustaining, requiring only minimal imports from the Earth. The microgravity environment allows for new possibilities in construction on a massive scale, including megascale engineering. These future projects might potentially assemble space elevators, massive solar array farms, very high capacity spacecraft, and rotating habitats capable of sustaining populations of tens of thousands of people in Earth-like conditions.

Chapter-3

Space-based Solar Power



On the left: Part of the solar energy is lost on its way through the atmosphere by the effects of reflection and absorption.

On the right: Space-based solar power systems convert sunlight to microwaves outside the atmosphere, avoiding these losses, and the downtime due to Earth's rotation, experienced by surface installations.

Space-based solar power (SBSP) (or historically **space solar power- SSP**) is a system for the collection of solar power in space, for use on Earth. SBSP differs from the usual

method of solar power collection in that the solar panels used to collect the energy would reside on a satellite in orbit, often referred to as a **solar power satellite** (SPS), rather than on Earth's surface. In space, collection of the Sun's energy is unaffected by the various obstructions which reduce efficiency or capacities of Earth surface solar power collection.

The World Radiation Centre's 1985 standard extraterrestrial level for solar irradiance is 1367 W/m^2 . The integrated total terrestrial solar irradiance is 950 W/m^2 . Extraterrestrial solar irradiance is thus 144% of the maximum terrestrial irradiance, and has a different radiation profile, including wavelengths blocked by the atmosphere. A major interest in SBSP stems from the length of time the solar collection panels can be exposed to a consistently high amount of solar radiation. For most of the year, a satellite-based solar panel can collect power 24 hours per day, whereas a terrestrial station can collect for at most 12 hours per day, if weather permits, and only during peak hours—irradiance under the best of conditions is quite reduced near sunset and sunrise.

Collection of solar energy in space for use on Earth introduces two new problems and can alleviate an existing one. First, installation of the collection satellites, and second transmitting energy from them to the surface for use. The first requires upgrading and extension of existing solar panel technologies. Since wires extending from Earth's surface to an orbiting satellite are neither practical nor currently possible, many SBSP designs have proposed the use of microwave beams for wireless power transmission. The collecting satellite would convert solar energy into electrical energy, powering a microwave emitter oriented toward a collector on the Earth's surface. Dynamic solar thermal power systems on satellites are also being investigated. Since the beam can be steered, it can be directed as needed to accommodate periods of high power use in particular locations (e.g., during the hottest part of the day in summer, or cold spells in winter). As well, one of the current problems of electricity use is long distance transmission from generating sites to usage sites. Because at least one type of receiving antenna, the rectenna, is relatively inexpensive, it may be possible to reduce the need for electricity transmission lines by sensible siting of receiving antennas, potentially reducing costs and grid interconnect failures, such as the blackouts of 1965 and 2003.

Some problems normally associated with terrestrial solar power collection would be entirely avoided by such a design, e.g., dependence on weather conditions, contamination or corrosion, damage by wildlife or plant encroachment, etc. Other problems will likely be encountered, such as more rapid radiation damage or micrometeoroid impacts.

Timeline

- **1968:** Dr. Peter Glaser introduced the idea of a large solar power satellite system with square miles of solar collectors in high geosynchronous orbit (GEO is an orbit 36,000 km above the equator), for collection and conversion of sun's energy into an electromagnetic microwave beam to transmit usable energy to large receiving antennas (rectennas) on Earth for distribution.

- **1973:** Dr. Peter Glaser was granted U.S. patent number 3,781,647 for his method of transmitting power over long distances (e.g., from an SPS to the Earth's surface) using microwaves from a large (on the close order of one square kilometer) antenna on the satellite to a much larger one on the ground, now known as a rectenna.
- **1970s:** DOE and NASA examined the Solar Power Satellite (SPS) concept extensively, publishing the design and feasibility studies.
- **1994:** The United States Air Force conducted the Advanced Photovoltaic Experiment using a satellite launched into low Earth orbit by a Pegasus rocket.
- **1995–1997:** NASA conducted a “Fresh Look” study of space solar power (SSP) concepts and technologies.
- **1998:** Space Solar Power Concept Definition Study (CDS) identified credible commercially viable SSP concepts, identifying technical and programmatic risks.
- **1998:** Japan's space agency starts a program for developing a Space Solar Power System (SSPS), which continues to the present day.
- **1999:** NASA's Space Solar Power Exploratory Research and Technology program begun.
- **2000:** John Mankins of NASA testified in the U.S. House of Representatives, saying "Large-scale SSP is a very complex integrated system of systems that requires numerous significant advances in current technology and capabilities. A technology roadmap has been developed that lays out potential paths for achieving all needed advances — albeit over several decades.
- **2001:** PowerSat Corporation founded by William Maness.
- **2001:** Dr. Neville Marzwell of NASA stated, "We now have the technology to convert the sun's energy at the rate of 42 to 56 percent... We have made tremendous progress. ...If you can concentrate the sun's rays through the use of large mirrors or lenses you get more for your money because most of the cost is in the PV arrays... There is a risk element but you can reduce it... You can put these small receivers in the desert or in the mountains away from populated areas. ...We believe that in 15 to 25 years we can lower that cost to 7 to 10 cents per kilowatt hour. ...We offer an advantage. You don't need cables, pipes, gas or copper wires. We can send it to you like a cell phone call—where you want it and when you want it, in real time."
- **2001:** NASDA (Japan's national space agency) announced plans to perform additional research and prototyping by launching an experimental satellite with 10 kilowatts and 1 megawatt of power.

- **2007:** The US Pentagon's National Security Space Office (NSSO) issued a report on October 10, 2007 stating they intend to collect solar energy from space for use on Earth to help the United States' ongoing relationship with the Middle East and the battle for oil. The International Space Station may be the first test ground for this new idea, even though it is in a low-earth orbit.
- **2007:** In May 2007 a workshop was held in the USA at MIT to review the current state of the market and technology.
- **2009:** A new company from the US, Space Energy, Inc., announced plans to provide commercial space-based solar power. They say they have developed a "rock-solid business platform" and should be able to provide space-based solar power within a decade.
- **2009:** American company Pacific Gas and Electric (PG&E) announced it is seeking regulatory approval for an agreement with Solaren to buy 200 MW of solar power, starting in 2016, which Solaren has plans to provide via SBSP. PG&E spokesman Jonathan Marshall stated that "We've been very careful not to bear risk in this."
- **2009:** PowerSat Corporation filed a patent application concerning ganging multiple power satellites to form a single coherent microwave beam, and a mechanism to use the solar array to power ion thrusters to lift a power satellite from LEO to GEO.
- **2009:** Japan announced plans to orbit solar power satellites that will transmit energy back to earth via microwaves. They hope to have the first prototype orbiting by 2030.
- **2010:** Europe's largest space company EADS Astrium plans to put a solar-collecting demo satellite in space.
- **2010:** Prof. Andrea Massa and Prof. Giorgio Franceschetti will organize a Special Session on the "Analysis of Electromagnetic Wireless Systems for Solar Power Transmission" at the 2010 IEEE International Symposium on Antennas and Propagation.

History

The SBSP concept, originally known as *Satellite Solar Power System* ("SSPS") was first described in November 1968. In 1973 Peter Glaser was granted U.S. patent number 3,781,647 for his method of transmitting power over long distances (e.g., from an SPS to the Earth's surface) using microwaves from a very large (up to one square kilometer) antenna on the satellite to a much larger one on the ground, now known as a rectenna.

Glaser then worked at Arthur D. Little, Inc., as a vice-president. NASA signed a contract with ADL to lead four other companies in a broader study in 1974. They found that, while the concept had several major problems—chiefly the expense of putting the required materials in orbit and the lack of experience on projects of this scale in space, it showed enough promise to merit further investigation and research.

Between 1978 and 1981 the US Congress authorized DOE and NASA to jointly investigate the concept. They organized the Satellite Power System Concept Development and Evaluation Program. The study remains the most extensive performed to date. Several reports were published investigating the engineering feasibility of such an engineering project. They include:

- Resource Requirements (Critical Materials, Energy, and Land)
- Financial/Management Scenarios
- Public Acceptance
- State and Local Regulations as Applied to Satellite Power System Microwave Receiving Antenna Facilities
- Student Participation
- Potential of Laser for SBSP Power Transmission
- International Agreements
- Centralization/Decentralization
- Mapping of Exclusion Areas For Rectenna Sites
- Economic and Demographic Issues Related to Deployment
- Some Questions and Answers
- Meteorological Effects on Laser Beam Propagation and Direct Solar Pumped Lasers
- Public Outreach Experiment
- Power Transmission and Reception Technical Summary and Assessment
- Space Transportation

The project was not continued with the change in Administrations after the 1980 US Federal elections.

The Office of Technology Assessment concluded

Too little is currently known about the technical, economic, and environmental aspects of SPS to make a sound decision whether to proceed with its development and deployment. In addition, without further research an SPS demonstration or systems-engineering verification program would be a high-risk venture.

More recently, the SBSP concept has again become interesting, due to increased energy demand, increased energy costs, and emission implications, starting in 1997 with the NASA "Fresh Look". In assessing "What has changed" since the DOE study, this study asserts that

Another important change has occurred at the US national policy level. US National Space Policy now calls for NASA to make significant investments in technology (not a particular vehicle) to drive the costs of ETO [*Earth to Orbit*] transportation down dramatically. This is, of course, an absolute requirement of space solar power.

One might take the NASA "Fresh Look" study as encouraging because the main difficulty identified is driving down Earth to Orbit costs. However, Dr. Pete Worden claimed that space-based solar is about five orders of magnitude more expensive than solar power from the Arizona desert. A major factor in this five orders of magnitude is the cost of transporting materials to orbit. Dr. Worden referred to possible solutions as speculative solutions that would not be available for decades at the best, leaving space-based solar power with no business case for the foreseeable future.

SERT

In 1999 NASA's Space Solar Power Exploratory Research and Technology program (SERT) was initiated for the following purpose:

- Perform design studies of selected flight demonstration concepts;
- Evaluate studies of the general feasibility, design, and requirements.
- Create conceptual designs of subsystems that make use of advanced SSP technologies to benefit future space or terrestrial applications.
- Formulate a preliminary plan of action for the U.S. (working with international partners) to undertake an aggressive technology initiative.
- Construct technology development and demonstration roadmaps for critical Space Solar Power (SSP) elements.

It was to develop a solar power satellite (SPS) concept for a future gigawatt space power systems to provide electrical power by converting the Sun's energy and beaming it to the Earth's surface. It was also to provide a developmental path to solutions for current space power architectures. Subject to further study, it proposed an inflatable photovoltaic gossamer structure with concentrator lenses or solar heat engines to convert sunlight into electricity. The program looked at both systems in sun-synchronous orbit and geosynchronous orbit.

Some of SERT's conclusions include the following:

- The increasing global energy demand is likely to continue for many decades resulting in new power plants of all sizes being built.
- The environmental impact of those plants and their impact on world energy supplies and geopolitical relationships can be problematic.
- Renewable energy is a compelling approach, both philosophically and in engineering terms.
- Many renewable energy sources are limited in their ability to affordably provide the base load power required for global industrial development and prosperity, because of inherent land and water requirements.

- Based on their Concept Definition Study, space solar power concepts may be ready to reenter the discussion.
- Solar power satellites should no longer be envisioned as requiring unimaginably large initial investments in fixed infrastructure before the emplacement of productive power plants can begin.
- Space solar power systems appear to possess many significant environmental advantages when compared to alternative approaches.
- The economic viability of space solar power systems depends on many factors and the successful development of various new technologies (not least of which is the availability of much lower cost access to space than has been available), however, the same can be said of many other advanced power technologies options.
- Space solar power may well emerge as a serious candidate among the options for meeting the energy demands of the 21st century.

Advantages

The SBSP concept is attractive because space has several major advantages over the Earth's surface for the collection of solar power. There is no air in space, so the collecting surfaces would receive much more intense sunlight, unaffected by weather. In geostationary orbit, an SPS would be illuminated over 99% of the time; such an SPS would be in Earth's shadow on only a few days at the spring and fall equinoxes; and even then for a maximum of 75 minutes late at night when power demands are at their lowest. This characteristic of SBSP avoids the expense of storage facilities (dams, oil storage tanks, coal dumps) necessary in many Earth-based power generation systems. Additionally, SBSP would have fewer or none of the ecological (or political) consequences of fossil fuel systems.

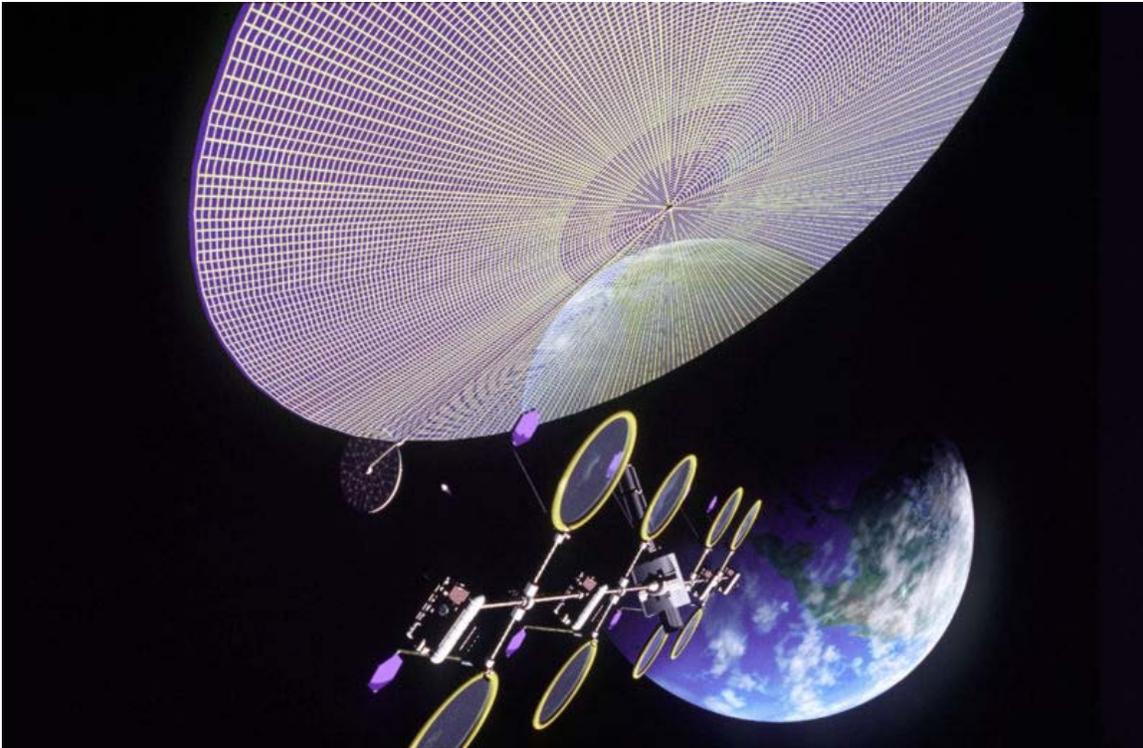
SBSP would also be applicable on a global scale. Nuclear power raises questions of proliferation and waste disposal, which pose problems everywhere, but especially in undeveloped areas which are less capable of coping with them. SBSP poses no such known potential threat.

This technology can be of value to relief efforts in disaster areas. SBSP could step in at short notice to provide as much power as is necessary both for the relief effort and to provide continuity of energy until ground based transfer methods are restored.

There is a significant military advantage to SBSP in that it would provide the option to have almost instantaneous sustained power nearly anywhere on the globe. It has been estimated that the average price of fuel for the US Army exceeds \$5 per gallon. During Operation Iraqi Freedom, there is an estimate that fuel costs in some areas approached \$20 per gallon. This is undoubtedly due to the cost of physically moving large quantities of fuel, and the massive security costs in protecting these convoys in a war zone. The estimated costs given above do not include the high cost in the lives of American servicemen and women who are killed or injured during attacks on supply convoys. With a mobile SBSP receiving station, the Army could quickly be provided with megawatts of

clean, sustained energy. If a conflict forced a rapid change in the geographic location of Army personnel, the power from SBSP could simply be redirected by altering the position of the SBSP satellites. If SBSP became an established source of power, it could also provide a military benefit in that the supply would inherently be much more secure than traditional energy delivery methods, chances of an energy scarcity based conflict could be much reduced.

Design



Space-based solar power essentially consists of three parts:

1. a means of collecting solar power in space, for example via solar cells or a heat engine
2. a means of transmitting power to earth, for example via microwave or laser
3. a means of receiving power on earth, for example via a microwave antenna (rectenna)

The space-based portion will be in a freefall, vacuum environment and will not need to support itself against gravity other than relatively weak tidal stresses. It needs no protection from terrestrial wind or weather, but will have to cope with space-based hazards such as micrometeors and solar storms.

Solar energy conversion (solar photons to DC current)

Two basic methods of converting sunlight to electricity have been studied: photovoltaic (PV) conversion, and solar dynamic (SD) conversion.

Most analyses of solar power satellites have focused on photovoltaic conversion (commonly known as “solar cells”). Photovoltaic conversion uses semiconductor cells (*e.g.*, silicon or gallium arsenide) to directly convert photons into electrical power via a quantum mechanical mechanism. Photovoltaic cells are not perfect in practice, as material purity and processing issues during production affect performance; each has been progressively improved for some decades. Some new, thin-film approaches are less efficient (about 20% vs 41% for best in class in each case as of late 2009), but are much less expensive and generally lighter.

In an SPS implementation, photovoltaic cells will likely be rather different from the glass-pane protected solar cell panels familiar to many in current terrestrial use, since they will be optimized for weight, and will be designed to be tolerant of the space radiation environment (some thin film silicon solar panels are highly insensitive to ionising radiation), but will not need to be encapsulated against corrosion from environmental exposure or biological deterioration. They do not require the structural support required for terrestrial use, where the considerable gravity and wind loading imposes structural requirements on terrestrial implementations.

Wireless power transmission to the Earth

Wireless power transmission was proposed early on as a means to transfer energy from collection to the Earth's surface. The power could be transmitted as either microwave or laser radiation at a variety of frequencies depending on system design. Whichever choice is made, the transmitting radiation would have to be non-ionizing to avoid potential disturbances either ecologically or biologically. This established an upper limit for the frequency used, as energy per photon (and consequently the ability to cause ionization) increases with frequency. Ionization of biological materials doesn't begin until ultraviolet or higher frequencies, so most radio frequencies would be feasible.

Microwave power transmission

William C. Brown demonstrated in 1964, during Walter Cronkite's CBS News program, a microwave-powered model helicopter that received all the power it needed for flight from a microwave beam. Between 1969 and 1975, Bill Brown was technical director of a JPL Raytheon program that beamed 30 kW of power over a distance of 1 mile at 84% efficiency.

Microwave power transmission of tens of kilowatts has been well proven by existing tests at Goldstone in California (1975) and Grand Bassin on Reunion Island (1997).

More recently, microwave power transmission has been demonstrated, in conjunction with solar energy capture, between a mountain top in Maui and the main island of Hawaii (92 miles away), by a team under John C. Mankins. Technological challenges in terms of array layout, single radiation element design, and overall efficiency, as well as the associated theoretical limits are presently a subject of research, as it is demonstrated by the upcoming Special Session on "Analysis of Electromagnetic Wireless Systems for Solar Power Transmission" to be held in the 2010 IEEE Symposium on Antennas and Propagation.

Laser power beaming experiments

A large-scale demonstration of power beaming is a necessary step to the development of solar power satellites. Laser power beaming was envisioned by some at NASA as a stepping stone to further industrialization of space.

In the 1980s researchers at NASA worked on the potential use of lasers for space-to-space power beaming, focusing primarily on the development of a solar-powered laser. In 1989 it was suggested that power could also be usefully beamed by laser from Earth to space. In 1991 the SELENE project (Space Laser ENergy) was begun, which included the study of laser power beaming for supplying power to a lunar base.

In 1988 the use of an Earth-based laser to power an electric thruster for space propulsion was proposed by Grant Logan, with technical details worked out in 1989. He proposed using diamond solar cells operating at six hundred degrees to convert ultraviolet laser light, a technology that has yet to be demonstrated even in the laboratory. His ideas were adapted to be more practical.

The SELENE program was a two-year research effort, but the cost of taking the concept to operational status was too high, and the official project was ended in 1993, before reaching a space-based demonstration.

Spacecraft sizing

The size of a solar power satellite would be dominated by two factors: the size of the collecting apparatus (e.g. panels and mirrors), and the size of the transmitting antenna. The distance from Earth to geostationary orbit (22,300 miles, 35,700 km), the chosen wavelength of the microwaves, and certain laws of physics (specifically the Rayleigh Criterion or diffraction limit) will all be factors.

It has been suggested that, for best efficiency, the satellite antenna should be circular and about 1 kilometer in diameter or larger; the ground antenna (rectenna) should be elliptical, 10 km wide, and a length that makes the rectenna appear circular from GEO (Geostationary Orbit). (Typically, 14 km at some North American latitudes.) Smaller antennas would result in increased losses to diffraction/sidelobes. For the desired (23 mW/cm²) microwave intensity these antennas could transfer between 5 and 10 gigawatts of power.

According to some research, to collect and convert the target volume of power, the satellite would require between 50 and 100 square kilometers of collector area (if readily available ~14% efficient monocrystalline silicon solar cells were deployed). State of the art multi-junction solar cells with a maximum efficiency of 43% could reduce the necessary collector area by two thirds. In any case, an SPS's structure will necessarily be large (perhaps kilometers across), making it larger than most man-made structures on Earth, and building structures of such size in orbit has never been attempted.

Location

GEO

The main advantage of locating a space power station in geostationary orbit is that the antenna geometry stays constant, and so keeping the antennas lined up is simpler. Another advantage is that nearly continuous power transmission is immediately available as soon as the first space power station is placed in orbit; other space-based power stations have much longer start-up times before they are producing nearly continuous power.

LEO/MEO instead of GEO

A collection of LEO (Low Earth Orbit) space power stations has been proposed as a precursor to GEO (Geostationary Orbit) space-based solar power. There would be both advantages (shorter energy transmission path, lower cost) and disadvantages (frequent changes in antenna geometries, increased debris collisions, more power stations needed to receive power continuously). It might be possible to deploy LEO systems sooner than GEO because the antenna development would take less time, but it may take longer to prepare and launch the number of required satellites.

Moon

People such as David Criswell suggest that the moon is the optimum location for solar power stations, and promote **lunar solar power**.

The main advantages of locating the solar power collector on the moon is that most of its mass could be constructed out of locally available lunar materials, using in-situ resource utilization, significantly reducing the amount of mass and therefore the launch costs required compared to other space-based solar power stations.

Earth-based infrastructure

The Earth-based receiver antenna (or rectenna) is a critical part of the original SPS concept. It would probably consist of many short dipole antennas, connected via diodes. Microwaves broadcast from the SPS will be received in the dipoles with about 85% efficiency. With a conventional microwave antenna, the reception efficiency is still better, but the cost and complexity is also considerably greater, almost certainly prohibitively so. Rectennas would be multiple kilometers across. Crops and farm animals may be raised underneath a rectenna, as the thin wires used for support and for the dipoles will only slightly reduce sunlight, or non arable land could be used, so such a rectenna would not be as expensive in terms of land use as might be supposed.

Dealing with launch costs

One problem for the SBSP concept is the cost of space launches and the amount of material that would need to be launched.

Much of the material launched need not be delivered to its eventual orbit immediately, which raises the possibility that high efficiency (but slower) engines could move SPS material from LEO to GEO at an acceptable cost. Examples include ion thrusters or nuclear propulsion.

Power beaming from geostationary orbit by microwaves carries the difficulty that the required 'optical aperture' sizes are very large. For example, the 1978 NASA SPS study required a 1-km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz. These sizes can be somewhat decreased by using shorter wavelengths, although they have increased atmospheric absorption and even potential beam blockage by rain or water droplets. Because of the thinned array curse, it is not possible to make a narrower beam by combining the beams of several smaller satellites. The large size of the transmitting and receiving antennas means that the minimum practical power level for an SPS will necessarily be high; small SPS systems will be possible, but uneconomic.

To give an idea of the scale of the problem, assuming a solar panel mass of 20 kg per kilowatt (without considering the mass of the supporting structure, antenna, or any significant mass reduction of any focusing mirrors) a 4 GW power station would weigh about 80,000 metric tons, all of which would, in current circumstances, be launched from the Earth. Very lightweight designs could likely achieve 1 kg/kW, meaning 4,000 metric tons for the solar panels for the same 4 GW capacity station. This would be the equivalent of between 40 and 150 heavy-lift launch vehicle (HLLV) launches to send the material to low earth orbit, where it would likely be converted into subassembly solar arrays, which then could use high-efficiency ion-engine style rockets to (slowly) reach GEO (Geostationary orbit). With an estimated serial launch cost for shuttle-based HLLVs of \$500 million to \$800 million, and launch costs for alternative HLLVs at \$78 million, total launch costs would range between \$11 billion (low cost HLLV, low weight panels) and \$320 billion ('expensive' HLLV, heavier panels). For comparison, the direct cost of a

new coal or nuclear power plant ranges from \$1 billion to \$1.5 billion dollars per GW (not including the full cost to the environment from CO2 emissions or storage of spent nuclear fuel, respectively); another example is the Apollo missions to the Moon cost a grand total of \$24 billion (1970's dollars), taking inflation into account, would cost \$140 billion today, more expensive than the construction of the International Space Station.

Building from space

Gerard O'Neill, noting the problem of high launch costs in the early 1970s, proposed building the SPS's in orbit with materials from the Moon. Launch costs from the Moon are potentially much lower than from Earth, due to the lower gravity. This 1970s proposal assumed the then-advertised future launch costing of NASA's space shuttle. This approach would require substantial up front capital investment to establish mass drivers on the Moon.

Nevertheless, on 30 April 1979, the Final Report ("Lunar Resources Utilization for Space Construction") by General Dynamics' Convair Division, under NASA contract NAS9-15560, concluded that use of lunar resources would be cheaper than Earth-based materials for a system of as few as thirty Solar Power Satellites of 10GW capacity each.

In 1980, when it became obvious NASA's launch cost estimates for the space shuttle were grossly optimistic, O'Neill et al. published another route to manufacturing using lunar materials with much lower startup costs. This 1980s SPS concept relied less on human presence in space and more on partially self-replicating systems on the lunar surface under remote control of workers stationed on Earth. This proposal suffers from the current lack of such automated systems. The design and construction of these automated systems and their use to produce a mass driver launching system on the moon from lunar materials is expected to take more than twenty years. The partially self replicating systems would include locally produced power generation, perhaps solar cells or heat engine produced electrical power.

Asteroid mining has also been seriously considered. A NASA design study evaluated a 10,000 ton mining vehicle (to be assembled in orbit) that would return a 500,000 ton asteroid fragment to geostationary orbit. Only about 3,000 tons of the mining ship would be traditional aerospace-grade payload. The rest would be reaction mass for the mass-driver engine, which could be arranged to be the spent rocket stages used to launch the payload. Assuming that 100% of the returned asteroid was useful, and that the asteroid miner itself couldn't be reused, that represents nearly a 95% reduction in launch costs. However, the true merits of such a method would depend on a thorough mineral survey of the candidate asteroids; thus far, we have only estimates of their composition.

Having a relatively cheap per pound source of raw materials from space would lessen the concern for low mass designs and result in a different sort of SPS being built. The low cost per pound of lunar materials in O'Neill's vision would be supported by using lunar material to manufacture more facilities in orbit than just solar power satellites.

Non-conventional launch methods

SBSP costs might be reduced if a means of putting the materials into orbit were developed that did not rely on rockets. Some possible technologies include ground launch systems such as mass drivers or Lofstrom loops, which would launch using electrical power, or the geosynchronous orbit space elevator. However, these require technology that is yet to be developed. John Hunter of Quicklaunch is working on commercialising the 'Hydrogen Gun', a new form of mass driver which proposes to deliver unmanned payloads to orbit for around 5% of regular launch costs (or \$500 per pound; US\$1,000 *per* kilogram) and perform 5 launches *per* day.

Advanced techniques for launching from the moon may reduce the cost of building a solar power satellite from lunar materials. Some proposed techniques include the lunar mass driver and the lunar space elevator, first described by Jerome Pearson. It would require establishing silicon mining and solar cell manufacturing facilities on the Moon.

Counter arguments

Safety

The use of microwave transmission of power has been the most controversial issue in considering any SPS design.

At the Earth's surface, a suggested microwave beam would have a maximum intensity at its center, of 23 mW/cm² (less than 1/4 the solar irradiation constant), and an intensity of less than 1 mW/cm² outside of the rectenna fence line (the receiver's perimeter). These compare with current United States Occupational Safety and Health Act (OSHA) workplace exposure limits for microwaves, which are 10 mW/cm², - the limit itself being expressed in voluntary terms and ruled unenforceable for Federal OSHA enforcement purposes. A beam of this intensity is therefore at its center, of a similar magnitude to current safe workplace levels, even for long term or indefinite exposure. Outside the receiver, it is far less than the OSHA long-term levels. Over 95% of the beam energy will fall on the rectenna. The remaining microwave energy will be absorbed and dispersed well within standards currently imposed upon microwave emissions around the world. It is important for system efficiency that as much of the microwave radiation as possible be focused on the rectenna. Outside of the rectenna, microwave intensities rapidly decrease, so nearby towns or other human activity should be completely unaffected.

Exposure to the beam is able to be minimized in other ways. On the ground, physical access is controllable (e.g., via fencing), and typical aircraft flying through the beam provide passengers with a protective metal shell (i.e., a Faraday Cage), which will intercept the microwaves. Other aircraft (balloons, ultralight, etc.) can avoid exposure by observing airflight control spaces, as is currently done for military and other controlled airspace.

The microwave beam intensity at ground level in the center of the beam would be designed and physically built into the system; simply, the transmitter would be too far away and too small to be able to increase the intensity to unsafe levels, even in principle.

In addition, a design constraint is that the microwave beam must not be so intense as to injure wildlife, particularly birds. Experiments with deliberate microwave irradiation at reasonable levels have failed to show negative effects even over multiple generations.

Some have suggested locating rectennas offshore, but this presents serious problems, including corrosion, mechanical stresses, and biological contamination.

A commonly proposed approach to ensuring fail-safe beam targeting is to use a retrodirective phased array antenna/rectenna. A "pilot" microwave beam emitted from the center of the rectenna on the ground establishes a phase front at the transmitting antenna. There, circuits in each of the antenna's subarrays compare the pilot beam's phase front with an internal clock phase to control the phase of the outgoing signal. This forces the transmitted beam to be centered precisely on the rectenna and to have a high degree of phase uniformity; if the pilot beam is lost for any reason (if the transmitting antenna is turned away from the rectenna, for example) the phase control value fails and the microwave power beam is automatically defocused. Such a system would be physically incapable of focusing its power beam anywhere that did not have a pilot beam transmitter.

The long-term effects of beaming power through the ionosphere in the form of microwaves has yet to be studied, but nothing has been suggested which might lead to any significant effect.

Atmospheric damage due to launches

When hot rocket exhaust reacts with atmospheric nitrogen, it can form nitrogen compounds. In particular these nitrogen compounds are problematic when they form in the stratosphere, as they can damage the ozone layer. However, the environmental effect of rocket launches is negligible compared to higher volume pollutants, such as airplanes and automobiles.

In fiction

- Space stations transmitting solar power have appeared in science-fiction works like Isaac Asimov's *Reason* (1941), that centers around the troubles caused by the robots operating the station. Asimov's short story "The Last Question" also features the use of SBSP to provide limitless energy for use on Earth.
- In the novel "Skyfall" (1976) by Harry Harrison an attempt to launch the core of powersat from Cape Canaveral ends in disaster when the launch vehicle fails trapping the payload in a decaying orbit.
- Solar Power Satellites have also been seen in the work of author Ben Bova's novels "Powersat" and "Colony".

- In Sid Meier's *Alpha Centauri*, an endgame 'building' that fulfills the same function as an SPS is the 'Orbital Power Transmitter' which provides every city that you own with a unit of energy per satellite launched, providing the city has an Aerospace Command building or your faction controls the space elevator. Building multiple Orbital Power Transmitters provides massive bonuses to energy generation and soon pay for themselves many times over.
- In a 1981 storyline from the Iron Man comic book (issues #142-144), a rogue microwave transmission from a secret Solar Power Satellite is responsible for numerous deaths in Allentown, Iowa.
- In the computer games *SimCity 2000* and *3000*, plants that implemented solar satellite technology called microwave powerplants were available in the future. One disaster scenario involved the beam missing the receiver and hitting the city's infrastructure. The plant was discontinued in *SimCity 4* but several fan-made microwave powerplants were available on various *SimCity 4* fan sites.
- In the film *Die Another Day*, a satellite weapon is disguised as a solar power satellite.
- In *Mobile Suit Gundam 00*, a solar power satellite array is constructed around the Earth and is used to harness solar energy for use. They play a critical plot role in the superpowers' power balance.
- In *After War Gundam X*, a solar power station is built on the moon, and is used to supply energy via microwave to various mobile suits, to energize their powerful "Satellite Cannons".