Space Colonization Handbook

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Space Colonization

Artist Les Bossinas' 1989 concept of Mars mission

Space colonization (also called *space settlement*, *space humanization*, or *space habitation*) is the concept of permanent human habitation outside of Earth. Although hypothetical at the present time, there are many proposals and speculations about the first space colony. It is seen as a long-term goal of some 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 impacter 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 free 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.

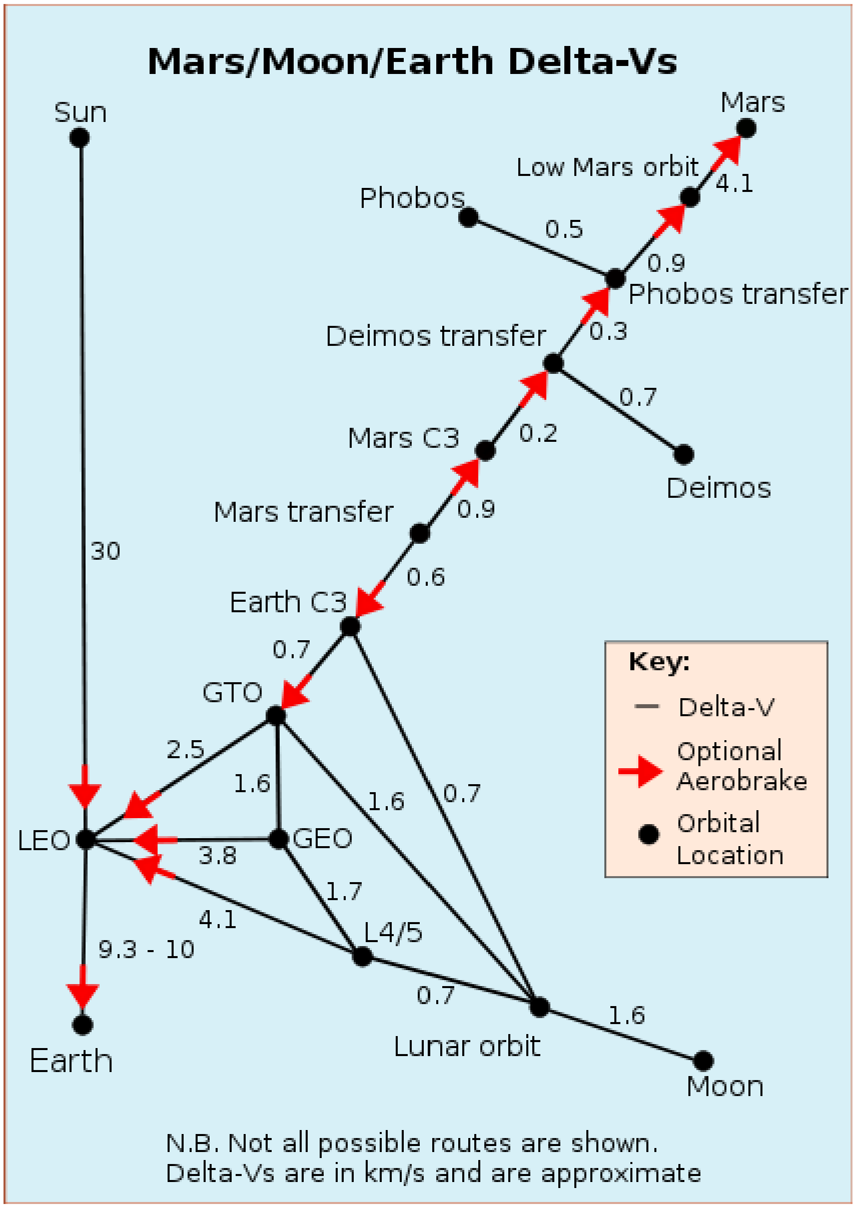
Large structures would be needed to convert sunlight into significant amounts of electrical power for settlers' use. In highly electrified nations on Earth, electrical consumption can average 1 kilowatt/person (or roughly 10 megawatt-hours per person per year.)

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 ½-⅔, 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:

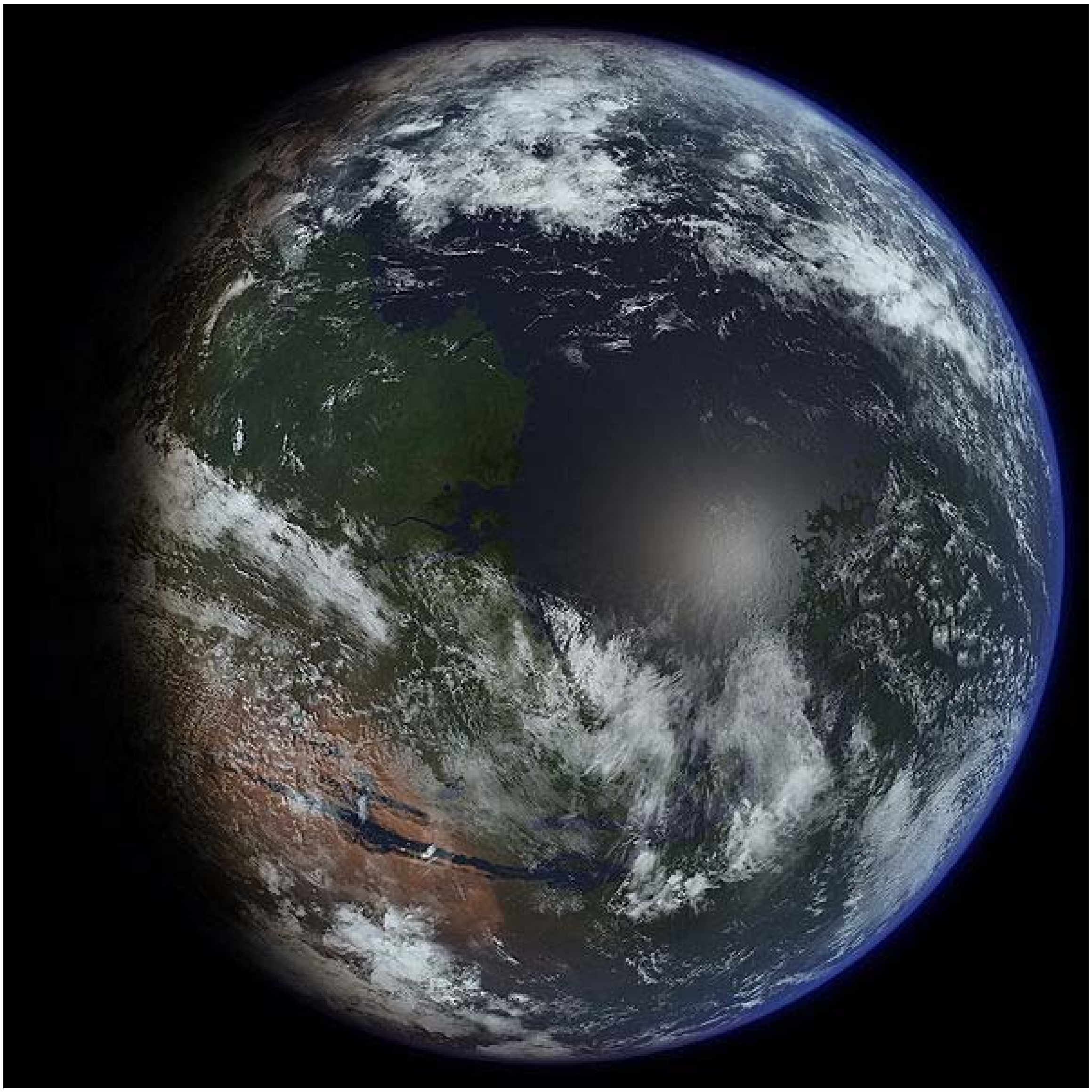
Mars

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)

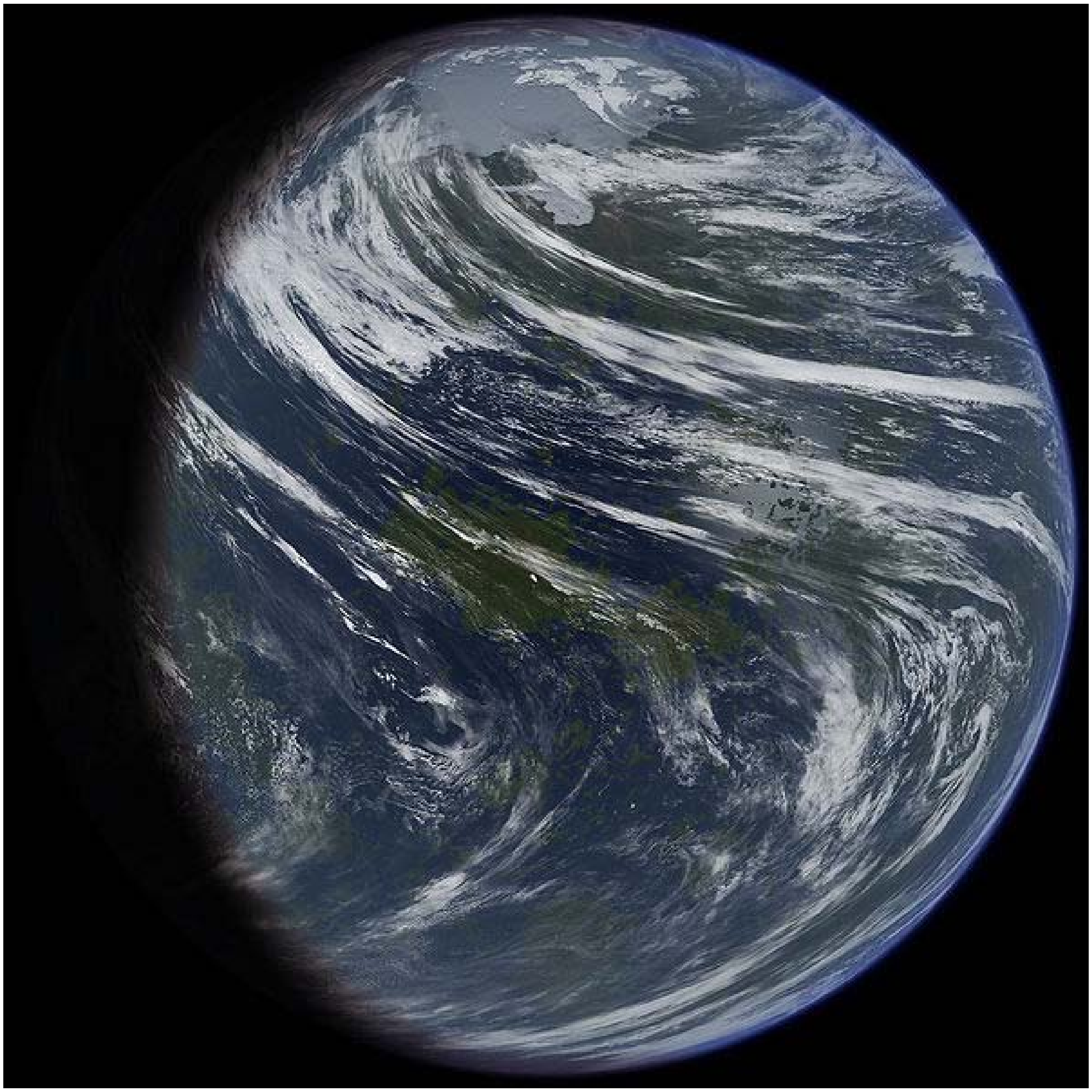
Terraforming Mars would make life outside of pressure vessels on the surface possible. There is some discussion of it actually being done.

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.

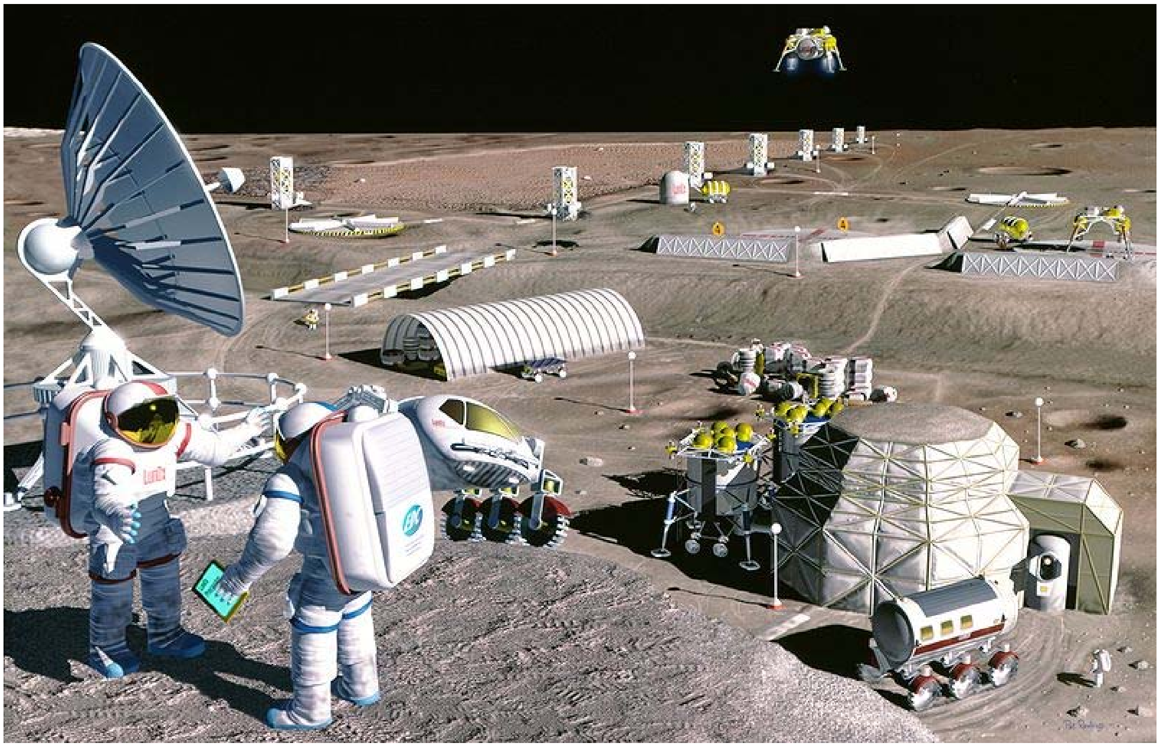
Gas giants

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 consisting of an orbital ring 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 Europan ice crust, exploring any sub-surface ocean. This plan discusses possible use of "air pockets" for human inhabitation. 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 colonization, and saying "In certain ways, Titan is the most hospitable extraterrestrial world within our solar system for human colonization".

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

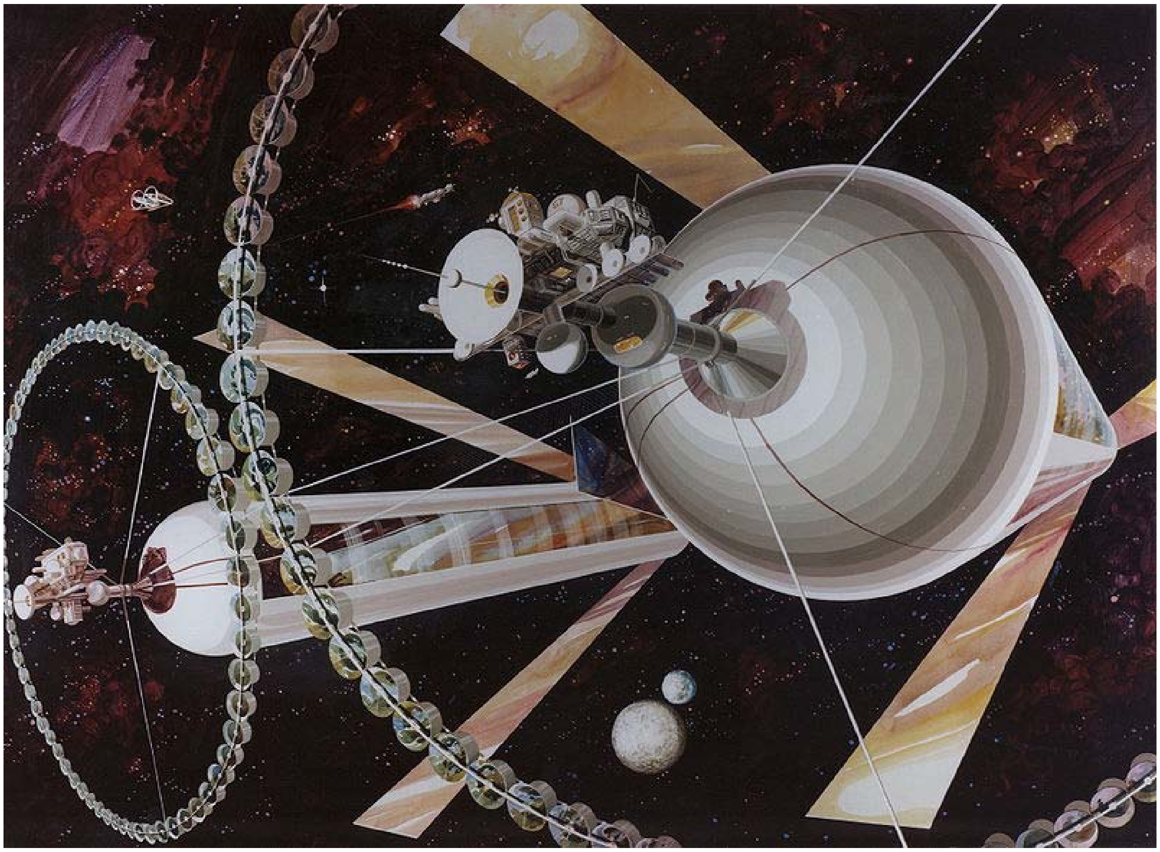
Colonization of asteroids would require space habitats. The asteroid belt has significant overall material available, the largest object being Ceres, although it is thinly distributed as it covers a vast region of space. Unmanned supply craft should be practical with little technological advance, even 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. It may be possible to Paraterraform Ceres, making life easier for the colonists. Given its low gravity and fast rotation, a space elevator would also be practical.

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.

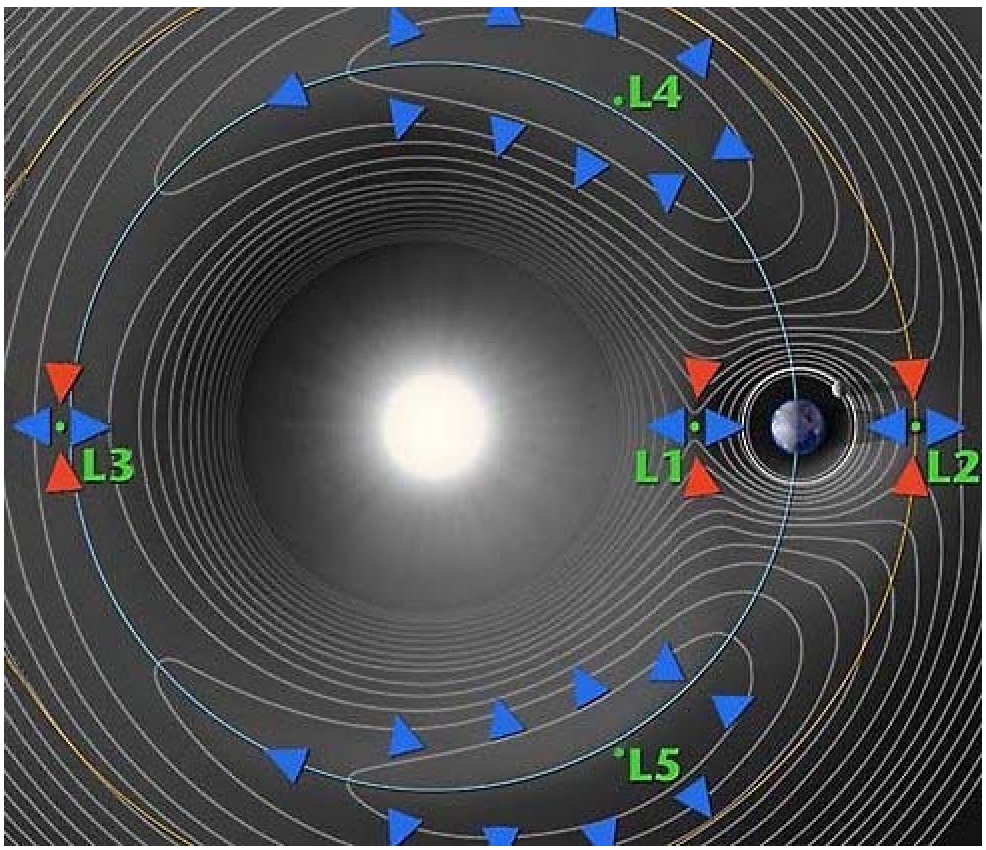
Earth orbit

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



A contour plot of the effective potential of the Sun and Earth, showing the five Lagrange points.

Another near-Earth possibility are the five Earth-Moon Lagrange points. Although they would generally also take a few days 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.

The five Earth-Sun Lagrange points would totally eliminate eclipses, but only L_1 and L_2 would be reachable in a few days' time. The other three Earth-Sun points would require months to reach.

However, the fact that Lagrange points L_4 and L_5 tend to collect dust and debris, while L_1-L_3 require active station-keeping measures to maintain a stable position, make them somewhat less suitable places for habitation than was originally believed. Additionally, the orbit of L_2 - L_5 takes them out of the protection of the Earth's magnetosphere for approximately two-thirds of the time, exposing them to the health threat from cosmic rays.

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 stars 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 ~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 Space.com 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 use 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

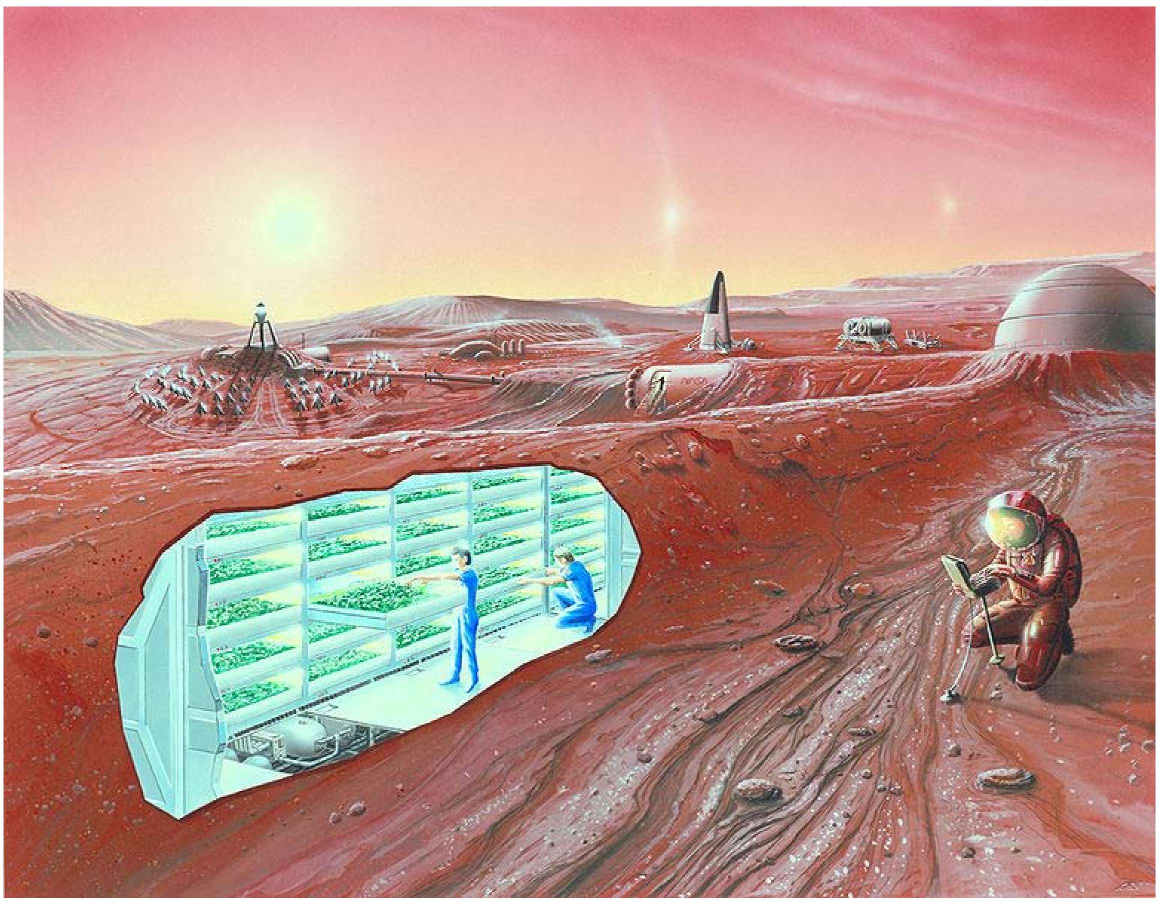
Space advocacy organizations include:

- The Space Studies Institute was founded by Gerard K. O'Neill to fund the study of space habitats.
- The Space Frontier Foundation promotes strong free market, capitalist views about space development.
- 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 Colonize the Cosmos site advocates orbital colonies.
- 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 Settlement Institute is searching for ways to make space colonization happen in our lifetimes.
- 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.
- The Alliance to Rescue Civilization plans to establish backups of human civilization on the Moon and other locations away from Earth.

Chapter- 2

Colonization of Mars



An artist's conception of the colonization of Mars, with a cutaway showing part of the interior (NASA Ames, 2005)

The **colonization of Mars** by humans is the focus of speculation and serious study because the surface conditions and availability of water on Mars make it arguably the most hospitable planet in the solar system other than Earth. The Moon has been proposed as the first location for human colonization but Mars has an atmosphere, giving it the potential capacity to host human and other organic life.

Relative similarity to Earth

The Earth is very like its "sister planet" Venus in bulk composition, size and surface gravity but Mars' similarities to Earth are arguably more compelling when considering colonization. These include:

- The Martian day (or **sol**) is very close to Earth's. A Mars solar day is 24 hours 39 minutes 35.244 seconds.
- Mars has a surface area that is 28.4% of Earth's, only slightly less than the amount of dry land on Earth (which is 29.2% of Earth's surface). Mars has half the radius of Earth and only one-tenth the mass. This means that it has a smaller volume (~15%) and lower average density than Earth.
- Mars has an axial tilt of 25.19°, compared with Earth's 23.44°. As a result, Mars has seasons much like Earth, though they last nearly twice as long because the Martian year is about 1.88 Earth years. The Martian north pole currently points at Cygnus, not Ursa Minor.
- Mars has an atmosphere. Although it is very thin (about 0.7% of Earth's atmosphere) it provides some protection from solar and cosmic radiation and has been used successfully for aerobraking of spacecraft.
- Recent observations by NASA's Mars Exploration Rovers, ESA's Mars Express and NASA's Phoenix Lander confirm the presence of water ice on Mars. Mars appears to have significant quantities of all the elements necessary to support Earth-based life.

Differences from Earth

- The surface gravity on Mars is 0.38 of that on Earth. It is not known if this is enough to prevent the health problems associated with weightlessness.
- Mars is much colder than Earth, with a mean surface temperature of -63°C and a low of -140°C. The lowest temperature ever recorded on Earth was −89.2°C, in Antarctica.
- There are no standing bodies of liquid water on the surface of Mars.
- Because Mars is further from the Sun, the amount of solar energy reaching the upper atmosphere (the solar constant) is less than half of what reaches the Earth's upper atmosphere or the Moon's surface. However, the solar energy that reaches the surface of Mars is not impeded by a thick atmosphere like on Earth.

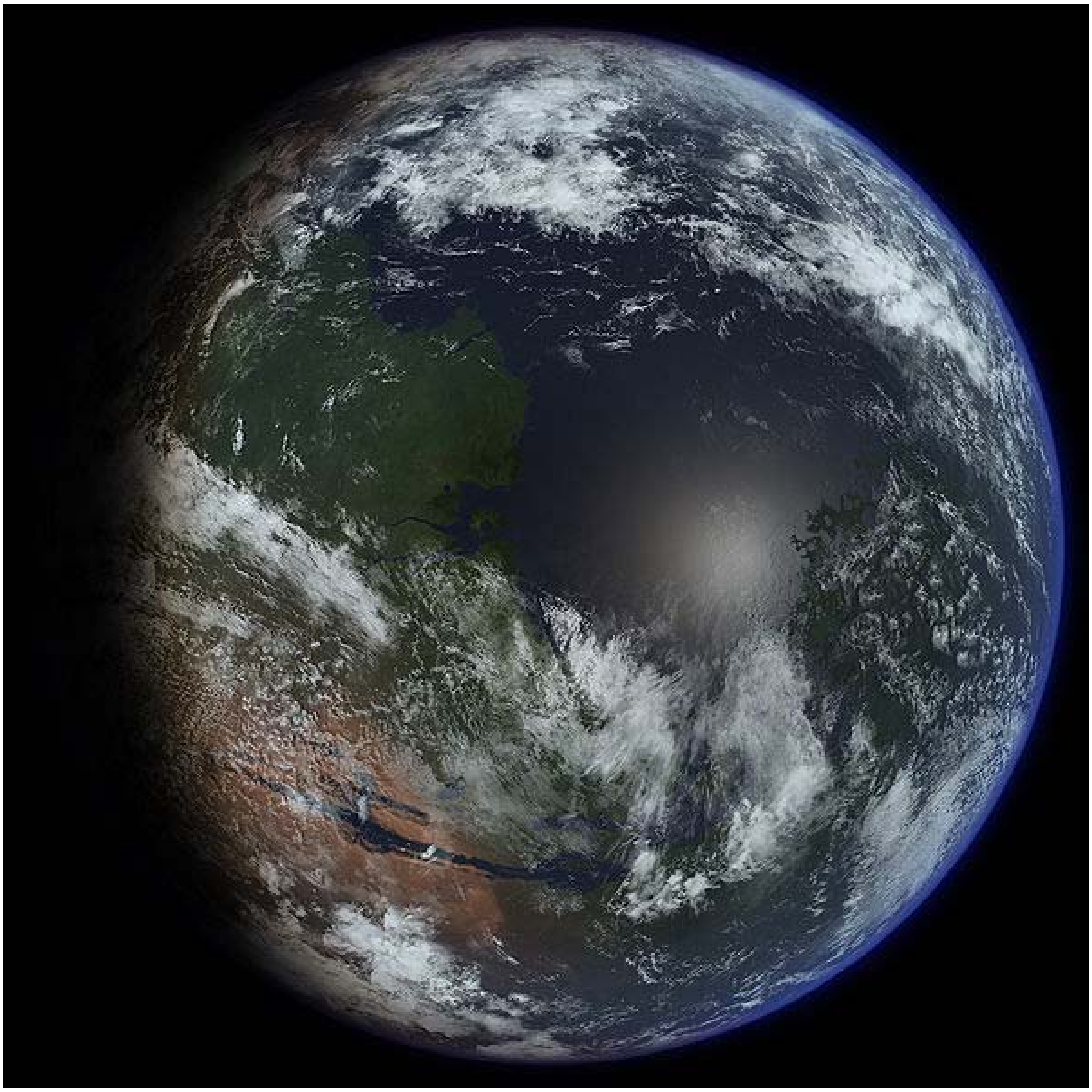
- Mars' orbit is more eccentric than Earth's, exacerbating temperature and solar constant variations.
- The atmospheric pressure on Mars is ~6 mbar, far below the Armstrong Limit (61.8 mbar) at which people can survive without pressure suits. Since terraforming cannot be expected as a near-term solution, habitable structures on Mars would need to be constructed with pressure vessels similar to spacecraft, capable of containing a pressure between a third and a whole bar.
- The Martian atmosphere consists mainly of carbon dioxide. Because of this, even with the reduced atmospheric pressure, the partial pressure of CO_2 at the surface of Mars is some 52 times higher than on Earth. It also has significant levels of carbon monoxide.
- Mars has a very weak magnetosphere, so it deflects solar winds poorly.

Habitability

Conditions on the surface of Mars are much closer to habitability than the surface of any other known planet or moon, as seen by the extremely hot and cold temperatures on Mercury, the furnace-hot surface of Venus, or the cryogenic cold of the outer planets and their moons. Only the cloud tops of Venus are closer in terms of habitability to Earth than Mars is. There are natural settings on Earth where humans have explored that match most conditions on Mars. The highest altitude reached by a manned balloon ascent, a record set in May 1961, was 34,668 meters (113,740 feet). The pressure at that altitude is about the same as on the surface of Mars. Extreme cold in the Arctic and Antarctic match all but the most extreme temperatures on Mars.

NASA Deputy Administrator Shana Dale said, "We also hope to discover if Mars can provide a second home for humans—an extension of our civilization—40 million miles from Earth."

Terraforming



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

It may be possible to terraform Mars to allow a wide variety of living things, including humans, to survive unaided on Mars' surface.

Radiation

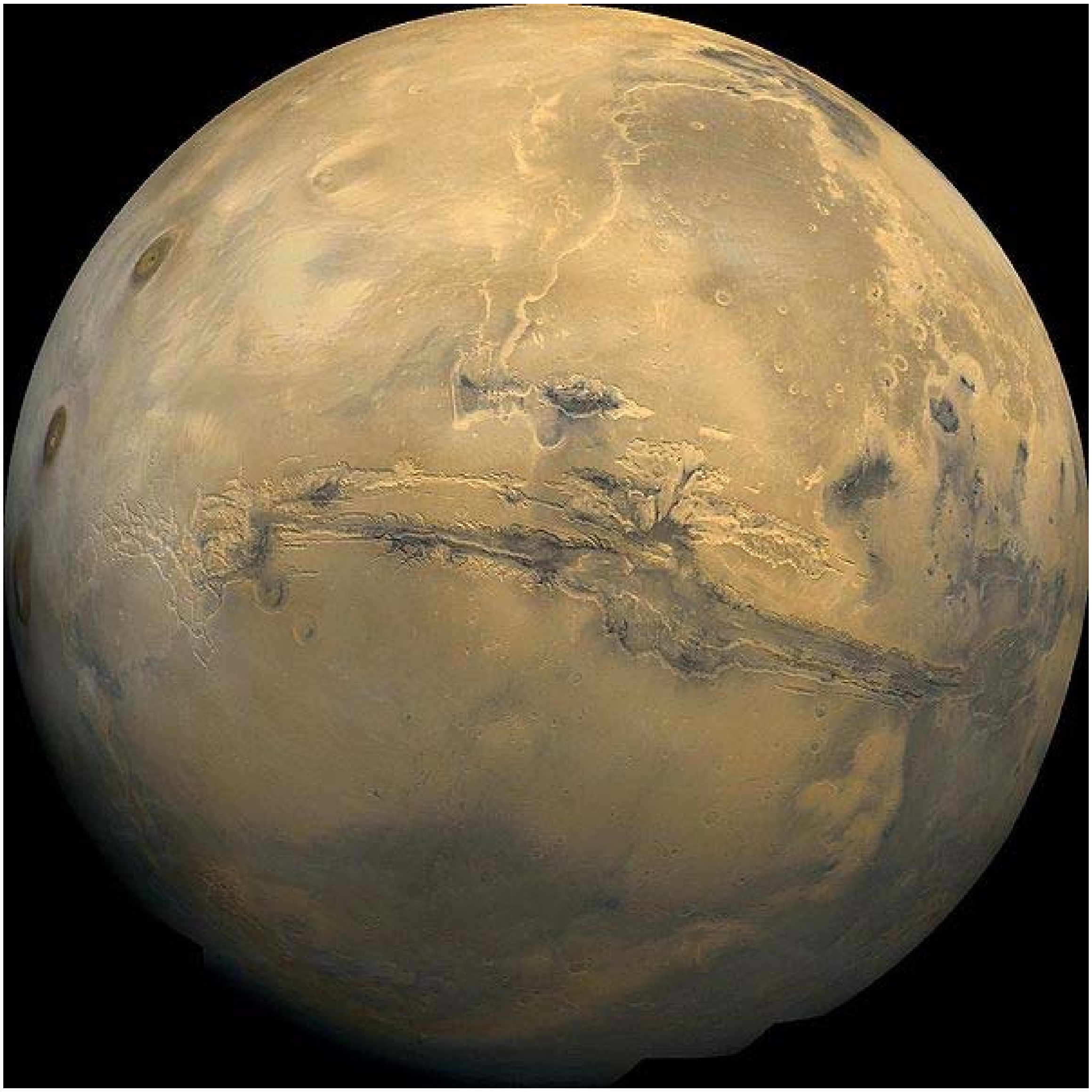
Mars has no global magnetic field comparable to Earth's geomagnetic field. Combined with a thin atmosphere, this permits a significant amount of ionizing radiation to reach the Martian surface. The Mars Odyssey spacecraft carried an instrument, the Mars Radiation Environment Experiment (MARIE), to measure the dangers to humans. MARIE found that radiation levels in orbit above Mars are 2.5 times higher than at the International Space Station. Average doses were about 22 millirads per day (220 micrograys per day or 0.08 gray per year.) A three year exposure to such levels would be close to the safety limits currently adopted by NASA. Levels at the Martian surface would be somewhat lower and might vary significantly at different locations depending on altitude and local magnetic fields.

Occasional solar proton events (SPEs) produce much higher doses. Some SPEs were observed by MARIE that were not seen by sensors near Earth due to the fact that SPEs are directional, making it difficult to warn astronauts on Mars early enough.

Much remains to be learned about space radiation. In 2003, NASA's Lyndon B. Johnson Space Center opened a facility, the NASA Space Radiation Laboratory, at Brookhaven National Laboratory that employs particle accelerators to simulate space radiation. The facility will study its effects on living organisms along with shielding techniques. There is some evidence that this kind of low level, chronic radiation is not quite as dangerous as once thought; and that radiation hormesis occurs. The consensus among those that have studied the issues is that radiation levels, with the exception of the SPEs, that would be experienced on the surface of Mars, and while journeying there, are certainly a concern, but are not thought to prevent a trip from being made with current technology.

Transportation

Interplanetary spaceflight



Mars (Viking 1, 1980)

Mars requires less energy per unit mass (delta V) to reach from Earth than any planet except Venus. Using a Hohmann transfer orbit, a trip to Mars requires approximately nine months in space. Modified transfer trajectories that cut the travel time down to seven or six months in space are possible with incrementally higher amounts of energy and fuel compared to a Hohmann transfer orbit, and are in standard use for robotic Mars missions. Shortening the travel time below about six months requires higher delta-v and an exponentially increasing amount of fuel, and is not feasible with chemical rockets, but would be perfectly feasible with advanced spacecraft propulsion technologies, some of which have already been tested, such as VASIMR, and nuclear rockets, in the formers case, a trip time of forty days could be attainable, and in the latter, a trip time down to about two weeks. Another possibility is constant-acceleration technologies such as space proven solar sails and ion drives which permits passage times at close approaches on the order of several weeks. Both of these propulsion systems have been deployed and could readily obtain a constant acceleration of 0.1g.

During the journey the astronauts are subject to radiation, which requires a means to protect them. Cosmic radiation and solar wind cause DNA damage, which increases the risk of cancer significantly. The effect of long term space travel in the interplanetary space is unknown, but scientists estimate up to 19% probability for male persons to die of cancer because of the radiation during the journey to Mars and back to Earth. Together with the base probability of 20% for a male person on Earth to die from cancer this gives a probability of 39%. For women the probability is even higher due to their larger glandular tissues.

Landing on Mars

Mars has a gravity 0.38 times that of the Earth and the density of its atmosphere is 1% of that on Earth. The relatively strong gravity and the presence of aerodynamic effects makes it difficult to land heavy, crewed spacecraft with thrusters only as was done with the Apollo moon landings, yet the atmosphere is too thin for aerodynamic effects to be of much help in braking and landing a large vehicle. Landing piloted missions on Mars will require braking and landing systems different from anything used to land crewed spacecraft on the Moon or robotic missions on Mars.

If one assumes carbon nanotube construction material will be available with a strength of 130 GPa then a space elevator could be built to land men and material on Mars. A space elevator on Phobos has also been proposed.

Communication

Communications with Earth are relatively straightforward during the half-sol when the Earth is above the Martian horizon. NASA and ESA included communications relay equipment in several of the Mars orbiters, so Mars already has communications satellites. While these will eventually wear out, additional orbiters with communication relay capability are likely to be launched before any colonization expeditions are mounted.

The one-way communication delay due to the speed of light ranges from about 3 minutes at closest approach (approximated by perihelion of Mars minus aphelion of Earth) to 22 minutes at the largest possible superior conjunction (approximated by aphelion of Mars plus aphelion of Earth). Telephone conversations or Internet Relay Chat between Earth and Mars would be highly impractical due to the long time lags involved. NASA has found that direct communication can be blocked for about two weeks every synodic period, around the time of superior conjunction when the Sun is directly between Mars and Earth, although the actual duration of the communications blackout varies from mission to mission depending on various factors - such as the amount of link margin designed into the communications system, and the minimum data rate that is acceptable from a mission standpoint. In reality most missions at Mars have had communications blackout periods of the order of a month.

A satellite at either of the Earth-Sun L_4/L_5 Lagrange points could serve as a relay during this period to solve the problem; even a constellation of communications satellites would be a minor expense in the context of a full colonization program. However the size and power of the equipment needed for these distances make the L4 and L5 locations unrealistic for relay stations, and the inherent stability of these regions, while beneficial in terms of station-keeping, also attracts asteroids, which could pose a severe risk to any satellite.

Recent work by the University of Strathclyde's Advanced Space Concepts Laboratory, in collaboration with the European Space Agency, has suggested an alternative relay architecture based on highly non-Keplerian orbits. These are a special kind of orbit produced when continuous low-thrust propulsion, such as that produced from an ion engine or solar sail, modifies the natural trajectory of a spacecraft. Such an orbit would enable continuous communications during solar conjunction by allowing a relay spacecraft to "hover" above Mars, out of the orbital plane of the two planets. Such a relay avoids the problems of satellites stationed at either L4 or L5 by being significantly closer to the surface of Mars while still maintaining continuous communication between the two planets.

Robotic precursors

The path to a human colony could be prepared by robotic systems such as the Mars Exploration Rovers *Spirit* and *Opportunity*. These systems could help locate resources, such as ground water or ice, that would help a colony grow and thrive. The lifetimes of these systems would be measured in years and even decades, and as recent developments in commercial spaceflight have shown, it may be that these systems will involve private as well as government ownership. These robotic systems also have a reduced cost compared with early crewed operations, and have less political risk.

Wired systems might lay the groundwork for early crewed landings and bases, by producing various consumables including fuel, oxidizers, water, and construction materials. Establishing power, communications, shelter, heating, and manufacturing basics can begin with robotic systems, if only as a prelude to crewed operations.

Early human missions

Early human missions to Mars, such as those being tentatively planned by NASA, FKA and ESA would not be direct precursors to colonization. They are intended solely as exploration missions, as the *Apollo* missions to the Moon were not planned to be sites of a permanent base.

Colonization requires the establishment of permanent bases that have potential for self-expansion. A famous proposal for building such bases is the Mars Direct plan, advocated by Robert Zubrin. The Mars Society has established the Mars Analogue Research Station Programme at sites Devon Island in Canada and in Utah, United States, to experiment with different plans for human operations on Mars, based on Mars Direct. Modern Martian architecture concepts often include facilities to produce oxygen and propellant on the surface of the planet.

Economics

As with early colonies in the New World, economics would be a crucial aspect to a colony's success. The reduced gravity well of Mars and its position in the solar system may facilitate Mars-Earth trade and provide the rationalization for continued settlement of the planet.

Mars' reduced gravity together with its rotation rate makes it possible for the construction of a space elevator with today's materials, although the low orbit of Phobos could present engineering challenges. If constructed, the elevator could transport minerals and other natural resources extracted from the planet.

A major economic problem is the enormous up-front investment required to establish the colony and perhaps also terraform the planet.

Some early Mars colonies might specialize in developing local resources for Martian consumption, such as water and/or ice.

Another main inter-Martian trade good during early colonization could be manure. Assuming that life doesn't exist on Mars, the soil is going to be very poor for growing plants, so manure and other fertilizers will be valued highly in any Martian civilization until the planet changes enough chemically to support growing vegetation on its own.

Solar power is a candidate for power for a Martian colony. Solar insolation (the amount of solar radiation that reaches Mars) is about 42% of that on Earth, since Mars is about 52% farther from the Sun and insolation falls off as the square of distance. But the thin atmosphere would allow almost all of that energy to reach the surface as compared to Earth, where the atmosphere absorbs roughly a quarter of the solar radiation.

Nuclear power is also a good candidate, since the fuel is very dense for cheap transportation from Earth. Nuclear power also produces heat, which would be extremely valuable to a Mars colony.

Heating requirements could be lowered if the colonists use domes to trap solar heat, especially for greenhouses.

Possible locations for colonies

Mars can be considered in broad regions for discussion of possible colony sites.

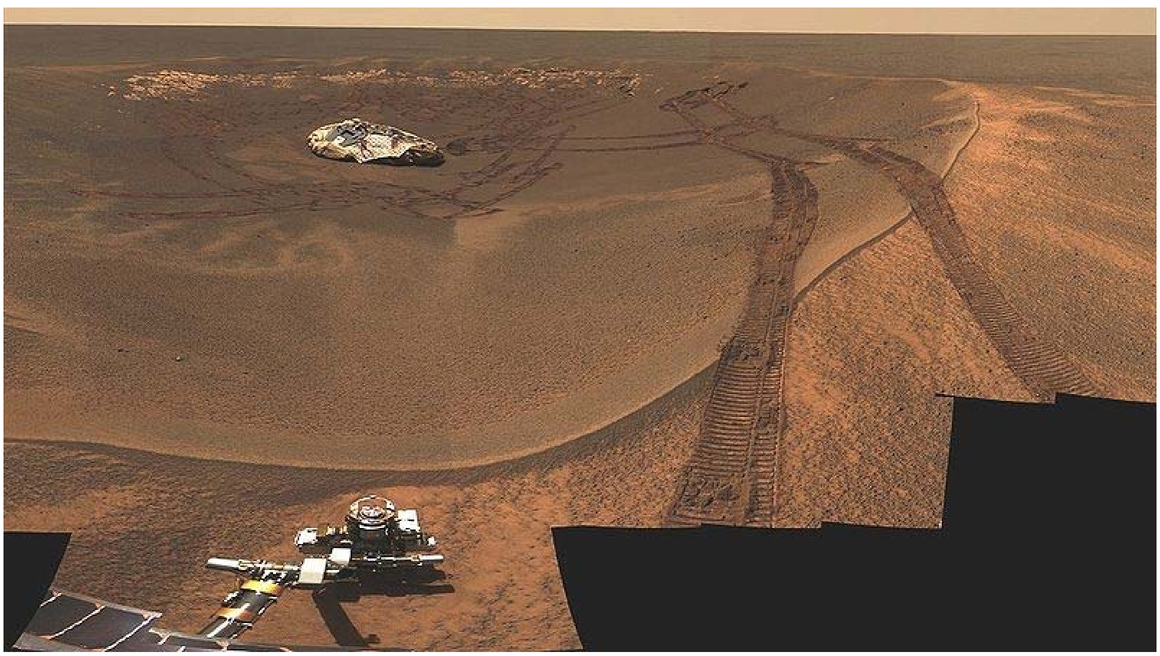
Polar regions

Mars' north and south poles once attracted great interest as colony sites because seasonally-varying polar ice caps have long been observed by telescope from Earth. Mars Odyssey found the largest concentration of water near the north pole, but also showed that water likely exists in lower latitudes as well, making the poles less compelling as a colony locale. Like Earth, Mars sees a midnight sun at the poles during local summer and polar night during local winter.

Equatorial regions

Mars Odyssey found what appear to be natural caves near the volcano Arsia Mons. It has been speculated that colonists could benefit from the shelter that these or similar structures could provide from radiation and micrometeoroids. Geothermal energy is also suspected in the equatorial regions.

Midlands



Eagle Crater, as seen from *Opportunity* (2004)

The exploration of Mars' surface is still underway. The two Mars Exploration Rovers, *Spirit* and *Opportunity*, have encountered very different soil and rock characteristics. This suggests that the Martian landscape is quite varied and the ideal location for a colony would be better determined when more data becomes available. As on Earth, seasonal variations in climate become greater with distance from the equator.

Valles Marineris

Valles Marineris, the "Grand Canyon" of Mars, is over 3,000 km long and averages 8 km deep. Atmospheric pressure at the bottom would be some 25% higher than the surface average, 0.9 kPa vs 0.7 kPa. The canyon runs roughly east-west, so shadows from its walls should not interfere too badly with solar power collection. River channels lead to the canyon, indicating it was once flooded.

Lava Tubes

Several lava tube skylights on Mars have been located. Earth based examples indicate that some should have lengthy passages offering complete protection from radiation and be relatively easy to seal using on site materials, especially in small subsections.

Advocacy

Making Mars colonization a reality is advocated by several groups with different reasons and proposals. One of the oldest is the Mars Society. They promote a NASA program to accomplish human exploration of Mars and have set up Mars analog research stations in Canada and the United States. Another group is Marsdrive, which is dedicated to private initiatives for the exploration and settlement of Mars.

Concerns

Besides the general criticism of human colonization of space, there are specific concerns about a colony on Mars:

- Mars has a gravity 0.38 times that of the Earth and a density of the atmosphere of 1% that on Earth. The stronger gravity than the Moon and the presence of aerodynamic effects makes it more difficult to land heavy, crewed spacecraft with thrusters only, yet the atmosphere is also too thin to get very much use out of aerodynamic effects for braking and landing. Landing piloted missions on Mars will require a braking and landing system different from anything used to land crewed spacecraft on the Moon or robotic missions on Mars.

- The question of whether life once existed or exists now on Mars has not been settled, raising concerns about possible contamination of the planet with Earth life.

- Advocates of a return to the Moon say the Moon is a more logical first location for a first planetary colony, perhaps using it as practice for future manned missions to Mars. However, in several ways experience gained on the moon would not be applicable to the task of colonizing Mars. The moon has no atmosphere, no analogous geology and a much greater temperature range and rotational period. These differences make Mars more in common with Earth than the Moon. Antarctica or desert areas of Earth provide much better training grounds at vastly lesser cost. Also, the Moon is extremely poor in several of the key elements required for life, most notably hydrogen, nitrogen and carbon (50 – 100 ppm), and has only 47.2% of the delta-v requirement for launching to orbit that Mars has.

- It is unknown whether Martian gravity can support human life in the long term (all experience is at either ~1g or zero gravity). Space medicine researchers have theorized on whether the health benefits of gravity rise slowly or quickly between weightlessness and full Earth gravity. One theory is that sleeping chambers built inside centrifuges would minimize the health problems. The Mars Gravity Biosatellite experiment was due to become the first experiment testing the effects of partial gravity, artificially generated at 0.38 *g* to match Mars gravity, on mammal life, specifically on mice, throughout the life cycle from conception to death. However, in 2009 the Biosatellite project was cancelled due to lack of funds.

- Mars' escape velocity is 5 km/s, which, though less than half that for Earth, is reasonably high compared to the Moon's 2.38 km/s or the negligible escape velocity of most asteroids. This could make physical export trade from Mars to other planets and habitats less viable economically.

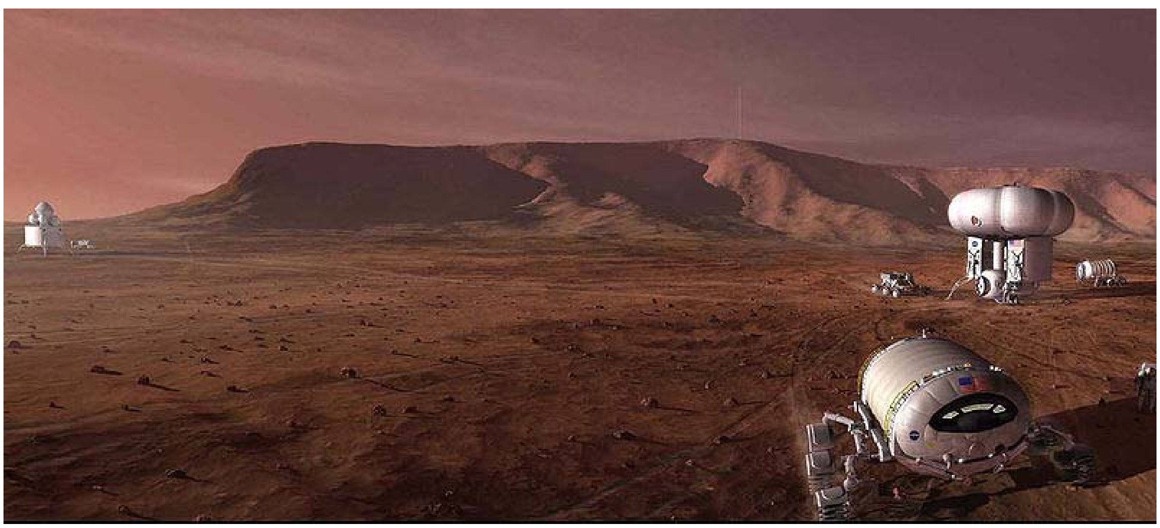
- There is likely to be little economic return from the colonization of Mars while Lunar and Near Earth Asteroid industry is likely to be exporting to Earth.

- Mars has dust storms which can reduce solar power. The largest of these storms can cover much of the planet.

Chapter- 3

Mars to Stay

Mars to Stay is the proposal that astronauts sent to Mars for the first time should stay there indefinitely, both to reduce mission cost and to ensure permanent settlement of Mars. Among many other notable Mars to Stay advocates, former Apollo astronaut Buzz Aldrin has been particularly outspoken, suggesting in numerous forums "Forget the Moon, Let's Head to Mars!" The Mars Underground, Mars Homestead Foundation, and Mars Artists Community have also adopted Mars to Stay policy initiatives. The earliest formal outline of a Mars to Stay mission architecture was given at the Case for Mars VI Workshop in 1990, during a presentation by George Herbert titled "One Way to Mars."



Concept for NASA Design Reference Mission Architecture 5.0 (2009)

Proposals

Original Aldrin Plan

Under a Mars to Stay mission architecture the first humans to travel to Mars would be composed of a six-person team. After this initial landing subsequent missions over five years will raise the number of persons on the Martian surface to 30, thereby beginning an organically evolving Martian settlement. Since the Martian surface offers all the natural resources and elements necessary to sustain human society—unlike, for example the moon—a permanent Martian settlement is thought to be the most effective way to ensure humankind becomes a space-faring, multi-planet species. Through the use of digital fabricators and in vitro fertilization it is assumed a permanent human settlement on Mars can grow organically from an original thirty to forty pioneers.

A Mars exploration program following Aldrin's Mars to Stay initiative would enlist astronauts in the following timeline:

- Age 30: an offer to help settle Mars is extended to select pioneers
- Age 30-35: training and social conditioning for long-duration isolation and time-delay communications
- Age 35: launch three married couples to Mars; followed in subsequent years by a dozen or more couples
- Age 35-65: development of sheltered underground living spaces; artificial insemination ensures genetic diversity
- Age 65: an offer to return to Earth or retire on Mars is given to first generation settlers

As Aldrin has said, "…who knows what advances will have taken place. The first generation can retire there, or maybe we can bring them back."

"Hundred Year Starship Initiative"

On October 2010 NASA Ames Research Center Director Pete Worden introduced the Hundred Year Starship initiative, a project to embark on a one-way mission from Earth to Mars by 2030. The astronauts would be sent supplies from Earth on a regular basis. The mission is planned to take place no earlier than 2030. Controversy immediately arose over the name of the enterprise, given that Mars settlement could have begun within five years of the announcement -- rather than portrayed as an exotic "100 year" fantasy.

"To Boldly Go: A One-Way Human Mission to Mars," Journal of Cosmology

The October-November, 2010, Journal of Cosmology reprinted an article by Dirk Schulze-Makuch (Washington State University) and Paul Davies (Arizona State University) from the book "The Human Mission to Mars. Colonizing the Red Planet." Highlights of their mission plan are:

- No base on the Moon is needed. Given the broad variety of resources available on Mars, the long-term survival of Martian settlers is much more feasible than Lunar settlers.
- Since Mars affords neither an ozone shield nor magnetospheric protection, robots would prepare a basic modular base inside near-surface lava tubes and ice caves for the human settlers.

- A volunteer signing up for a one-way mission to Mars would do so with the full understanding that he or she will not return to Earth; Mars exploration would proceed for a long time on the basis of outbound journeys only.
- The first human contingent would consist of a crew of four, ideally (if budget permits) distributed between two two-man spacecraft for mission redundancy.
- Over time humans on Mars will increase with follow-up missions. Several subsurface biospheres would be created until there were 150+ individuals in a viable gene pool. Genetic engineering would further contribute to the health and longevity of settlers.

Initial and permanent settlement

Initial explorers leave equipment in orbit and at landing zones scattered considerable distances from the main settlement. Subsequent missions therefore are assumed to become easier and safer to undertake, with the likelihood of back-up equipment being present if accidents in transit or landing occur.

Large subsurface, pressurized habitats would be the first step toward human settlement; as Dr. Robert Zubrin suggests in the first chapter of his book *Mars Direct* these structures can be built as Roman-style atria in mountainsides or underground with easily produced Martian brick. During and after this initial phase of habitat construction, hard-plastic radiation- and abrasion-resistant geodesic domes could be deployed on the surface for eventual habitation and crop growth. Nascent industry would begin using indigenous resources: the manufacture of plastics, ceramics and glass could be easily achieved.

The longer-term work of terraforming Mars requires an initial phase of global warming to release atmosphere from the Martian regolith and to create a water-cycle. There would be no cost issue associated to terraforming as it would be in the best interest of settlers to make sure that their daily activities positively influence the improvement of the environment. Three methods of global warming are described by Zubrin, who suggests they are best deployed in tandem: orbital mirrors to heat the surface; factories on the ground to pump halocarbons into the atmosphere; and the seeding of bacteria which can metabolize water, nitrogen and carbon to produce ammonia and methane (these gases would aid in global warming). While the work of terraforming Mars is on-going, robust settlement of Mars can continue.

The Case for Mars acknowledges any Martian colony will be partially Earth-dependent for centuries. However, Zubrin suggests Mars may be profitable for two reasons. First, it may contain concentrated supplies of metals equal to or of greater value than silver, which have not been subjected to millennia of human scavenging; it is suggested such ores may be sold on Earth for profit. Secondly, the concentration of deuterium–an extremely expensive but essential fuel for the nuclear power industry–is five times greater on Mars. Humans emigrating to Mars, under this paradigm, thus have an assured industry; it is assumed the planet will be a magnet for settlers as wage costs will be high. Because of the labor shortage on Mars and its subsequent high pay-scale, Martian civilization and the value placed upon each individual's productivity is proposed as a future engine of both technological and social advancement.”

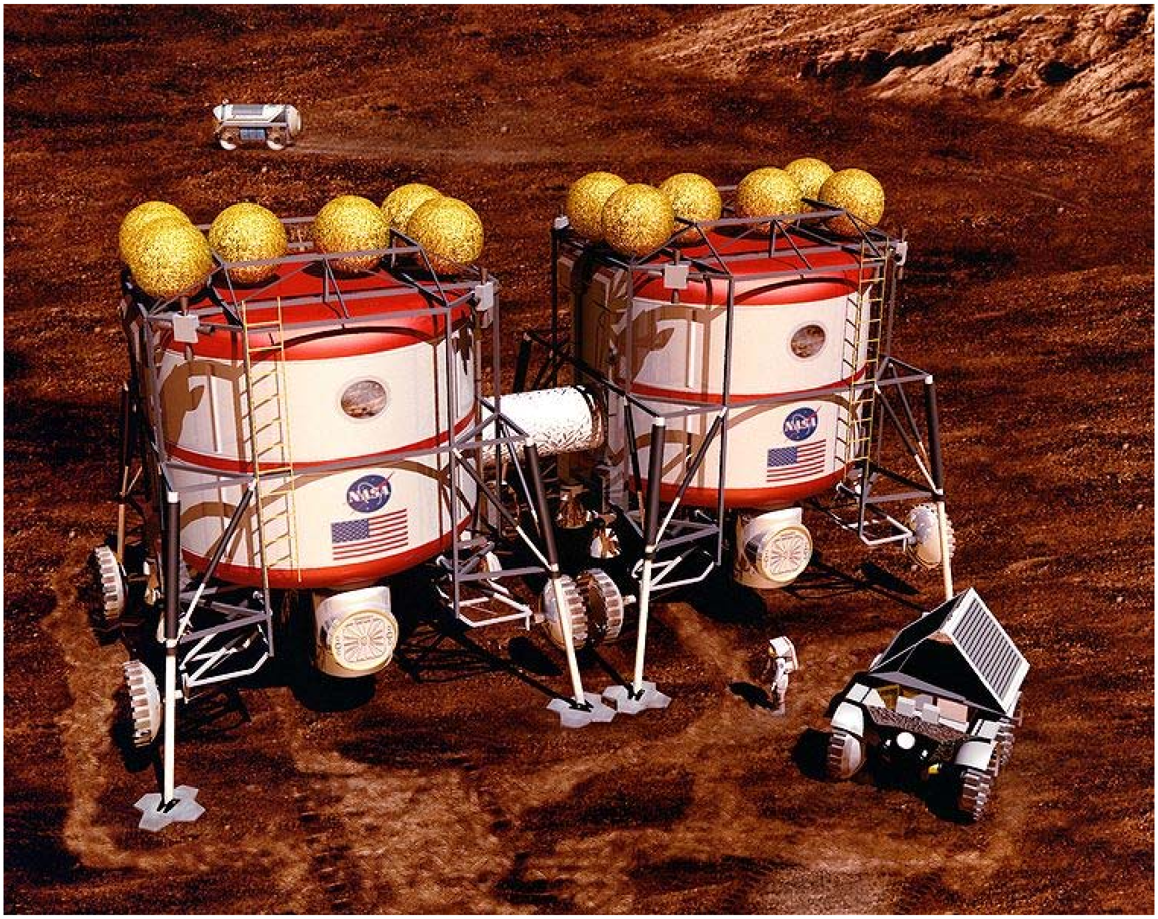
Risks

Artist's conception of a human mission on Mars
1989 painting by Les Bossinas of Lewis Research Center for NASA

In the fifth chapter of "Mars Direct", Zubrin dismisses the idea that radiation and zero-gravity are unduly hazardous. He claims that cancer rates *do* increase for astronauts who have spent extensive time in space, but only marginally. Similarly, while zero-gravity presents challenges, near total recovery of musculature and immune system vitality is assumed once on the Martian surface. Back-contamination — humans acquiring and spreading Martian viruses — is described as "just plain nuts", because there are no host organisms on Mars for disease organisms to have evolved.

In the same chapter, Zubrin decisively denounces and rejects suggestions that the Moon should be used as waypoint to Mars or as a preliminary training area. "It is ultimately much easier to journey to Mars from low Earth orbit than from the moon and using the latter as a staging point is a pointless diversion of resources." While the Moon may superficially appear a good place to perfect Mars exploration and habitation techniques, the two bodies are radically different. The moon has no atmosphere, no analogous geology and a much greater temperature range and rotational period of illumination. It is argued Antarctica, desert areas of Earth, and precisely controlled chilled vacuum chambers on easily accessible NASA centers on Earth provide much better training grounds at lesser cost.

Public reception



Artist's conception of a Mars Habitat
1993 by John Frassanito and Associates for NASA

"Should the United States space program send a mission to Mars, those astronauts should be prepared to stay there," said Lunar astronaut Buzz Aldrin during a high-profile, widely reported interview on "Mars to Stay" initiatives. The time and expense required to send astronauts to Mars, argues Aldrin, "warrants more than a brief sojourn, so those who are on board should think of themselves as pioneers. Like the Pilgrims who came to the New World or the families who headed to the Wild West, they should not plan on coming back home." While the Moon is a shorter trip of two or three days, according to Mars advocates, it offers virtually no potential for independent settlements. Studies have found that Mars, on the other hand, has vast reserves of frozen water, all of the basic elements, and more closely mimics both gravitational and illumination conditions on Earth. "It is easier to subsist, to provide the support needed for people there than on the Moon." In an interview with reporters, the second man to set foot on the Moon said the Red Planet offered far greater potential than Earth's satellite as a place for habitation.

"If we are going to put a few people down there and ensure their appropriate safety, would you then go through all that trouble and then bring them back immediately, after a year, a year and a half?" Aldrin asks. "They need to go there more with the psychology of knowing that you are a pioneering settler and you don't look forward to go back home again after a couple of years," he said.

The most comprehensive statement of a rationale for "Mars to Stay" was laid out by Dr. Aldrin in a May 2009 Popular Mechanics article, as follows:

"The agency's current Vision for Space Exploration will waste decades and hundreds of billions of dollars trying to reach the moon by 2020—a glorified rehash of what we did 40 years ago. Instead of a steppingstone to Mars, NASA's current lunar plan is a detour. It will derail our Mars effort, siphoning off money and engineering talent for the next two decades. If we aspire to a long-term human presence on Mars—and I believe that should be our overarching goal for the foreseeable future—we must drastically change our focus. Our purely exploratory efforts should aim higher than a place we've already set foot on six times. In recent years my philosophy on colonizing Mars has evolved. I now believe that human visitors to the Red Planet should commit to staying there permanently. One-way tickets to Mars will make the missions technically easier and less expensive and get us there sooner. More importantly, they will ensure that our Martian outpost steadily grows as more homesteaders arrive. Instead of explorers, one-way Mars travelers will be 21st-century pilgrims, pioneering a new way of life. It will take a special kind of person. Instead of the traditional pilot/ scientist/engineer, Martian homesteaders will be selected more for their personalities—flexible, inventive and determined in the face of unpredictability. In short, survivors."

The Mars Artists Community has adopted Mars to Stay as their primary policy initiative. During a 2009 public hearing of the U.S. Human Space Flight Plans Committee at which Dr. Robert Zubrin presented a summary of the arguments in book The Case for Mars, dozens of placards reading "Mars Direct Cowards Return to the Moon" were placed throughout the Carnegie Institute. The passionate uproar among space exploration advocates - both favorable and critical - resulted in the Mars Artists Community creating several dozen more designs, with such slogans as, "Traitors Return to Earth" and "What Would Zheng He Do?"

In October 2009, Eric Berger of the Houston Chronicle wrote of 'Mars to Stay' as perhaps the only program which can revitalize America's space program:

"What if NASA could land astronauts on Mars in a decade, for not ridiculously more money than the $10 billion the agency spends annually on human spaceflight? It's possible, say some space buffs, although there's a catch. The astronauts we'd send would never come home. Relieving NASA of the need to send fuel and rocketry to blast humans off the Martian surface, which has slightly more than twice the gravity of the moon, would actually reduce costs by about a factor of 10, by some estimates."

Hard Science Fiction writer Mike Brotherton has found "Mars to Stay" appealing for both economic and safety reasons, but more emphatically, as a fulfillment of the ultimate mandate by which "our manned space program is sold, at least philosophically and long-term, as a step to colonizing other worlds." Two thirds of the respondents to a poll on his website expressed interest in a one-way ticket to Mars "if mission parameters are well-defined" (not suicidal).

In June 2010 Buzz Aldrin gave an interview to Vanity Fair in which he restated Mars to Stay:

"Did the Pilgrims on the Mayflower sit around Plymouth Rock waiting for a return trip? They came here to settle. And that's what we should be doing on Mars. When you go to Mars, you need to have made the decision that you're there permanently. The more people we have there, the more it can become a sustaining environment. Except for very rare exceptions, the people who go to Mars shouldn't be coming back. Once you get on the surface, you're there."

The October-November, 2010, Journal of Cosmology reprinted an article by Dirk Schulze-Makuch (Washington State University) and Paul Davies (Arizona State University) from the book "The Human Mission to Mars. Colonizing the Red Planet." The following summarizes their rational for Mars to Stay:

"A human mission to Mars is technologically feasible, but hugely expensive requiring enormous financial and political commitments. A creative solution to this dilemma would be a one-way human mission to Mars in place of the manned return mission that remains stuck on the drawing board. Our proposal would cut the costs several fold but ensure at the same time a continuous commitment to the exploration of Mars in particular and space in general. It would also obviate the need for years of rehabilitation for returning astronauts, which would not be an issue if the astronauts were to remain in the low-gravity environment of Mars. We envision that Mars exploration would begin and proceed for a long time on the basis of outbound journeys only."

"New York Times" op-eds

"Mars to Stay" has been explicitly proposed by two op-ed pieces in the "New York Times".

"A One-Way Ticket to Mars" Krauss, Lawrence. New York Times Op-Ed, Sept 1, 2009:"

Following a similar line of argument to Buzz Aldrin, Lawrence Krauss asks in an Op-Ed, "Why are we so interested in bringing the Mars astronauts home again?". While the idea of sending astronauts aloft never to return may be jarring upon first hearing, the rationale for one-way exploration and settlement trips has both historical and practical roots. For example, colonists and pilgrims seldom set off to the New World with the expectation of a return trip. As Lawrence Krauss writes, "To boldly go where no one has gone before does not require coming home again."

Dr. Krauss modifies the standard "Mars to Stay" architecture by "restricting the voyage to older astronauts, whose longevity is limited. Here again, I have found a significant fraction of scientists older than 65 who would be willing to live out their remaining years on the red planet or elsewhere." This initial first generation of elderly astronauts would accept higher radiation doses while building eventual subsurface habitats, presumably, because the effects of increased radiation would not affect them during the remainder of their lives.

"If it sounds unrealistic to suggest that astronauts would be willing to leave home never to return alive, then consider the results of several informal surveys I and several colleagues have conducted recently. One of my peers in Arizona recently accompanied a group of scientists and engineers from the Jet Propulsion Laboratory on a geological field trip. During the day, he asked how many would be willing to go on a one-way mission into space. Every member of the group raised his hand." Krauss, Lawrence. New York Times Op-Ed "A One-Way Ticket to Mars"

Additional immediate and pragmatic reasons to consider one-way human space exploration missions are explored by Krauss. Since much of the cost of a voyage to Mars will be spent on coming home again, if the fuel for the return is carried onboard, this greatly increases the mission mass requirement - which in turn requires even more fuel. "Human space travel is so expensive and so dangerous" according to Krauss, "we are going to need novel, even extreme solutions if we really want to expand the range of human civilization beyond our own planet." Delivering food and supplies to pioneers via unmanned spacecraft is less expensive than designing an immediate return trip.

"Life (and Death) on Mars," Davies, Paul. New York Times Op-Ed, January 15, 2004:"

In an earlier 2004 Op-Ed for the New York Times, Paul Davies motivation for the less expensive, permanent "one-way to stay option" arises from a theme common in "Mars to Stay" advocacy: "Mars is one of the few accessible places beyond Earth that could have sustained life [...and] alone among our sister planets, it is able to support a permanent human presence."

"Why is going to Mars so expensive? Mainly it's the distance from Earth. At its closest point in orbit, Mars lies 35 million miles away from us, necessitating a journey of many months, whereas reaching the Moon requires just a few days' flight. On top of this, Mars has a surface gravity that, though only 38 percent of Earth's, is much greater than the Moon's. It takes a lot of fuel to blast off Mars and get back home. If the propellant has to be transported there from Earth, costs of a launching soar. Without some radical improvements in technology, the prospects for sending astronauts on a round-trip to Mars any time soon are slim, whatever the presidential rhetoric. What's more, the president's suggestion of using the Moon as a base — a place to assemble equipment and produce fuel for a Mars mission less expensively — has the potential to turn into a costly sideshow. There is, however, an obvious way to slash the costs and bring Mars within reach of early manned exploration. The answer lies with a one-way mission."

Under Davies' plan an initial colony of four astronauts equipped with a small nuclear reactor and a couple of rover vehicles would make their own oxygen, grow food, and even initiate building projects using local raw materials. Supplemented by food shipments, medical supplies, and replacement gadgets from Earth, the colony would be indefinitely sustained. Davies argues that since, "some people gleefully dice with death in the name of sport or adventure [and since] dangerous occupations that reduce life expectancy through exposure to hazardous conditions or substances are commonplace," we ought to not find the risks involved in a Mars to Stay architecture unusual.

"A century ago, explorers set out to trek across Antarctica in the full knowledge that they could die in the process, and that even if they succeeded their health might be irreversibly harmed. Yet governments and scientific societies were willing sponsors of these enterprises." Asks Davies, "Why should it be different today?"

Chapter- 4

Terraforming of Mars

Artist's conception of the process of terraforming Mars.

The **terraforming of Mars** is the hypothetical process by which the climate, surface, and known properties of Mars would be deliberately changed with the goal of making it habitable by humans and other terrestrial life, thus providing the possibility of safe and sustainable colonization of large areas of the planet.

The concept is reliant on the assumption that the environment of a planet can be altered through man-made means; the feasibility of creating an unconstrained planetary biosphere is undetermined. There are several proposed methods, some of which present economic and natural resources do not allow, and others which are currently technologically achievable.

Reasons for terraforming

In the future, population growth and demand for resources may create pressure for humans to colonize new habitats such as Mars, the Moon and nearby planets, as well as harvest the Solar System's energy and material resources. Terraforming Mars would hypothetically make Mars habitable to humans.

Terraforming Mars may allow for preservation of Earth's species in the event of a catastrophic extinction event. In approximately 7.6 billion years, the Sun will enter a red giant phase, its outer layers expanding as the hydrogen fuel in the core is consumed and the core contracts and heats up. At this point the Sun's upper atmosphere will extend as far as 1.2AU, out past the present orbit of the Earth. This expansion will likely destabilize the orbits of the inner planets, causing them to spiral in towards the sun and be destroyed. The Sun will lose a significant fraction of its mass in the process of becoming a red giant, and this may cause a widening of the orbits of the other planets. Earth could technically achieve a widening of its orbit and could potentially maintain a sufficiently high angular velocity to keep it from being engulfed. In order to do so, its orbit would need to increase to between 1.3 AU and 1.7 AU.

It is speculated that Earth will be out of its habitable zone before the Sun enters its Red Giant phase. Astronomers estimate that the Sun will be 33% more luminous in three billion years. The heating Sun and increased solar radiation will cause the Earth's oceans to evaporate, and the Earth will eventually become molten again. The habitable zone would eventually move farther out to Mars, giving potential Mars colonists some thousands of additional years to develop further space technology to settle elsewhere in the Solar System.

Background

Mars already consists of many soil minerals that could theoretically be used for terraforming. Large amounts of water ice exist below the Martian surface, as well as on the surface at the poles, where it is mixed with dry ice, frozen CO_2. It has been found that significant amounts of water are stored in the south pole of Mars, and if all of this ice suddenly melted, it would form a planetwide ocean 11 meters deep. Frozen carbon dioxide (CO_2) at the poles sublimates into the atmosphere during the Martian summer, and small amounts of water residue are left behind, which fast winds sweep off the poles at speeds approaching 250 mph (400 km/h). This seasonal occurrence transports large amounts of dust and water vapor into the atmosphere, giving potential for Earth-like cirrus clouds.

Molecular oxygen (O_2) is only present in the atmosphere in trace amounts, but it is present in the carbon dioxide (CO_2) that is the main component of the Martian atmosphere. Elemental oxygen is also present in large amounts in metal-oxides on the Martian surface, and in the soil, in the form of per-nitrates. An analysis of soil samples taken by the Phoenix lander indicated the presence of perchlorate, which has been used to liberate oxygen in chemical oxygen generators. Electrolysis could be employed to separate water on the planet into oxygen and hydrogen if sufficient liquid water and electricity were available.

It has been suggested that Mars once had an environment relatively similar to that of Earth during an earlier stage in its development. While water once appears to have existed on the Martian surface, it now only appears to exist at the poles and just below the planetary surface as permafrost. Gravity of Mars today indicates that lighter gases in the upper atmosphere could have contributed to the thinning of the atmosphere, with the excess atoms escaping into space; also the evident lack of plate tectonics on Mars would in theory slow the recycling of gases from being locked in sediments back into the atmosphere, and the high amounts of Solar Wind on Mars are other plausible contributing factors. The lack of a magnetic field and geologic activity may both be a result of Mars' smaller size, which allows its interior to cool more quickly than Earth's, though the details of such a process are still not well understood.

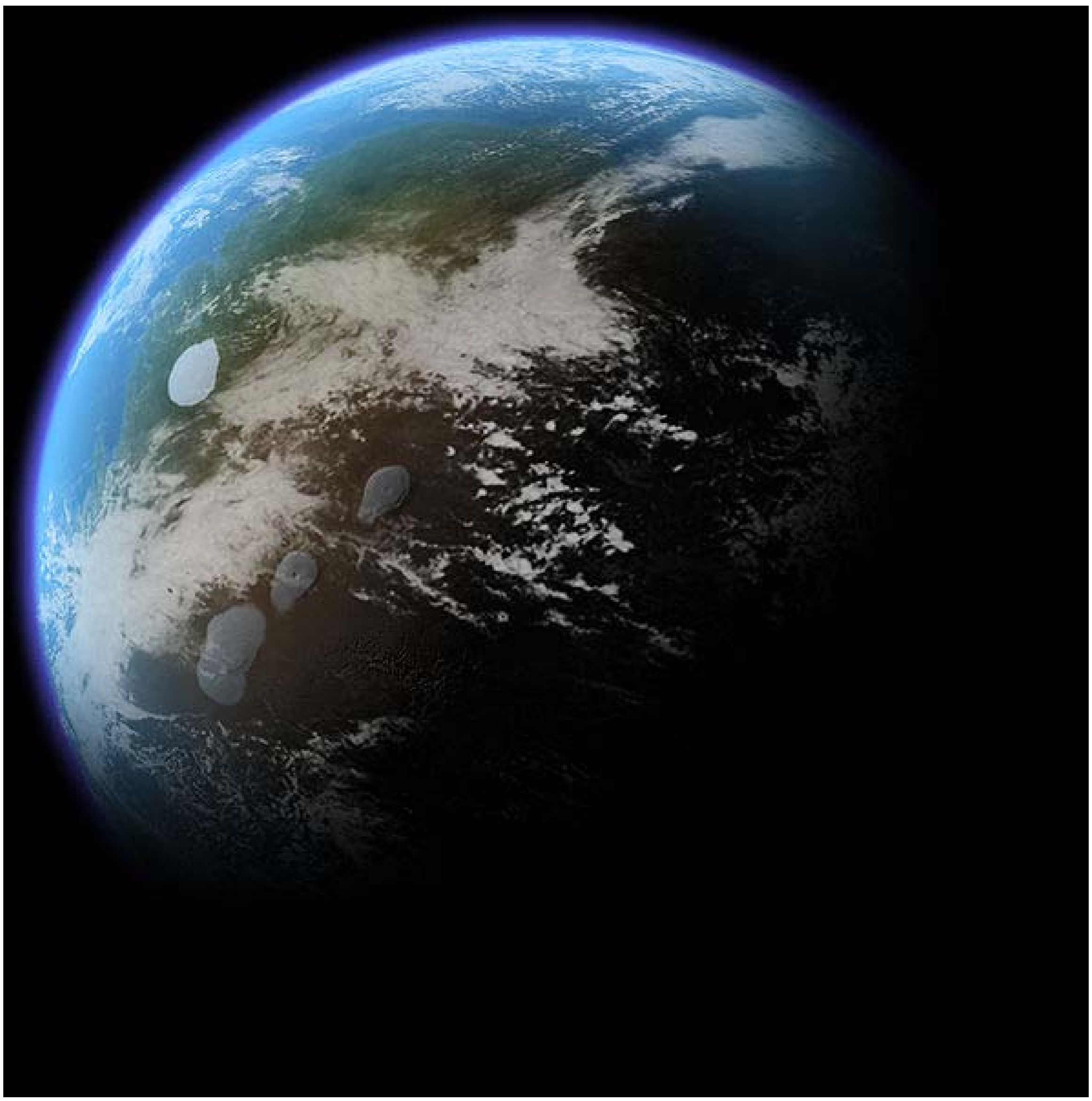
Changes required

Comparison of dry atmosphere

	Mars	Earth
Pressure	**0.6 kPa (0.087 psi)**	**101.3 kPa (14.69 psi)**
Carbon dioxide (CO_2)	**95.32%**	**0.04%**
Nitrogen (N_2)	**2.70%**	**78.08%**
Argon (Ar)	**1.60%**	**0.93%**
Oxygen (O_2)	**0.13%**	**20.94%**

Terraforming Mars would entail three major interlaced changes: building up the atmosphere, keeping it warm, and keeping the atmosphere from being lost into outer space. The atmosphere of Mars is relatively thin and thus has a very low surface pressure of 0.6 kilopascals (0.087 psi); compared to Earth with 101.3 kilopascals (14.69 psi) at sea level and 0.86 kilopascals (0.125 psi) at an altitude of 32 kilometres (20 mi). The atmosphere on Mars consists of 95% carbon dioxide (CO_2), 3% nitrogen, 1.6% argon, and contains only traces of oxygen, water, and methane. Since its atmosphere consists mainly of CO_2, a known greenhouse gas, once the planet begins to heat, more CO_2 enters the atmosphere from the frozen reserves on the poles, adding to the greenhouse effect. This means that the two processes of building the atmosphere and heating it would augment one another, favoring terraforming. However, on a large scale, controlled application of certain techniques (*explained below*) over enough time to achieve sustainable changes would be required to make this hypothesis a reality.

Building the atmosphere, water content

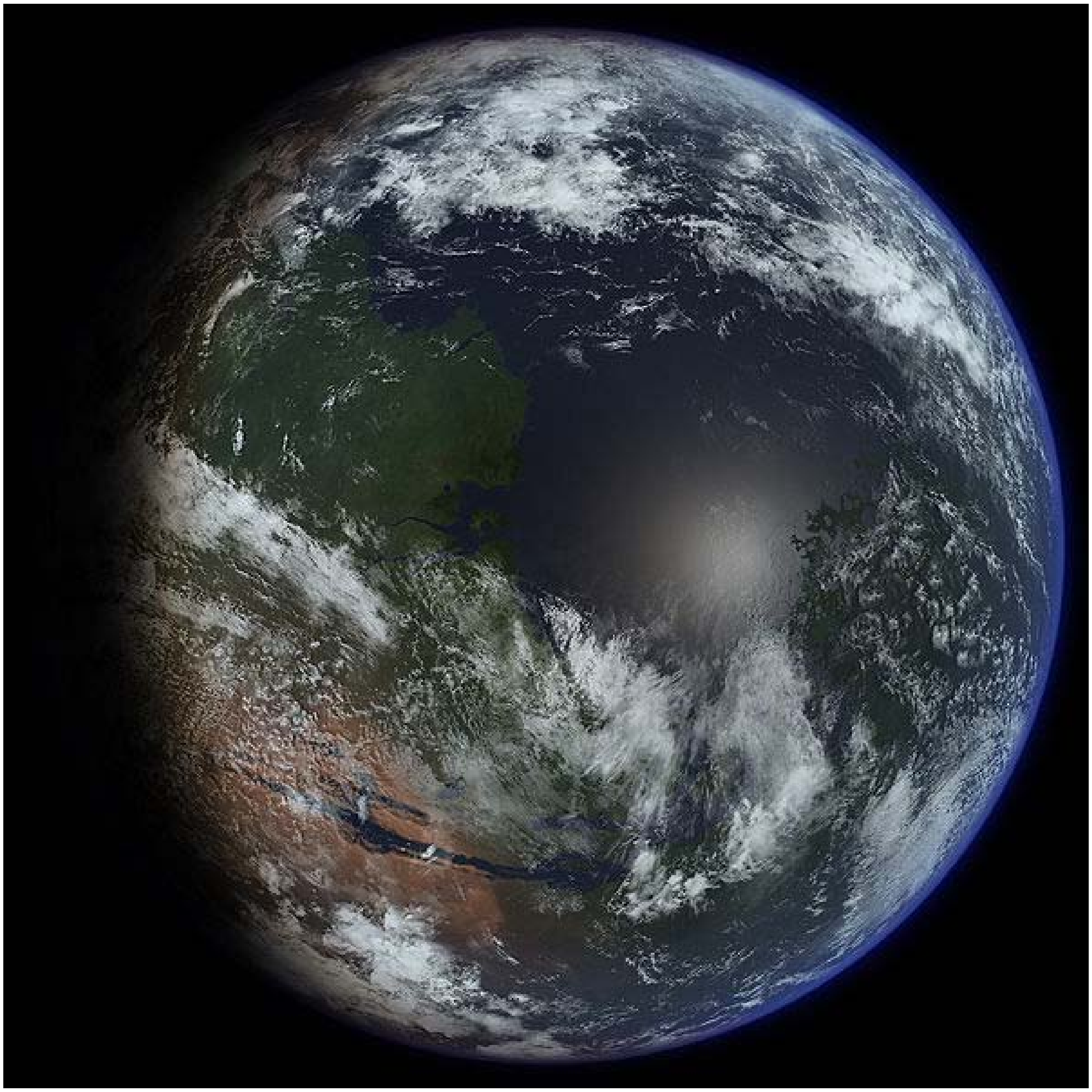


Artist's conception of a terraformed Mars centered on the Tharsis region.

An important step in building the martian atmosphere would be the importation of water, that can be obtained, for example, from ice asteroids or from ice moons of Jupiter or Saturn, beyond the water ice already present at the Martian north pole.

Sources of water

A substantial, nearby source of water is the dwarf planet Ceres, which, according to various studies accounts for 25% to 33% of the mass of the Asteroid Belt. Ceres' mass is approximately 9.43×10^{20} kg. Estimates of how much of Ceres is water varies widely but 20% is a typical estimate and it is thought that much of the water forms the outer or near-surface level. The mass of Ceres' water equals approximately 1.9×10^{20} kg using the previous estimates. The total mass of Mars is approximately 6.42×10^{23} kg. Therefore a very rough estimate is that the amount of water on Ceres equals approximately 0.03 % of the total mass of Mars. Transporting a significant portion of this water, or water from any of the icy moons, could prove difficult. Any attempt to perturb the orbit of Ceres in order to add it whole to Mars (similar to the strategy of using a gravitational tractor for asteroid deflection,) must account for any resultant perturbation of the martian orbit and account for prolonged geological tumult, such as reestablishment of hydrostatic equilibrium, that could result from impact.



Artist's conception of a terraformed Mars. This portrayal is approximately centered on the prime meridian and 30° North latitude, and a hypothesized ocean with a sea level at approximately two kilometers below average surface elevation. The ocean submerges what are now Vastitas Borealis, Acidalia Planitia, Chryse Planitia, and Xanthe Terra; the visible landmasses are Tempe Terra at the left, Aonia Terra at the bottom, Terra Meridiani at the lower right, and Arabia Terra at the upper right. Rivers that feed the ocean at the lower right occupy what are now Valles Marineris and Ares Vallis, while the large lake at the lower right occupies what is now Aram Chaos.

Carbon dioxide sublimation

There is presently enough carbon dioxide (CO_2) as ice in the Martian south pole and absorbed by regolith (soil) around the planet that, if sublimated to gas by a climate warming of only a few degrees, would increase the atmospheric pressure to 300 millibars, which is comparable to that at the peak of Mount Everest. While this would not be breathable by humans, it would eliminate the present need for pressure suits, melt the water ice at Mars' north pole (flooding the northern basin), and bring the year-round climate above freezing over approximately half of Mars' surface. This would enable the introduction of plant life, particularly plankton in the new northern sea, to start converting the atmospheric CO_2 into oxygen.

Ammonia importation

Another, more intricate method, uses ammonia as a powerful greenhouse gas (as it is possible that large amounts of it exist in frozen form on asteroidal objects orbiting in the outer Solar System), it may be possible to move these (for example, by using very large nuclear bombs to blast them in the right direction) and send them into Mars' atmosphere. Since ammonia (NH_3) is high in nitrogen it might also take care of the problem of needing a buffer gas in the atmosphere. Sustained smaller impacts will also contribute to increases in the temperature and mass of the atmosphere.

The need for a buffer gas is a challenge that will face any potential atmosphere builders. On Earth, nitrogen is the primary atmospheric component making up 77% of the atmosphere. Mars would require a similar buffer gas component although not necessarily as much. Still, obtaining significant quantities of nitrogen, argon or some other comparatively inert gas is difficult.

Hydrocarbons importation

Another way would be to import methane or other hydrocarbons, which are common in Titan's atmosphere (and on its surface). The methane could be vented into the atmosphere where it would act to compound the greenhouse effect.

Methane (or other hydrocarbons) also can be helpful to produce a quick increase for the insufficient martian atmospheric pressure. These gases also can be used for production (at the next step of terraforming of Mars) of water and CO_2 for martian atmosphere, by reaction:

$$CH_4 + 4\ Fe_2O_3 \Rightarrow CO_2 + 2\ H_2O + 8\ FeO$$

This reaction could probably be initiated by heat or by martian solar UV-irradiation. Large amounts of the resulting products (CO_2 and water) are necessary to initiate the photosynthetic processes.

Hydrogen importation

Hydrogen importation could also be done for atmospheric and hydrospheric engineering. For example, hydrogen could react with iron(III) oxide from the martian soil, that would give water as a product:

$H_2 + Fe_2O_3 \Rightarrow H_2O + 2FeO$

Depending on the level of carbon dioxide in the atmosphere, importation and reaction of hydrogen would produce heat, water and graphite via the Bosch reaction. Alternatively, reacting hydrogen with the carbon dioxide atmosphere via the Sabatier reaction would yield methane and water.

Using fluorine compounds

Since long-term climate stability would be required for sustaining a human population, the use of especially powerful fluorine-bearing greenhouse gases possibly including sulfur hexafluoride or halocarbons such as chlorofluorocarbons (or CFCs) and perfluorocarbons (or PFCs) has been suggested. These gases are the most cited candidates for artificial insertion into the Martian atmosphere because of their strong effect as a greenhouse gas. This can conceivably be done relatively cheaply by sending rockets with a payload of compressed CFCs on a collision course with Mars. When the rocket crashes onto the surface it releases its payload into the atmosphere. A steady barrage of these "CFC rockets" would need to be sustained for a little more than a decade while the planet changes chemically and becomes warmer.

In order to sublimate the south polar CO_2 glaciers, Mars would require the introduction of approximately 0.3 microbars of CFC (chloro-fluoro-carbons) into Mars' atmosphere. CFC are powerful greenhouse gases that are thousands of times more effective at warming than CO_2. The 0.3 microbars needed would mass approximately 39 million metric tonnes, which is about three times the amount of CFC manufactured on Earth from 1972 to 1992 when CFC production was banned by international treaty. Mineralogical surveys of Mars have found significant amounts of the ores necessary to produce the amount of CFC gas required.

A proposal to mine fluorine-containing minerals as a source of CFCs and PFCs is supported by the belief that since the quantities present are expected to be at least as common on Mars as on Earth, this process could sustain the production of sufficient quantities of optimal greenhouse compounds (CF_3SCF_3, $CF_3OCF_2OCF_3$, $CF_3SCF_2SCF_3$, $CF_3OCF_2NFCF_3$) to maintain Mars at 'comfortable' temperatures, as a method of maintaining an Earth-like atmosphere produced previously by some other means.

Adding heat

Adding heat and conserving the heat present is a particularly important stage of this process, as heat from the Sun is the primary driver of planetary climate. As the planet would become warmer through various methods the CO_2 on the polar caps would sublime into the atmosphere and would further contribute to the warming effect. The tremendous air currents generated by the moving gasses would create large, sustained dust storms, which would heat (through absorbing solar radiation) the molecules in the atmosphere.

Orbiting mirrors

Mirrors made of thin aluminized PET film could be placed in orbit around Mars to increase the total insolation it receives. This would direct the sunlight onto the surface and could increase the planet's surface temperature directly. The mirror could be positioned as a statite, using its effectiveness as a solar sail to orbit in a stationary position relative to Mars, near the poles, to sublimate the CO_2 ice sheet and contribute to the warming greenhouse effect.

Albedo

Reducing the albedo of the Martian surface would also make more efficient use of incoming sunlight. This could be done by spreading dark dust from Mars' moons, Phobos and Deimos, which are among the blackest bodies in the Solar System; or by introducing dark extremophile microbial life forms such as lichens, algae and bacteria. The ground would then absorb more sunlight, warming the atmosphere.

If algae or other green life were established, it would also contribute a small amount of oxygen to the atmosphere, though not enough to allow humans to breathe.

Asteroid impact

Another way to increase the temperature could be to direct small cosmic bodies (asteroids) onto the Martian surface; the impact energy would be released as heat and could vaporize Martian water ice to steam, which is also a greenhouse gas. Asteroids could also be chosen for their composition, such as Ammonia, which would then disperse into the atmosphere on impact, adding greenhouse gases to the atmosphere. Lightning may have built up nitrate beds in the soil over the life of the planet. Impacting asteroids on these nitrate beds would release additional nitrogen and oxygen into the atmosphere.

Magnetic field and solar radiation

Earth abounds with water because its ionosphere is permeated with a magnetic field. The hydrogen ions present in its ionosphere move very fast due to their small mass, but they cannot escape to outer space because their trajectories are deflected by the magnetic field. Venus has a dense atmosphere, but only traces of water vapor (20 ppm) because it has no magnetic field. The Martian atmosphere is devoid of water vapor.

Earth's ozone layer provides additional protection. Ultraviolet light is blocked before it can dissociate water into hydrogen and oxygen. Since little water vapor rises above the troposphere and the ozone layer is in the upper stratosphere, little water is dissociated into hydrogen and oxygen.

It is believed that Mars would be uninhabitable to most life-forms due to high solar radiation levels. Because of the planet's lack of a magnetosphere, the Sun is thought to have thinned the Martian atmosphere to its current state; the solar wind adding a significant amount of energy to the atmosphere's top layers which enables the atmospheric particles to reach escape velocity and leave Mars. Indeed, this effect has even been detected by Mars-orbiting probes. Another theory is that solar wind rips the atmosphere away from the planet as it becomes trapped in bubbles of magnetic fields called plasmoids.

Venus, however, shows that the lack of a magnetosphere does not preclude a dense (albeit dry) atmosphere. A thick atmosphere could also provide solar radiation protection to the surface, similar to Earth's. In the past, Earth has regularly had periods where the magnetosphere changed direction and collapsed for some time.

The lack of a protective magnetic field would also have possible health effects on colonists due to increased cosmic ray flux. The health threat depends on the flux, energy spectrum, and nuclear composition of the rays. The flux and energy spectrum depend on a variety of factors, which are incompletely understood. The Mars Radiation Environment Experiment (MARIE) was launched in 2001 in order to collect more data. Estimates are that humans unshielded in interplanetary space would receive annually roughly 400 to 900 milli-Sieverts (mSv) (compared to 2.4 mSv on Earth) and that a Mars mission (12 months in flight and 18 months on Mars) might expose shielded astronauts to ~500 to 1000 mSv. These doses approach the 1 to 4 Sv career limits advised by the National Council on Radiation Protection and Measurements for Low Earth orbit activities.

Shielding from cosmic rays can be accomplished by placing habitation modules either within lava tubes or under igloo structures built from sintered regolith bricks.

Chapter- 5

Colonization of Mercury

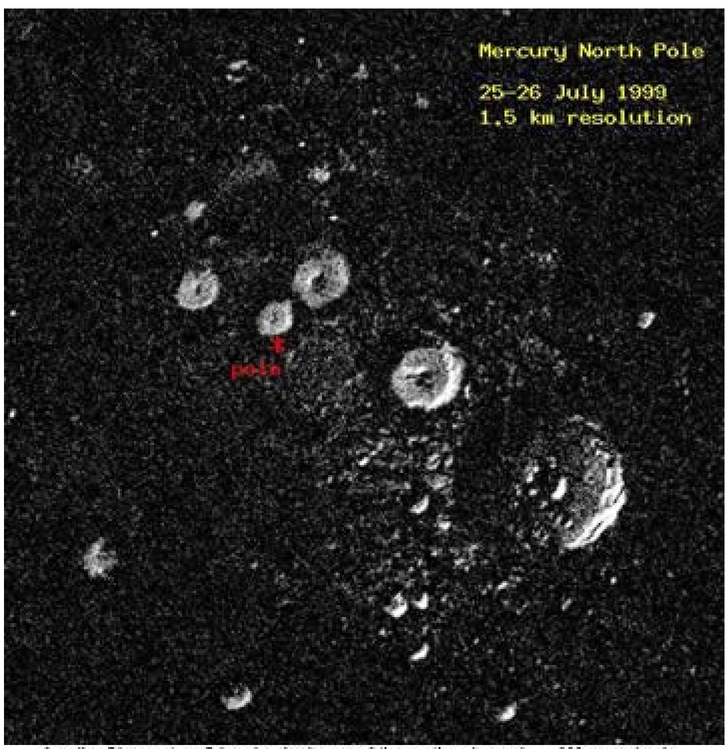
Mercury

Mercury has been suggested as one possible target for space colonization of the inner solar system, along with Mars, Venus, the Moon and the asteroid belt. Permanent colonies would almost certainly be restricted to the polar regions due to the extreme daytime temperatures elsewhere on the planet. Excursions to the other parts of the planet would be feasible with appropriate measures, particularly along the very slowly moving terminator, which would approximate polar conditions.

Advantages

Similarity to the Moon

Like the Earth's Moon, Mercury does not have any significant atmosphere. It is close to the Sun and performs slow rotations with a very small tilt of its axis. Because of this similarity any colonization of Mercury might be performed with the same general technology, approach and equipment as a colonization of the Moon. Bruce Murray referred to Mercury as "A Mini-Earth in Moon's Clothing". Unlike the Moon however, Mercury has the additional advantage of a magnetic field protecting it from cosmic rays and solar storms, and a larger surface gravity of about 0.38 g, nearly equal to that of Mars.



Arecibo Observatory S-band radar image of the north polar region of Mercury by J. Harmon, P. Perrilat, and M. Slade. The resolution is 1.5 kilometers (about 1 mile) and the image measures 450 kilometers on a side. The bright features are thought to be ice deposits on permanently shadowed crater floors.

Radar image of Mercury's north pole

Ice in polar craters

Due primarily to its distance from the Sun, the surface of Mercury can reach 700 K (427 °C, 800 °F), hot enough to melt lead. However, temperatures at the polar regions are much colder and there may even be deposits of ice inside permanently shaded craters. The polar areas do not experience the extreme daily variation in temperature seen on more equatorial areas of Mercury's surface.

Solar energy

Being the closest planet to the Sun, Mercury has vast amounts of solar power available. Its solar constant is 9.13 kW/m², 6.5 times that of Earth or the Moon. Because the tilt of its axis of rotation relative to its orbit is so low, approximately 0.01 degrees, there is also the possibility of so-called peaks of eternal light, similar to those of the Moon—high points located at the poles of the planet that are continuously radiated by the Sun. Even if they do not exist, it is possible that they could be constructed artificially.

In 1986, C.R. Pellegrino and J.R. Powell proposed covering Mercury with solar power farms, and transferring some of the resulting energy into a form useful for propulsion for interstellar travel.

Valuable resources

There are predictions that Mercury's soil may contain large amounts of helium-3, which could become an important source of clean nuclear fusion energy on Earth and a driver for the future economy of the solar system. However, Mercury's magnetic field could have prevented helium-3 from reaching the surface.

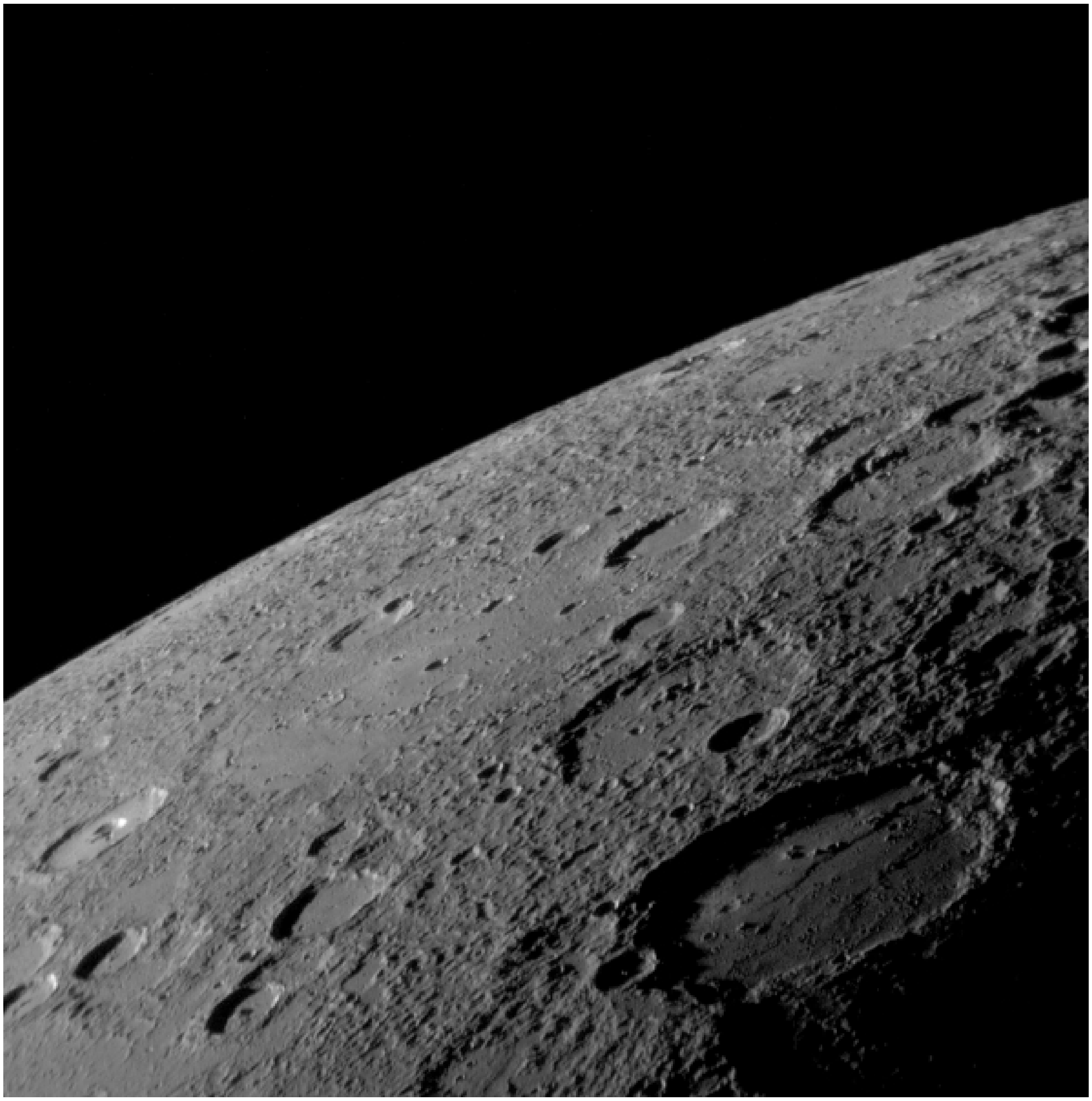
Mercury is also theorized to have a crust rich in iron and magnesium silicates, with the highest concentrations of many valuable minerals of any surface in the solar system, in highly concentrated ores.

Geologist Stephen Gillett has suggested this will make Mercury an ideal place to build solar sails, which could launch as folded up "chunks" by mass driver from Mercury's surface. Once in space the solar sails would deploy. Since Mercury's solar constant is 6.5 times higher than Earth's, energy for the mass driver should be easy to come by, and solar sails near Mercury would have 6.5 times the thrust they do near Earth. This could make Mercury an ideal place to acquire materials useful in building hardware to send to (and terraform) Venus.

Considerable gravity

Mercury is bigger than the Moon, with a diameter of 4879 km versus 3476 km, and has a higher density due to its large iron core. As a result, gravity on the surface of Mercury is 0.377 *g*, more than twice that of the Moon (0.1654 g) and very close to the surface gravity on Mars. Since there is evidence of human health problems associated with extended exposure to low gravity, from this point of view, Mercury might be more attractive for long-term human habitation than the Moon.

Difficulties



Mercury as imaged by the MESSENGER spacecraft in 2008

The lack of any substantial atmosphere, close proximity to the Sun and long solar days (176 Earth days) would all lead to significant challenges for any future human settlement. A permanent colony would almost certainly be restricted to the polar regions, but temporary excursions toward the equator could take place during the long night. Outside of the possibility of ice at the poles, it is unlikely that the lighter elements needed for life exist on the planet. These would have to be imported.

Mercury is also deep in the Sun's gravitational potential well, requiring a larger velocity change (delta V) to travel to and from Mercury than is needed for other planets, although, in the past, gravity assist orbits using Venus have been used to reach Mercury. However, entering orbit around Mercury and landing on the surface would take 6 years with current propulsion methods. Solar sails and mass drivers may assist in transportation in the future, but are not viable options at present.

Chapter- 6

Colonization of Venus

Venus

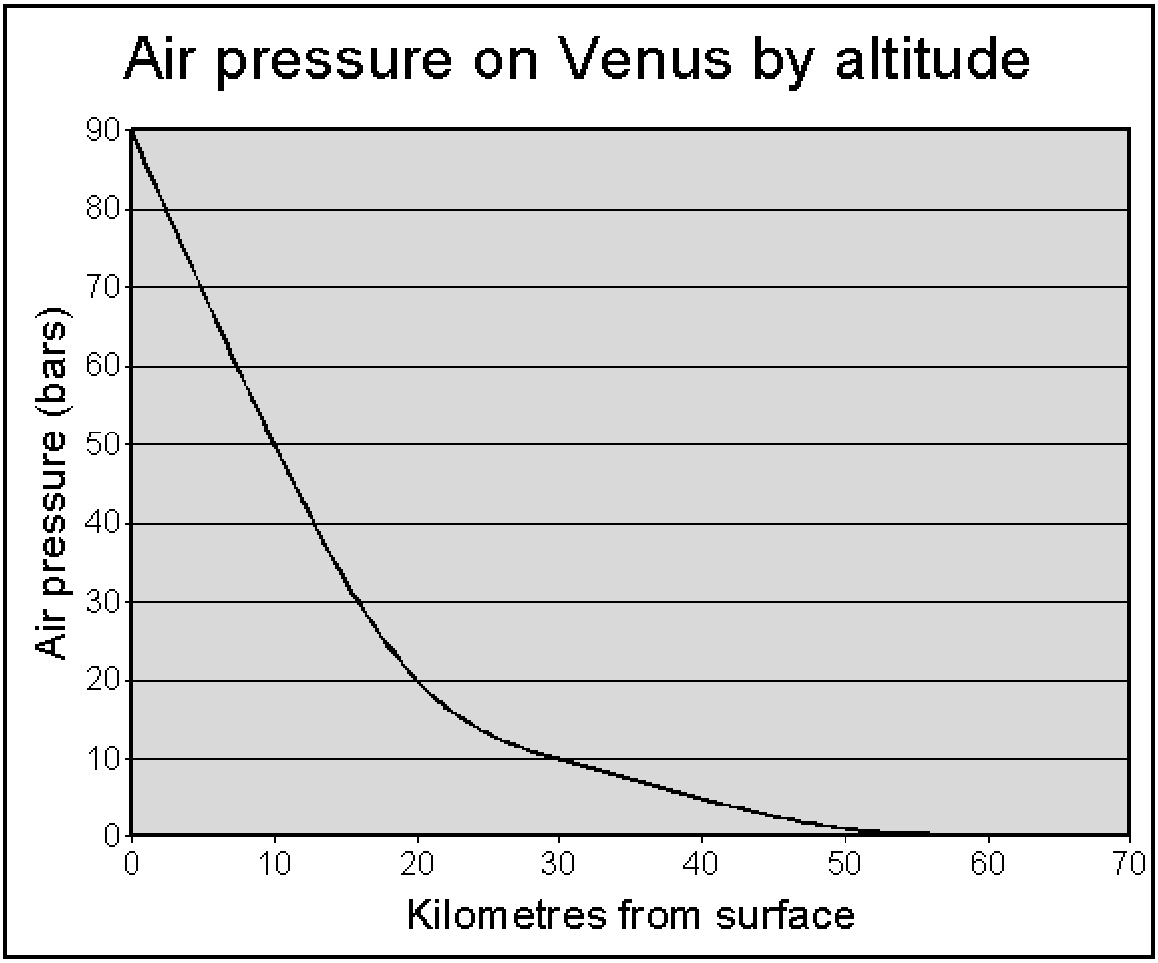
The **colonization of Venus** has been a subject of much speculation and many works of science fiction since before the dawn of spaceflight, and is still much discussed. With the discovery of Venus' hostile surface environment, attention has largely shifted towards the colonization of the Moon and the colonization of Mars.

Reasons for colonization

Space colonization is a step beyond space exploration, and implies the permanent or long-term presence of humans in an environment outside Earth. Colonization of space is arguably the best way to ensure the survival of humans as a species. Other reasons for colonizing space include economic interests, long-term scientific research best carried out by humans, and sheer curiosity. Venus is the second largest terrestrial planet and Earth's closest neighbour, which makes it a potential target.

Advantages

Scale representations of Venus and the Earth shown next to each other. Venus is only slightly smaller.



Air pressure on Venus, beginning at a pressure on the surface 90 times that of Earth and reaching a single bar by 50 kilometres.

Venus has certain similarities to Earth which might make colonization easier in many respects in comparison with other possible destinations. These similarities, and its proximity, have led Venus to be called Earth's "sister planet".

At present it has not been established whether the gravity of Mars, 0.38 times that of the Earth, would be sufficient to avoid bone decalcification and loss of muscle tone experienced by astronauts living in an environment of microgravity (the probe Mars Gravity Biosatellite was going to be the first probe to investigate this, however it has since been canceled due to lack of funding). In contrast, Venus is close in size and mass to the Earth, resulting in a similar surface gravity (0.904 *g*). Most other space exploration and colonization plans face concerns about the damaging effect of long-term exposure to fractional *g* or zero gravity on the human musculoskeletal system. Humans born on Venus would probably have little difficulty adapting to Earth gravity should there be a reason to visit or return; contrasted to return trips from Mars where humans would likely need rehabilitation or the use of an exoskeleton.

Venus's relative proximity makes transportation and communications easier than for most other locations in the solar system. With current propulsion systems, launch windows to Venus occur every 584 days, compared to the 780 days for Mars. Flight time is also somewhat shorter; the probe Venus Express which recently arrived at Venus spent slightly over five months en route, compared to nearly six months for Mars Express. This is because at closest approach, Venus is 45 million km from Earth compared to 56 million km for Mars, making Venus the closest planet to the Earth.

Difficulties

Venus also presents several significant challenges to human colonization. Surface conditions on Venus are practically impossible to deal with: the temperature at the equator averages around 500 °C (932 °F), higher than the melting point of lead. The atmospheric pressure on the surface is also at least ninety times greater than on Earth, which is equivalent to the pressure experienced under a kilometer of water. These conditions have caused missions to the surface to be extremely brief: the probes Venera 5 and Venera 6 for example were crushed by high pressure whilst still 18 km above the surface. Following landers such as Venera 7 and Venera 8 succeeded in transmitting data after reaching the surface, but these missions were brief as well, surviving no more than a single hour on the surface.

Furthermore, water, in any form, is almost entirely absent from Venus. The atmosphere is devoid of molecular oxygen and is primarily carbon dioxide in poisonously high concentrations. In addition, the visible clouds are composed partly of corrosive sulfuric acid and sulfur dioxide vapor.

Methods of colonization and exploration

Given the hostile conditions of Venus, a colony on the Venusian surface in its present form is far beyond current technological capabilities.

This has not prevented some science-fiction authors from speculating on ways of overcoming this by, for example, terraforming Venus – making the planet more earth-like. The energy requirements for all terraforming plans are daunting when compared with our current technology, and the time required could possibly span hundreds of years. Other authors speculate that, if a large portion or the entire planet could be shaded, Venus would cool to a useful temperature in mere decades. Such authors postulate methods which would include placing sails (Solar shades) between Venus and the sun at the Lagrange point between the two, controlled dust clouds in space, and a large number of other ideas.

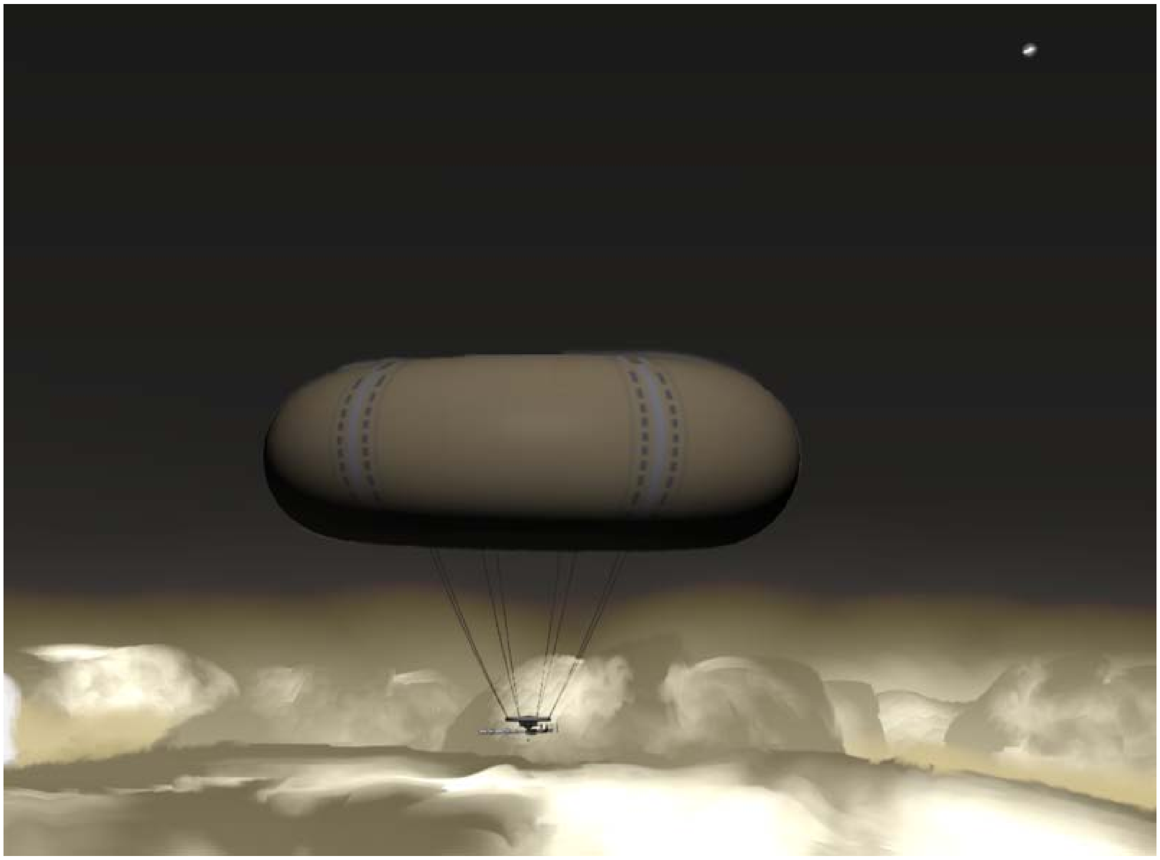
Others suggest a different approach, however, claiming that rather than attempting to colonize Venus' hostile surface, humans might attempt to colonize the Venusian atmosphere (the most habitable known part of any planet outside Earth). This is because at an altitude of approximately 50 kilometers (in Venus's upper atmosphere), the pressure and temperature are Earth-like (1 bar and 0-50 degrees Celsius).

Exploration and research

As Venus has not been studied as much as objects such as the moon and Mars have, further research would have to be conducted on the planet before a human-powered mission could be approved. The probe Venus Express is currently in orbit around the planet, but other low-cost missions have been proposed to further explore the planet's atmosphere, as the area 50 kilometres above the surface where air pressure is at the same level as Earth has not yet been explored.

It is currently possible to successfully land a robot on the surface. The Soviet Venera program succeeded in doing so – the Venera 13 lander survived for 127 minutes, and the Venera 14 lander for 57 minutes. It is not inconceivable that this survival time could be extended. Improved materials and technology designed to work at the high temperatures and pressures would be necessary. As the survival times of the robotic probes grows longer, enhanced missions might be feasible, including the establishment of a robotic base at locations where important (perhaps fissionable) compounds might be found. The technology for operating under such conditions is at the current time so exotic as to be difficult to conceive, and funding is likely to go elsewhere.

Aerostat habitats and floating cities



Hypothetical prototype floating outpost studying colonization of Venus around 50 km above the surface supported by a torus full of hydrogen.

Geoffrey A. Landis has summarized the perceived difficulties in colonizing Venus as being merely from the assumption that a colony would need to be based on the surface of a planet:

> "However, viewed in a different way, the problem with Venus is merely that the ground level is too far below the one atmosphere level. At cloud-top level, Venus is the paradise planet."

He has proposed aerostat habitats followed by floating cities, based on the concept that breathable air (21:79 Oxygen-Nitrogen mixture) is a lifting gas in the dense Venusian atmosphere, with over 60% of the lifting power that helium has on Earth. In effect, a balloon full of human-breathable air would sustain itself and extra weight (such as a colony) in midair. At an altitude of 50 km above Venusian surface, the environment is the most Earth-like in the solar system – a pressure of approximately 1 bar and temperatures in the 0°C–50°C range. Because there is not a significant pressure difference between the inside and the outside of the breathable-air balloon, any rips or tears would cause gases to diffuse at normal atmospheric mixing rates, giving time to repair any such damages. In addition, humans would not require pressurized suits when outside, merely air to breathe and a protection from the acidic rain. Alternatively, two-part domes could contain a lifting gas like hydrogen or helium (extractable from the atmosphere) to allow a higher mass density.

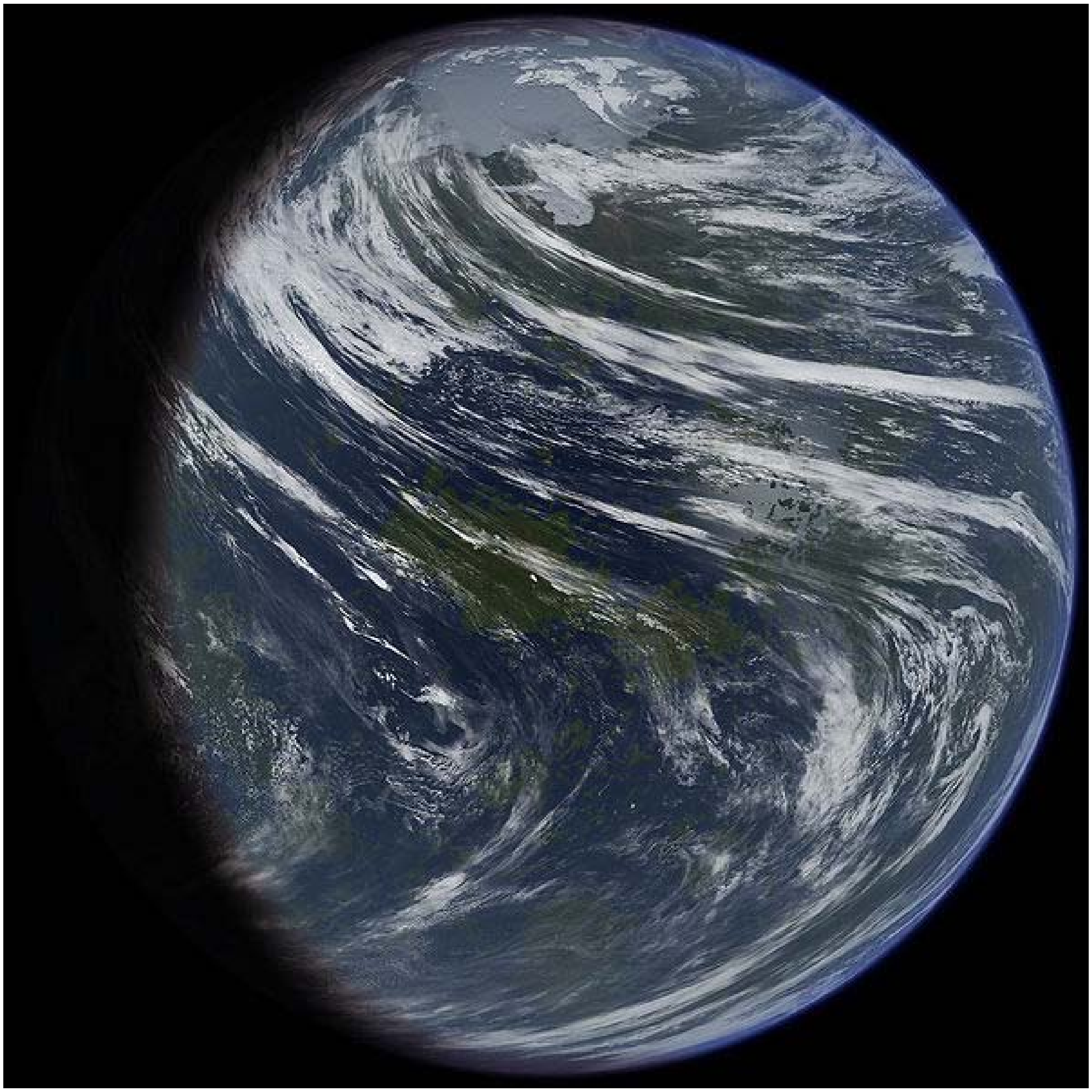
Cloud-top colonization also offers a way to avoid the issue of slow Venusian rotation. At the top of the clouds the wind speed on Venus reaches up to 95 m/s (approximately 212 mph), circling the planet approximately every four Earth days in a phenomenon known as "super-rotation". Colonies floating in this region could therefore have a much shorter day length by remaining untethered to the ground and moving with the atmosphere. While a space elevator extending to the surface of Venus is impractical due to the slow rotation, constructing a skyhook that extended into the upper atmosphere and rotated at the wind speed would not be difficult compared to constructing a space elevator on Earth.

Since such colonies would be viable in current Venusian conditions, this allows a dynamic approach to colonization instead of requiring extensive terraforming measures in advance. The main challenge would be using a substance resistant to sulfuric acid to serve as the structure’s outer layer; ceramics or metal sulfates could possibly serve in this role. Dyneema, Polyethene and Polypropylene would be well usable for the skin of the balloon.

Landis has suggested that as more floating cities were built, they could form a solar shield around the planet, and could simultaneously be used to process the atmosphere into a more desirable form. If made from carbon nanotubes (recently fabricated into sheet form) or graphene (a sheet-like carbon allotrope), the major structural materials can be produced using carbon dioxide gathered in situ from the atmosphere. The recently synthesised amorphous carbonia might prove a useful structural material if it can be quenched to STP conditions, perhaps in a mixture with regular silica glass. According to Birch's analysis such colonies and materials would provide an immediate economic return from colonizing Venus, funding further terraforming efforts.

In remarking that the ground is too far below the one-atmosphere level, Landis echoes the descriptions of the planets Rustum, in the novel *Orbit Unlimited* by Poul Anderson, and Plateau, in *A Gift from Earth* by Larry Niven. Each has a dense poisonous atmosphere, with a small region of land rising to a habitable level.

Terraforming



Artist's conception of a terraformed Venus.

Terraforming (literally, "Earth-shaping") is the theoretical process of modifying a planet, moon, or other body to a more habitable atmosphere, temperature, or ecology. Venus has been the subject of a number of terraforming proposals. The proposals seek to remove or convert the dense carbon dioxide atmosphere, reduce Venus's 500 °C (770 K) surface temperature, and establish a day/night light cycle closer to that of Earth's.

Most proposals involve deployment of a solar shade and/or a system of orbital mirrors, for the purpose of reducing insolation and providing light to the dark side of Venus. Another common thread in most proposals involves some introduction of large quantities of hydrogen or water. Proposals also involve either freezing most of Venus's atmospheric CO_2, or converting it to carbonates, urea or other forms.

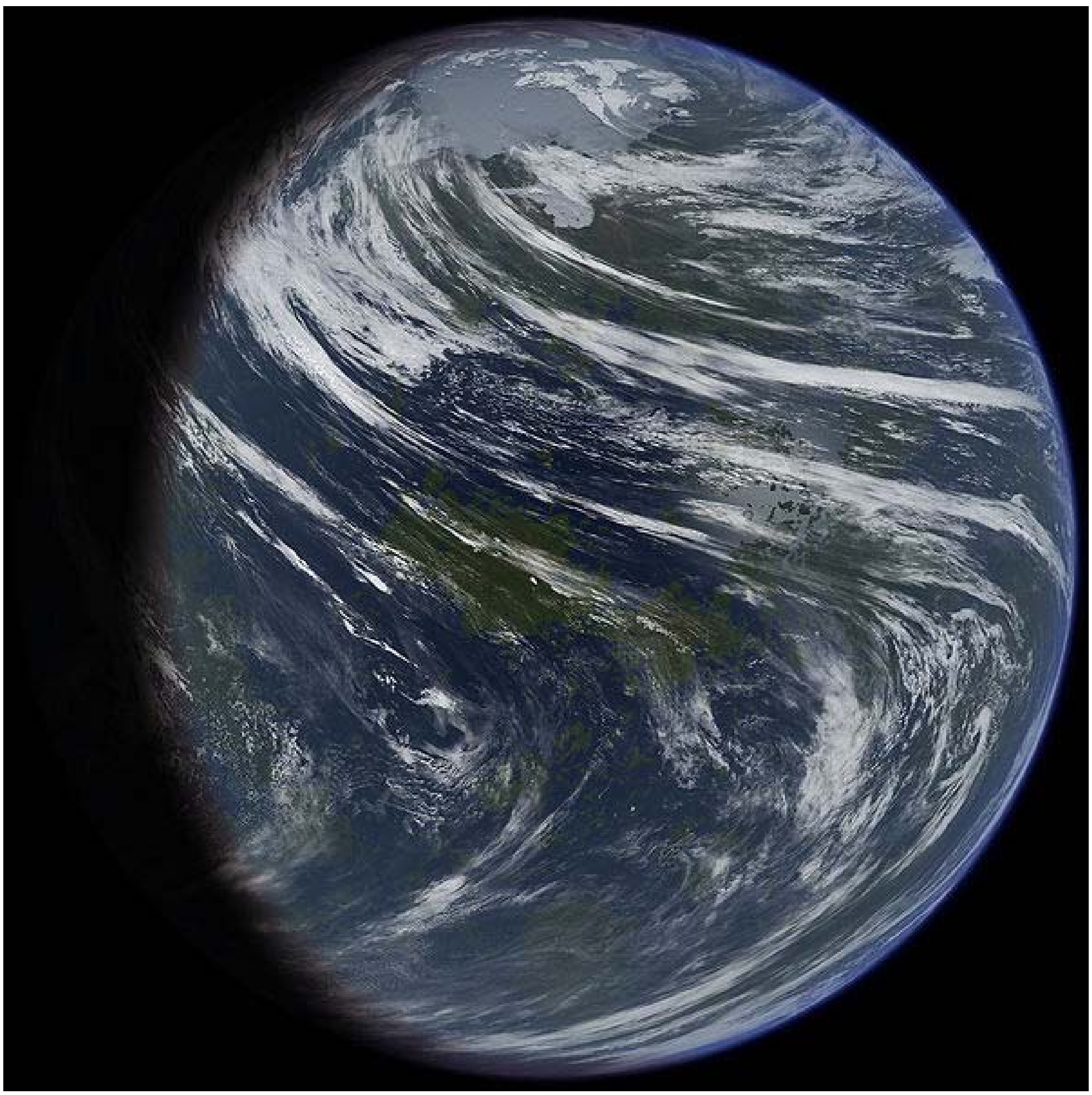
Colonies in Venus Orbit

Another promising pathway to colonization is the use of near-Venus space for the orbital capture and development of comets and asteroids. Although Venus currently has no moons, in the near future it may be practical to nudge smaller bodies into orbit around the inner planets. Venus is especially good for this because aerobraking in its thick atmosphere can be used to slow these bodies down. Unlike near-Earth space where the danger of hitting the Earth would have severe effects on the civilization, near-Venus space does not suffer from this problem. The available free solar energy from the Sun makes Venus a desirable location for industrial development.

It is also a likely precursor to any serious attempt to develop economic activity in the gravity well of Venus. Resources in Venus orbit would be used to extend activity downward. A space elevator would likely not be feasible, given Venus' slow rotation (243 Earth days), but a skyhook into the atmosphere is possible.

Chapter- 7

Terraforming of Venus



Artist's conception of a terraformed Venus. The cloud formations are depicted assuming the planet's rotation has not been sped up.

Terraforming of Venus is the hypothetical process of engineering the global environment of the planet Venus in such a way as to make it suitable for human habitation. Terraforming Venus was first seriously proposed by the astronomer Carl Sagan in 1961. The minimum adjustments to the existing environment of Venus to support human life would require three major changes to the planet:

- Reducing Venus's 450°C (850°F) surface temperature.
- Eliminating most of the planet's dense 9 MPa (~90 atm) carbon dioxide atmosphere, via removal or conversion to some other form.
- Addition of breathable oxygen to the atmosphere.

These three goals are closely interrelated, since Venus's extreme temperature is due to the greenhouse effect caused by its dense carbon-dioxide atmosphere. In addition, two additional changes would be highly desirable:

- Establishing a day/night light cycle shorter than Venus's current solar day (currently equal to 116.75 Earth days).
- Establishing a planetary magnetic field or substitute for protection against solar and cosmic radiation.

Solar shades

Venus receives about twice the sunlight that Earth does, which is thought to have contributed to its runaway greenhouse effect. Terraforming Venus will likely involve reducing the insolation at Venus' surface to prevent the planet from heating up again.

Space based

Solar shades could be used to reduce the total insolation received by Venus, cooling the planet somewhat. A shade placed in the Sun-Venus L_1 Lagrange point also serves to block the solar wind, removing the radiation exposure problem on Venus.

Construction of a suitably large solar shade is a daunting task. The size of the shade would be four times the diameter of Venus itself if at the L_1 point. This size would necessitate construction in space. There would also be the difficulty of balancing a thin-film shade perpendicular to the Sun's rays at the Sun-Venus Lagrangian point with the incoming radiation pressure, which would tend to turn the shade into a huge solar sail. If the shade were left at the L_1 point, the pressure would add force to the sunward side and necessitate moving the shade even closer to the Sun than the L_1 point.

Modifications to the L_1 solar shade design have been suggested to solve the solar sail problem. One suggested method is to use polar orbiting, solar-synchronous mirrors that reflect light toward the back of the sunshade, from the non-sunward side of Venus. Photon pressure would push the support mirrors to an angle of 30 degrees away from the sunward side.

Paul Birch proposed a slatted system of mirrors near the L_1 point between Venus and the Sun. The shade's panels would not be perpendicular to the sun's rays, but instead at an angle of 30 degrees, such that the reflected light would strike the next panel, negating the photon pressure. Each successive row of panels would be +/- 1 degree off the 30-degree deflection angle, causing the reflected light to be skewed 4 degrees from striking Venus.

Another possibility, suggested by Bradley C. Edwards, is to put into orbit around Venus a belt of material, blocking a portion of sunlight. Multiple thinner belts may be used, and may be composed of a thin net of fibers spaced so that certain wavelengths could not get through while using less material.

Solar shades could also serve as solar power generators. Space-based solar shade techniques, and thin-film solar sails in general, are only in an early stage of development. The vast sizes require a quantity of material that is many orders of magnitude greater than any man-made object that has ever been brought into space or constructed in space.

Atmospheric or surface-based

Cooling could also be effected by placing reflectors in the atmosphere or on the surface. Reflective balloons floating in the upper atmosphere could create shade. The number and/or size of the balloons would necessarily be great. Geoffrey A. Landis has suggested that if enough floating cities were built, they could form a solar shield around the planet, and could simultaneously be used to process the atmosphere into a more desirable form, thus combining the solar shield theory and the atmospheric processing theory with a scalable technology that would immediately provide living space in the Venerian atmosphere. If made from carbon nanotubes (recently fabricated into sheet form) or graphene (a sheet-like carbon allotrope), then the major structural materials can be produced using carbon dioxide gathered in situ from the atmosphere. The recently synthesised amorphous carbonia might prove a useful structural material if it can be quenched to STP conditions, perhaps in a mixture with regular silica glass. According to Birch's analysis such colonies and materials would provide an immediate economic return from colonizing Venus, funding further terraforming efforts.

Increasing the planet's albedo by deploying light color or reflective material on the surface could help keep the atmosphere cool. The amount would be large and would have to be put in place after the atmosphere had been modified already, since Venus's surface is currently completely shrouded by clouds.

An advantage of atmospheric and surface cooling solutions is that they take advantage of existing technology. A disadvantage is that Venus already has highly reflective clouds (giving it an albedo of 0.65), so any approach would have to significantly surpass this to make a difference.

Eliminating the dense carbon dioxide atmosphere

Biological approaches

A method proposed in 1961 by Carl Sagan involves the use of genetically engineered bacteria to fix carbon into organic forms. Although this method is still commonly proposed in discussions of Venus terraforming, later discoveries showed it would not be successful. The production of organic molecules from carbon dioxide requires an input of hydrogen, which on Earth is taken from its abundant supply of water but which is nearly nonexistent on Venus. Since Venus lacks a magnetic field, the upper atmosphere is exposed to direct erosion by solar wind and has lost most of its original hydrogen to space.

Furthermore, any carbon that was bound up in organic molecules would quickly be converted to carbon dioxide again by the hot surface environment. Venus would not begin to cool down until after most of the carbon dioxide has already been removed. 23 years later, in *Pale Blue Dot*, Sagan conceded that his original proposal for terraforming would not work because the atmosphere of Venus is far denser than was known in 1961.

Floating colonies could gradually transform the Venerian atmosphere: for example, their reflectivity could alter the overall albedo of Venus. Colonies could also grow plant matter, if water or another source of hydrogen were imported, which would gradually sequester carbon dioxide in the air. However, it would take an enormous number of such colonies, and large quantities of introduced hydrogen, to have a significant atmospheric impact, as there is over 1.2×10^{20} kg of carbon in Venus's atmosphere.

Introduction of hydrogen

Bombarding Venus with hydrogen, possibly from some outer solar system source, and reacting with carbon dioxide, could produce elemental carbon (graphite) and water by the Bosch reaction. It would take about 4×10^{19} kg of hydrogen to convert the whole Venerian atmosphere. (Loss of hydrogen due to the solar wind is unlikely to be significant on the timescale of terraforming.) Due to the relatively flat surface, this water would cover about 80% of the surface compared to 70% for Earth, even though it would amount to only roughly 10% of the water found on Earth.

The remaining atmosphere, at around 3 bars (about three times that of Earth), will mainly be composed of nitrogen, some of which will dissolve into the new oceans of water, reducing atmospheric pressure further, in accordance with Henry's law.

Capture in carbonates

Bombardment of Venus with refined magnesium and calcium metal could sequester carbon dioxide in the form of calcium and magnesium carbonates. About 8×10^{20} kg of calcium or 5×10^{20} kg of magnesium would be required, which would entail a great deal of mining and mineral refining. 8×10^{20} kg is a few times the mass of the asteroid 4 Vesta (more than 300 miles in diameter).

Modelling by Mark Bullock of Venus' atmospheric evolution suggests that existing surface minerals, particularly calcium and magnesium oxides, could serve as a sink of carbon dioxide and sulphur dioxide. If these could be exposed to the atmosphere then the planet would cool and its atmospheric pressure decline somewhat. One of the possible end states modelled by Bullock was a 43 bar atmosphere and 400 K surface temperature.

Direct liquefaction and sequestration

Birch's proposal involves using a solar shade to cool Venus down sufficiently to permit liquefaction, from a temperature less than 304.18 K and partial pressures of CO_2 down to 73.8 bar (carbon dioxide's critical point) and then down to 5.185 bar and 216.85 K (carbon dioxide's triple point). Below that temperature, freezing of atmospheric carbon dioxide into dry ice will cause it to deposit onto the surface, after which the frozen CO_2 would be buried and maintained in that condition by pressure, or shipped off-world. After this process was complete, the shades could be removed or solettas added, allowing the planet to partially warm again to temperatures comfortable for Earth life. A source of hydrogen or water would still be needed, and some of the remaining 3.5 bar of atmospheric nitrogen would need to be fixed into the soil. Birch suggests disrupting an ice-moon of Saturn and bombarding Venus with its fragments to provide perhaps an average depth of 100 meters of water over the whole planet.

Removing atmosphere

The removal of Venus's atmosphere could be attempted by a variety of methods, possibly in combination. Directly lifting atmospheric gas from Venus into space would likely prove difficult. Venus has sufficiently high escape velocity to make blasting it away with asteroid impacts impractical. Pollack and Sagan calculated in 1993 that an impactor of 700 km diameter striking Venus at greater than 20 km/s, would eject all the atmosphere above the horizon as seen from the point of impact, but since this is less than a thousandth of the total atmosphere and there would be diminishing returns as the atmosphere's density decreased a very great number of such giant impactors would be required. Smaller objects would not work either, requiring even more. The violence of the bombardment could well result in significant outgassing that replaces removed atmosphere. Most of the ejected atmosphere would go into solar orbit near Venus, and, without further intervention, could be captured by Venus' gravitational field and become part of the atmosphere once again.

Removal of atmospheric gas in a more controlled manner could also prove difficult. Venus's extremely slow rotation means that space elevators would be very difficult to construct as the planet's geostationary orbit lies an impractical distance above the surface; and the very thick atmosphere to be removed makes mass drivers useless for removing payloads from the planet's surface. Possible workarounds include placing mass drivers on high-altitude balloons or balloon-supported towers extending above the bulk of the atmosphere, using space fountains, or rotovators.

Rotation

Venus rotates once every 243 days – by far the slowest rotation period of any of the major planets. A Venerian sidereal day thus lasts more than a Venerian year (243 versus 224.7 Earth days). However, the length of a solar day on Venus is significantly shorter than the sidereal day; to an observer on the surface of Venus the time from one sunrise to the next would be 116.75 days. Nevertheless, Venus's extremely slow rotation rate would result in extremely long days and nights, which could prove difficult for most known Earth species of plants and animals to adapt to. The slow rotation also likely accounts for the lack of a significant magnetic field.

One proposal is a system of orbiting solar mirrors which might be used to provide sunlight to the night side of Venus and possibly shade to the day side surface. In addition to his suggestion of slatted system of mirrors near the L_1 point between Venus and the Sun, Paul Birch has proposed a rotating soletta mirror in a polar orbit, which would produce a 24-hour light cycle.

Increasing the speed of Venus's rotation would require many orders of magnitude greater amounts of energy than construction of orbiting solar mirrors, or even than the removal of Venus's atmosphere. Recent scientific research suggests that close fly-bys of asteroids or cometary bodies larger than 60 miles across could be used to move a planet in its orbit, or increase the speed of rotation. G. David Nordley has suggested, in fiction, that Venus might be spun-up to a day-length of 30 Earth-days by exporting the atmosphere of Venus into space via mass drivers. This concept was also explored more rigorously by Birch.

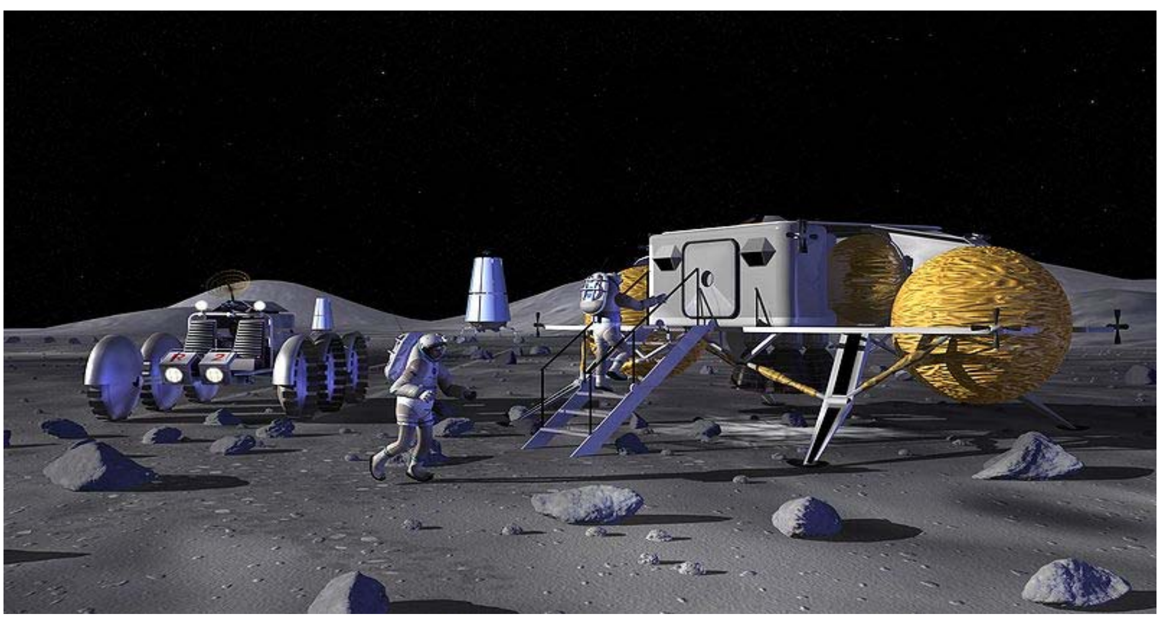
Chapter- 8

Colonization of the Moon

The **colonization of the Moon** is the proposed establishment of permanent human communities on the Moon. Advocates of space exploration have seen settlement of the Moon as a logical step in the expansion of humanity beyond the Earth. Recent indication that water might be present in quantities at the Lunar poles have increased interest in the Moon. Polar colonies could also avoid the problem of long Lunar nights (about 354 hours, a little more than two weeks) and take advantage of the sun continuously.

Permanent human habitation on a planetary body other than the Earth is one of science fiction's most prevalent themes. As technology has advanced, and concerns about the future of humanity on Earth have increased, the argument that space colonization is an achievable and worthwhile goal has gained momentum. Because of its proximity to Earth, the Moon has been seen as a prime candidate for the location of humanity's first permanently occupied extraterrestrial base.

Proposals



Concept art from NASA showing astronauts entering a Lunar outpost.

The notion of siting a colony on the Moon originated before the space age. In 1638 Bishop John Wilkins wrote *A Discourse Concerning a New World and Another Planet,* in which he predicted a human colony on the Moon. Konstantin Tsiolkovsky (1857–1935), among others, also suggested such a step. From the 1950s onwards, a number of concepts and designs have been suggested by scientists, engineers and others.

In 1954 the noted science-fiction author Arthur C. Clarke proposed a Lunar base of inflatable modules covered in Lunar dust for insulation . A spaceship, assembled in low Earth orbit, would launch to the Moon, and astronauts would set up the igloo-like modules and an inflatable radio mast. Subsequent steps would include the establishment of a larger, permanent dome; an algae-based air purifier; a nuclear reactor for the provision of power; and electromagnetic cannons to launch cargo and fuel to interplanetary vessels in space.

In 1959, John S. Rinehart suggested that the safest design would be a structure that could "[float] in a stationary ocean of dust", since there were, at the time this concept was outlined, theories that there could be mile-deep dust oceans on the Moon. The proposed design consisted of a half-cylinder with half-domes at both ends, with a micrometeoroid shield placed above the base.

Project Horizon

Project Horizon was a 1959 study regarding the U.S. Army's plan to establish a fort on the Moon by 1967. H. H. Koelle, a German rocket engineer of the Army Ballistic Missile Agency (ABMA) led the Project Horizon study. The first landing would be carried out by two "soldier-astronauts" in 1965 and more construction workers would soon follow. Through numerous launches (61 Saturn I and 88 Saturn II), 245 tons of cargo would be transported to the outpost by 1966.

Lunar ark

In 2007 Jim Burke of the International Space University in France said people should plan to preserve humanity's culture in the event of a civilization stopping asteroid impact with Earth. A Lunar ark was proposed. Subsequent planning may be taken up by the International Lunar Exploration Working Group (ILEWG).

Moon exploration

Exploration of the Lunar surface by spacecraft began in 1959 when the Soviet Luna 2 mission crash-landed into the surface. The same year, the Luna 3 mission radioed photographs to Earth of the Moon's hitherto unseen far side, marking the beginning of a decade-long series of unmanned Lunar explorations.

Responding to the Soviet program of space exploration, US President John F. Kennedy in 1961 told the U.S. Congress on May 25: "I believe that this nation should commit itself to achieving the goal before this decade is out of landing a man on the moon and returning him safely to the Earth." The same year the Soviet leadership made some of its first public pronouncements about landing a man on the Moon and establishing a Lunar base.

In 1962, John DeNike and Stanley Zahn published their idea of a sub-surface base located at the Sea of Tranquility. This base would house a crew of 21, in modules placed 4 meters below the surface, which was believed to provide radiation shielding as well as the Earth's atmosphere does. They favored nuclear reactors for energy production, because they are more efficient than solar panels, and would also overcome the problems with the long Lunar nights. For life support system, an algae-based gas exchanger was proposed.

Manned exploration of the Lunar surface began in 1968 when the Apollo 8 spacecraft orbited the Moon with three astronauts on board. This was mankind's first direct view of the far side. The following year, the Apollo 11 Lunar module landed two astronauts on the Moon, proving the ability of humans to travel to the Moon, perform scientific research work and bring back sample materials.

Additional missions to the Moon continued this exploration phase. In 1969 the Apollo 12 mission landed next to the Surveyor 3 spacecraft, demonstrating precision landing capability. Following the near-disaster of Apollo 13, Apollo 14 was the last mission on which astronauts were quarantined on their return from the Moon. The use of a manned vehicle was demonstrated in 1971 with the Lunar Rover during Apollo 15. Apollo 16 made the first landing within the rugged Lunar highlands. However, interest in further exploration of the Moon was beginning to wane among the American public. In 1972 Apollo 17 was the final Apollo Lunar mission, and further planned missions were scrapped at the directive of President Nixon. Instead, focus was turned to the Space Shuttle and manned missions in near Earth orbit.

The Soviet Luna program failed to send a manned mission to the Moon. However, in 1966 Luna 9 was the first probe to achieve a soft landing and return close-up shots of the Lunar surface. Luna 16 in 1970 returned the first Soviet Lunar soil samples, while in 1970 and 1973 during the Lunokhod program two robotic rovers landed on the Moon. Lunokhod 1 explored the Lunar surface for 322 days, but the contact with Lunokhod 2 was lost after about 4 months of its operation. 1974 saw the end of the Soviet Moonshot, two years after the last American manned landing.

In the decades following, interest in exploring the Moon faded considerably, and only a few dedicated enthusiasts supported a return. However, evidence of Lunar ice at the poles gathered by NASA's Clementine (1994) and Lunar Prospector (1998) missions rekindled some discussion, as did the potential growth of a Chinese space program that contemplated its own mission to the Moon. Subsequent research suggested that there was far less ice present (if any) than had originally been thought, but that there may still be some usable deposits of hydrogen in other forms. However, in September 2009, the Chandrayaan probe, carrying a NASA instrument, discovered that the Lunar regolith contains 0.1% water by weight, overturning theories that had stood for 40 years.

In 2004, U.S. President George W. Bush called for a plan to return manned missions to the Moon by 2020. Propelled by this new initiative, NASA issued a new long-range plan that includes building a base on the Moon as a staging point to Mars. This plan envisions a Lunar outpost at one of the moon's poles by 2024 which, if well-sited, might be able to continually harness solar power; at the poles, temperature changes over the course of a Lunar day are also less extreme, and reserves of water and useful minerals may be found nearby. In addition, the European Space Agency has a plan for a permanently manned Lunar base by 2025. Russia has also announced similar plans to send a man to the moon by 2025 and establish a permanent base there several years later.

A Chinese space scientist has said that the People's Republic of China could be capable of landing a human on the moon by 2022, and Japan and India also have plans for a Lunar base by 2030. Neither of these plans involves permanent residents on the Moon. Instead they call for sortie missions, in some cases followed by extended expeditions to the Lunar base using rotating crew members, as is currently done for the International Space Station.

NASA’s LCROSS/LRO mission had been scheduled to launch in October 2008. The launch was delayed until the 18th of June 2009, resulting in LCROSS's impact with the Moon at 11:30 UT on the 9th of October, 2009. The purpose is preparing for future Lunar exploration.

Water discovered on moon

In September 2009 it was announced that NASA's Moon Mineralogy Mapper on India's Chandrayaan-1 had detected water on the moon.
On November 13, 2009 NASA announced that the LCROSS mission had discovered large quantities of water ice on the moon around the LCROSS impact site at Cabeus. "Large" is a relative term. The amount of water discovered is put in perspective by this comment from Robert Zubrin: "The 30 m crater ejected by the probe contained 10 million kilograms of regolith. Within this ejecta, an estimated 100 kg of water was detected. That represents a proportion of 10 parts per million, which is a lower water concentration than that found in the soil of the driest deserts of the Earth. In contrast, we have found continent sized regions on Mars, which are 600,000 parts per million, or 60% water by weight."
In March 2010, NASA reported that the NASA mini-SAR radar aboard Chandrayaan-1 detected ice deposits at the moon's north pole. It is estimated there is at least 600 million tons of ice at the north pole in sheets of relatively pure ice at least a couple of meters thick.

Advantages and disadvantages

Putting aside the general questions of whether a human colony beyond the Earth is feasible or scientifically desirable in light of cost-efficiency, proponents of space colonization point out that the Moon offers both advantages and disadvantages as a site for such a colony.

Advantages

Placing a colony on a natural body would provide an ample source of material for construction and other uses, including shielding from radiation. The energy required to send objects from the Moon to space is much less than from Earth to space. This could allow the Moon to serve as a construction site or fueling station for spacecraft. Some proposals include using electric acceleration devices (mass drivers) to propel objects off the Moon without building rockets. Others have proposed momentum exchange tethers (see below). Furthermore, the Moon does have some gravity, which experience to date indicates may be vital for fetal development and long-term human health. Whether the Moon's gravity (roughly one sixth of Earth's) is adequate for this purpose, however, is uncertain.

In addition, the Moon is the closest large body in the solar system to Earth. While some Earth-crosser asteroids occasionally pass closer, the Moon's distance is consistently within a small range close to 384,400 km. This proximity has several benefits:

- Monetary (including space tourism), security, and technological gains.
- The energy required to send objects from Earth to the Moon is lower than for most other bodies.
- Transit time is short. The Apollo astronauts made the trip in three days and future technologies could improve on this time.
- If the Moon were colonized then it could be tested if humans can survive in low gravity. Those results could be utilized for a viable Mars colony as well.
- The short transit time would also allow emergency supplies to quickly reach a Moon colony from Earth, or allow a human crew to evacuate relatively quickly from the Moon to Earth in case of emergency. This could be an important consideration when establishing the first human colony.

- The round trip communication delay to Earth is less than three seconds, allowing near-normal voice and video conversation, and allowing some kinds of remote control of machines from Earth that are not possible for any other celestial body. The delay for other solar system bodies is minutes or hours; for example, round trip communication time between Earth and Mars ranges from about eight minutes to about forty minutes. This again would be of particular value in an early colony, where life-threatening problems requiring Earth's assistance could occur. (See, for example, Apollo 13.)
- On the Lunar near side, the Earth appears large and is always visible as an object 60 times brighter than the Moon appears from Earth, unlike more distant locations where the Earth would be seen merely as a star-like object, much as the planets appear from Earth. As a result, a Lunar colony might feel less remote to humans living there.
- A Lunar base would provide an excellent site for any kind of observatory. Particular advantages arise from building observatory facilities on the Moon from Lunar materials. As the Moon's rotation is so slow, visible light observatories could perform observations for days at a time. It is possible to maintain near-

constant observations on a specific target with a string of such observatories spanning the circumference of the Moon. The fact that the Moon is geologically inactive along with the lack of widespread human activity results in a remarkable lack of mechanical disturbance, making it far easier to set up interferometric telescopes on the Lunar surface, even at relatively high frequencies such as visible light.

- A Lunar base could also hold a future site for launching rockets, to distant planets such as Mars. Launching rockets from the Moon would be an easier prospect than on Earth due to the Moon's lower gravity requiring a lower escape velocity. A lower escape velocity would require less propellant, but there is no guarantee that less propellant would cost less money is required to launch from Earth.
- A farm at the Lunar North Pole could provide eight hours of sunlight per day for rotating crops, a beneficial temperature, radiation protection, insects for pollination, and all other plant needs artificially during the local summer for a cost. One estimate suggested a 0.5 hectare space farm could feed 100 people.
- A moon colony provides us with most of the experiments, skills, and knowledge we need to colonize another planet.
- A moon colony can easily be seen from the Earth, and might inspire many more humans to seriously consider the advantages and future of colonization. A clear sign or signal can be made to remind humans on Earth, inspiring future leaders, astronauts, and scientists.

Disadvantages

There are several disadvantages to the Moon as a colony site:

- The long Lunar night would impede reliance on solar power and require a colony to be designed that could withstand large temperature extremes. An exception to this restriction are the so-called "peaks of eternal light" located at the Lunar north pole that are constantly bathed in sunlight. The rim of Shackleton Crater, towards the Lunar south pole, also has a near-constant solar illumination. Other areas near the poles that get light most of the time could be linked in a power grid.
- The Moon is highly depleted in light elements (volatiles), such as carbon, nitrogen and hydrogen. A number of robot probes including Lunar Prospector gathered evidence of hydrogen generally in the Moon's crust consistent with what would be expected from implantation from the solar wind, and higher concentrations near the poles. There had been some disagreement whether the hydrogen must necessarily be in the form of water. The LCROSS mission has definitely found evidence of water. This water would be in ice form perhaps mixed in small crystals in the regolith in a colder landscape than people have ever mined. Other volatiles containing carbon and nitrogen could conceivably also be in the same cold traps as the ice. If no sufficient means is found for recovering these volatiles on the Moon, they would need to be imported from some other source to support life and industrial processes. Volatiles would need to be stringently recycled. This would limit the colony's rate of growth and keep it dependent on Earth. The transportation cost of importing volatiles from Earth could be reduced by

constructing the upper stage of supply ships using materials high in volatiles, such as carbon fiber and other plastics. The 2006 announcement by the Keck Observatory that the binary Trojan asteroid 617 Patroclus, and possibly large numbers of other Trojan objects in Jupiter's orbit, are likely composed of water ice, with a layer of dust, and the hypothesized large amounts of water ice on the closer, main-belt asteroid 1 Ceres, suggest that importing volatiles from this region via the Interplanetary Transport Network may be practical in the not-so-distant future. However, these possibilities are dependent on complicated and expensive resource utilization from the mid to outer solar system, which are not likely to become available to a Moon colony for a significant period of time.

- It is uncertain whether the low (one-sixth *g*) gravity on the Moon is strong enough to prevent detrimental effects to human health in the long term. Exposure to weightlessness over month-long periods has been demonstrated to cause deterioration of physiological systems, such as loss of bone and muscle mass and a depressed immune system. Similar effects could occur in a low-gravity environment, although virtually all research into the health effects of low gravity has been limited to zero gravity. Countermeasures such as an aggressive routine of daily exercise have proven at least partially effective in preventing the health deterioration that is caused by low gravity.
- The lack of a substantial atmosphere for insulation results in temperature extremes and makes the Moon's surface conditions somewhat like a deep space vacuum. It also leaves the Lunar surface exposed to half as much radiation as in interplanetary space (with the other half blocked by the moon itself underneath the colony) raising the issues of the health threat from cosmic rays and the risk of proton exposure from the solar wind, especially since two-thirds of the Moon's orbit is outside the protection of the Earth's magnetosphere. Although Lunar materials would potentially be useful as a simple radiation shield for living quarters, shielding against solar flares during expeditions outside is more problematic.
- Also, the lack of an atmosphere increases the chances of the colonial site being hit by meteors, which would impact upon the surface directly, as they have done throughout the Moon's history. Even small pebbles and dust (micrometeoroids) have the potential to damage or destroy insufficiently protected structures.
- Moon dust is an extremely abrasive glassy substance formed by micrometeorites and unrounded due to the lack of weathering. It sticks to everything, can damage equipment, and it may be toxic.
- Growing crops on the moon faces many difficult challenges due to the long Lunar night (354 hour), extreme variation in surface temperature, exposure to solar flares, and lack of insects for pollination. (Due to the lack of any atmosphere on the Moon, plants would need to be grown in sealed chambers, though experiments have shown that plants can thrive at pressures much lower than those on Earth.) The use of electric lighting to compensate for the 354 hour night might be difficult: a single acre of plants on Earth enjoys a peak 4 megawatts of sunlight power at noon. Experiments conducted by the Soviet space program in the 1970s suggest it is possible to grow conventional crops with the 354 hour light, 354 hour dark cycle. A variety of concepts for Lunar agriculture have been proposed,

including the use of minimal artificial light to maintain plants during the night and the use of fast growing crops that might be started as seedlings with artificial light and be harvestable at the end of one Lunar day.

Locations

Three criteria that a Lunar outpost should meet are:

- good conditions for transport operations;
- a great number of different types of natural objects and features on the Moon of scientific interest; and
- natural resources, such as oxygen. The abundance of certain minerals, such as iron oxide, varies dramatically over the Lunar surface.

While a colony might be located anywhere, potential locations for a Lunar colony fall into three broad categories.

Polar regions

There are two reasons why the Lunar poles might be attractive as locations for a human colony. First, there is evidence that water may be present in some continuously shaded areas near the poles. Second, because the Moon's axis of rotation is almost perfectly perpendicular to the ecliptic plane, it may be possible to power polar colonies exclusively with solar energy. Power collection stations can be located so that at least one is in sunlight at all times. Some sites have nearly continuous sunlight. For example, Malapert mountain, located near the Shackleton crater at the Lunar south pole, offers several advantages as a site:

- It is exposed to the sun most of the time; two closely spaced arrays of solar panels would receive nearly continuous power.
- Its proximity to Shackleton Crater (116 km, or 69.8 mi) means that it could provide power and communications to the crater. This crater is potentially valuable for astronomical observation. An infrared instrument would benefit from the very cold temperatures. A radio telescope would benefit from being shielded from Earth's broad spectrum radio interference.
- The nearby Shoemaker and other craters are in constant deep shadow, and might contain valuable concentrations of hydrogen and other volatiles.
- At around 5,000 meters (16,500 ft) elevation, it offers line of sight communications over a large area, as well as to Earth.
- The South Pole-Aitken basin is located at the south Lunar pole. This is the second largest known impact basin in the solar system, as well as the oldest and biggest impact feature on the Moon, and should provide geologists access to deeper layers of the Moon's crust.

NASA chose to use a south-polar site for the Lunar outpost reference design in the Exploration Systems Architecture Study chapter on Lunar Architecture.

At the north pole, the rim of Peary crater has been proposed as a favorable location for a base. Examination of images from the Clementine mission appear to show that parts of the crater rim are permanently illuminated by sunlight (except during Lunar eclipses). As a result, the temperature conditions are expected to remain very stable at this location, averaging −50 °C (−58 °F). This is comparable to winter conditions in Earth's Poles of Cold in Siberia and Antarctica. The Peary crater interior may also harbor hydrogen deposits.

Although hydrogen appears to be concentrated at the poles, the presence of Lunar ice has not yet been confirmed. A bistatic radar experiment performed during the Clementine mission suggested the presence of water ice around the south pole. The Lunar Prospector spacecraft reported enhanced hydrogen abundances not only at the south pole, but also at the north pole — actually more so. On the other hand, results reported using the Arecibo radio telescope have been interpreted by some to indicate that the anomalous Clementine radar signatures are not indicative of ice, but surface roughness. This interpretation, however, is not universally agreed upon.

A potential limitation of the polar regions is that the inflow of solar wind can create an electrical charge on the leeward side of crater rims. The resulting voltage difference can affect electrical equipment, change surface chemistry, erode surfaces and levitate Lunar dust.

Equatorial regions

The Lunar equatorial regions are likely to have higher concentrations of helium-3 (rare on Earth but much sought after for use in nuclear fusion research) because the solar wind has a higher angle of incidence. They also enjoy an advantage in extra-Lunar traffic: The rotation advantage for launching material is slight due to the Moon's slow rotation, but the corresponding orbit coincides with the ecliptic, nearly coincides with the Lunar orbit around Earth and nearly coincides with the equatorial plane of Earth.

Several probes have landed in the Oceanus Procellarum area. There are many areas and features that could be subject to long-term study, such as the Reiner Gamma anomaly and the dark-floored Grimaldi crater.

Far side

The Lunar far side lacks direct communication with Earth, though a communication satellite at the L_2 Lagrangian point, or a network of orbiting satellites, could enable communication between the far side of the Moon and Earth. The far side is also a good location for a large radio telescope because it is well shielded from the Earth. Due to the lack of atmosphere, the location is also suitable for an array of optical telescopes, similar to the Very Large Telescope in Chile. To date, there has been no ground exploration of the far side.

Scientists have estimated that the highest concentrations of helium-3 will be found in the maria on the far side, as well as near side areas containing concentrations of the titanium-based mineral ilmenite. On the near side the Earth and its magnetic field partially shields the surface from the solar wind during each orbit. But the far side is fully exposed, and thus should receive a somewhat greater proportion of the ion stream.

Lunar lava tubes

Lunar lava tubes form a potentially important location for constructing a future Lunar base, which may be used for local exploration and development, or as a human outpost to serve exploration beyond the Moon. Any intact lava tube on the moon could serve as a shelter from the severe environment of the Lunar surface, with its frequent meteorite impacts, high-energy ultra-violet radiation and energetic particles, and extreme diurnal temperature variations.; March 5, 2010; Discover Magazine; Phil Plait Astronomy The second lunar lava tube was discovered by LRO.

Structure

Habitat

A NASA model of a proposed inflatable module

There have been numerous proposals regarding habitat modules. The designs have evolved throughout the years as mankind's knowledge about the Moon has grown, and as the technological possibilities have changed. The proposed habitats range from the actual spacecraft landers or their used fuel tanks, to inflatable modules of various shapes. Early on, some hazards of the Lunar environment such as sharp temperature shifts, lack of atmosphere or magnetic field (which means higher levels of radiation and micrometeoroids) and long nights, were recognized and taken into consideration.

Some suggest building the Lunar colony underground, which would give protection from radiation and micrometeoroids. This also greatly reduce the risk of air leakage, as the colony will be fully sealed from the outside except for a few exits to the surface. This is not the only advantage to this option. The average temperature on the moon is about −5 °C. The day period (about 354 hours) has an average temperature of about 107 °C (225 °F), although it can rise as high as 123 °C (253 °F). The night period (also 354 hours) has an average temperature of about −153 °C (−243 °F). Underground, both periods would be around -23 °C (-9 °F), and humans could install ordinary air conditioners.

The construction of such a base would probably be more complex; one of the first machines from Earth might be a remote controlled excavating machine to excavate living quarters. Once created, some sort of hardening would be necessary to avoid collapse, possibly a spray-on concrete-like substance made from available materials. A more porous insulating material also made *in-situ* could then be applied. Mining methods such as the room and pillar might also be used. Inflatable self-sealing fabric habitats might then be put in place to retain air. Eventually an underground city similar to The Forum Shops at Caesars and Underground City, Montreal can be constructed. Farms setup underground would need artificial sunlight. As an alternative to excavating, a lava tube could be covered and insulated, thus solving the problem of radiation exposure. One such lava tube has been discovered in early 2009.

A possibly easier solution would be to build the Lunar base on the surface, and cover the modules with Lunar soil. The Lunar regolith is composed of a unique blend of silica and iron-containing compounds that may be fused into a glass-like solid using microwave energy. This may allow for the use of "Lunar bricks" in structural designs, or the "glassing" of loose dirt to form a hard, ceramic crust. Others have put forward the idea that the Lunar base could be built on the surface and protected by other means, such as improved radiation and micrometeoroid shielding. Building the Lunar base inside a deep crater would provide at least partial shielding against radiation and micrometeoroids. Artificial magnetic fields have been proposed as a means to provide radiation shielding for long range deep space manned missions, and it might be possible to use similar technology on a Lunar colony. Some regions on the Moon possess strong local magnetic fields that might partially mitigate exposure to charged solar and galactic particles.

Moon Capital

The Moon Capital Competition will be offering a prize for an architectural design of a Lunar habitat intended to be an underground international commercial center capable of supporting a residential staff of 60 people and their families. The Moon Capital is intended to be self-sufficient with respect to food and other material required for life support. Prize money will be provided primarily by the Boston Society of Architects and The New England Council of the American Institute of Aeronautics and Astronautics.

Energy

A Lunar base would need power for its operations — from fuel production and communications to life support systems and scientific research.

Nuclear power

A nuclear fission reactor might fulfill most of the base's power requirements. Fission reactors can also overcome the difficulty of the 354 hour Lunar night. Radioisotope thermoelectric generators could be used as backup and emergency power sources for solar powered colonies.

Solar energy

Solar energy is a possible source of power for a Lunar base. Many of the raw materials needed for solar panel production can be extracted on site. However, the long Lunar night (354 hours) is a drawback for solar power on the Moon's surface. This might be solved by building several power plants, so that at least one of them is always in daylight. Another possibility would be to build such a power plant where there is constant or near-constant sunlight, such as at the Malapert mountain near the Lunar south pole, or on the rim of Peary crater near the north pole. A third possibility would be to leave the panels in orbit, and beam the power down as microwaves.

The solar energy converters need not be silicon solar panels. It may be more advantageous to use the larger temperature difference between sun and shade to run heat engine generators. Concentrated sunlight could also be relayed via mirrors and used in Stirling engines or solar trough generators, or it could be used directly for lighting, agriculture and process heat. The focused heat might also be employed in materials processing to extract various elements from Lunar surface materials.

Energy storage

In the early days, a combination of solar panels for 'day-time' operation and fuel cells for 'night-time' operation could be used.

Fuel cells on the Space Shuttle have operated reliably for up to 17 Earth days at a time. On the Moon, they would only be needed for 354 hours — the length of the Lunar night. Fuel cells produce water directly as a waste product. Current fuel cell technology is more advanced than the Shuttle's cells — PEM (Proton Exchange Membrane) cells produce considerably less heat (though their waste heat would likely be useful during the Lunar night) and are physically lighter, not to mention the reduced mass of the smaller heat-dissipating radiators. This makes PEMs more economical to launch from Earth than the shuttle's cells, but PEMs have not yet been proven in space.

Combining fuel cells with electrolysis would provide a 'perpetual' source of electricity - solar energy could be used to provide power during the Lunar day, and fuel cells at night. During the Lunar day, solar energy would also be used to electrolyze the water created in the fuel cells - although there would be small losses of gases that would have to be replaced.

Transport

Earth to Moon

Conventional rockets have been used for most Lunar exploration to date. The ESA's SMART-1 mission from 2003 to 2006 used Hall effect thrusters. NASA will use chemical rockets on its Ares V booster and Lunar Surface Access Module, being developed for a planned return to the Moon around 2019. The construction workers, location finders, and other astronauts vital to building, will be taken in NASA's Orion spacecraft.

On the surface

A Lunar rover being unloaded from a cargo spacecraft. Conceptual drawing.

Within the colony it will be difficult to set up a public transport system. However a system of Escalators, moving walkways and elevator can be used to quickly transport people and cargo around.

Lunar colonists will also want the ability to move over long distances, to transport cargo and people to and from modules and spacecraft, and to carry out scientific study of a larger area of the Lunar surface for long periods of time. Proposed concepts include a variety of vehicle designs, from small open rovers to large pressurised modules with lab equipment, and also a few flying or hopping vehicles.

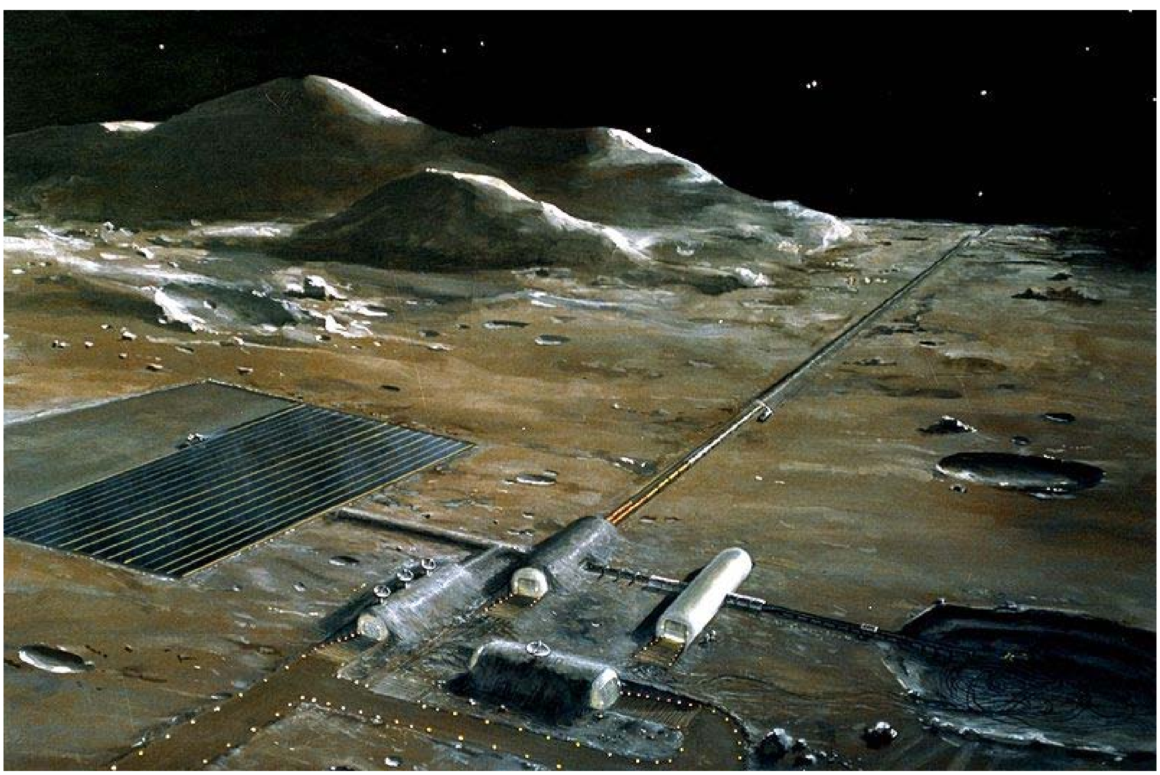
Rovers could be useful if the terrain is not too steep or hilly. The only rovers to have operated on the surface of the Moon (as of 2008) are the three Apollo Lunar Roving Vehicles (LRV), developed by Boeing, and the two robotic Soviet Lunokhods. The LRV was an open rover for a crew of two, and a range of 92 km during one Lunar day. One NASA study resulted in the Mobile Lunar Laboratory concept, a manned pressurised rover for a crew of two, with a range of 396 km. The Soviet Union developed different rover concepts in the Lunokhod series and the L5 for possible use on future manned missions to the Moon or Mars. These rover designs were all pressurised for longer sorties.

If multiple bases were established on the Lunar surface, they could be linked together by permanent railway systems. Both conventional and magnetic levitation (Mag-Lev) systems have been proposed for the transport lines. Mag-Lev systems are particularly attractive as there is no atmosphere on the surface to slow down the train, so the vehicles could achieve velocities comparable to aircraft on the Earth. In addition achieving the extremely cold temperatures necessary for the superconducting magnets that levitate and drive the Mag-Lev trains would be much easier to achieve than on Earth due to the lack of an atmosphere. One significant difference with Lunar trains, however, is that the cars would need to be individually sealed and possess their own life support systems. The trains would also need to be highly resistant to derailment, as a punctured car could lead to rapid loss of life.

For difficult areas, a flying vehicle may be more suitable. Bell Aerosystems proposed their design for the Lunar Flying Vehicle as part of a study for NASA. Bell also developed the Manned Flying System, a similar concept.

Surface to space

Launch technology



A Lunar base with a mass driver (the long structure that goes toward the horizon.) NASA conceptual illustration.

A Lunar base will need efficient ways to transport people and goods of various kinds between the Earth and the Moon and, later, to and from various locations in interplanetary space. One advantage of the Moon is its relatively weak gravity field, making it easier to launch goods from the Moon than from the Earth. The lack of a Lunar atmosphere is both an advantage and a disadvantage; while it is easier to launch from the Moon because there is no drag, aerobraking is not possible, which makes it necessary to bring extra fuel in order to land. An alternative, which may work for supplies, is to surround the payload with impact-absorbing materials, something that was tried in the Ranger program. This can be efficient if the impact protection is made of needed lighter elements that are absent from the Moon (Ranger used balsa wood)

One way to get materials and products from the Moon to an interplanetary waystation might be with a mass driver, a magnetically accelerated projectile launcher. Cargo would be picked up from orbit or an Earth-Moon Lagrangian point by a shuttle craft using ion propulsion, solar sails or other means and delivered to Earth orbit or other destinations such as near-Earth asteroids, Mars or other planets, perhaps using the Interplanetary Transport Network. If a Lunar space elevator is ever built, it could transport people, raw materials and products to and from an orbital station at Lagrangian points L_1 or L_2.

Launch costs

- Estimates of the cost per pound of launching cargo or people from the Moon vary and the cost impacts of future technological improvements are difficult to predict. An upper bound on the cost of launching material from the Moon might be about $40,000,000 per kilogram, based on dividing the Apollo program costs by the amount of material returned. At the other extreme, the incremental cost of launching material from the moon using an electromagnetic accelerator could be quite low. The efficiency of launching material from the Moon with a proposed electric accelerator is suggested to be about 50%. If the carriage of a mass driver weighs the same as the cargo, two kilograms must be accelerated to orbital velocity for each kilogram put into orbit. The overall system efficiency would then drop to 25%. So 1.4 kilowatt-hours would be needed to launch an incremental kilogram of cargo to low orbit from the Moon. At $0.1/kilowatt-hour, a typical cost for electrical power on Earth, that amounts to $0.16 for the energy to launch a kilogram of cargo into orbit. For the actual cost of an operating system, energy loss for power conditioning, the cost of radiating waste heat, the cost of maintaining all systems, and the interest cost of the capital investment are considerations. David R. Criswell believes that there is a potential for the cost of electrical power on the Moon to become enough less than the cost on Earth for electrical power to be exported from the Moon to Earth by microwave.
- Passengers cannot be divided into the parcel size suggested for the cargo of a mass driver, nor subjected to hundreds of gravities acceleration. However, technical developments could also affect the cost of launching passengers to orbit from the Moon. Instead of bringing all fuel and oxidizer from Earth, liquid oxygen could be produced from Lunar materials and hydrogen should be available from the Lunar poles. The cost of producing these on the Moon is yet

unknown, but they will be more expensive than on Earth. The situation of the local hydrogen is most open to speculation. As a rocket fuel, hydrogen could be extended by combining it chemically with silicon to form silane, which has yet to be demonstrated in an actual rocket engine. In the absence of more technical developments, the cost of transporting people from the Moon will be an impediment to colonization.

Surface to and from cis-Lunar space

A cis-Lunar transport system has been proposed using tethers to achieve momentum exchange. This system requires zero net energy input, and could not only retrieve payloads from the Lunar surface and transport them to Earth, but could also soft land payloads on to the Lunar surface.

Economic development

For long term sustainability, a space colony should be close to self sufficient. On site mining and refining of the Moon's materials could provide an advantage over deliveries from Earth – for use both on the Moon and elsewhere in the solar system – as they can be launched into space at a much lower energy cost than from Earth. It is possible that vast sums of money will be spent in interplanetary exploration in the 21st century, and the cost of providing goods from the Moon might be attractive.

Space-based materials processing

In the long term, the Moon will likely play an important role in supplying space-based construction facilities with raw materials. Zero gravity allows for the processing of materials in ways impossible or difficult on Earth, such as "foaming" metals, where a gas is injected into a molten metal, and then the metal is annealed slowly. On Earth, the gas bubbles rise and burst, but in a zero gravity environment, that does not happen. Annealing is a process that requires large amounts of energy, as a material is kept very hot for an extended period of time. (This allows the molecular structure to realign.) Materials which cannot be alloyed or mixed on Earth because of gravity-field effects on density differences could be combined in space, resulting in composites which could have exceptional qualities. No one knows, because no one has been able to experiment along these lines on any scale. However, it is possible that materials or processes will be identified which will be highly valuable on Earth, but impossible to make here. (This is the foundation of the free MoonBaseOne game made by a non-profit that teaches children about space.)

Exporting material to Earth

Exporting material to Earth in trade from the Moon is more problematic due to the cost of transportation which will vary greatly if the Moon is industrially developed (see above). One suggested candidate is Helium-3 from the solar wind, which is thought to have accumulated on the Moon's surface over billions of years, and which is rare on Earth. Helium might be present in the Lunar regolith in quantities of 0.01 ppm to 0.05 ppm (depending on soil). 2006 market price for He-3 was about $46,500 per troy ounce ($1500/gram, $1.5M/kg), more than 120 times the value per unit weight of Gold and over eight times the value of Rhodium.

In the long term future He-3 may prove to be a desirable fuel in thermonuclear fusion reactors.

Solar power satellites

Gerard K. O'Neill, noting the problem of high launch costs in the early 1970s, came up with the idea of building Solar Power Satellites in orbit with materials from the Moon. Launch costs from the Moon will vary greatly if the Moon is industrially developed (see above). This 1970s proposal was predicated on the then advertised future launch costs of NASA's space shuttle.

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 terrestrial materials for a system comprising as few as thirty Solar Power Satellites of 10 GW 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 telepresence control of workers stationed on Earth.

Chapter- 9

Colonization of the Outer Solar System

Some of the moons of the outer planets of the solar system are large enough to be suitable places for colonization. Many of the larger moons contain water ice, liquid water, and organic compounds that might be useful for sustaining human life . Colonies in the outer solar system could also serve as centers for long term investigation of the planet and the other moons. In particular, robotic devices could be controlled by humans without the very long time delays needed to communicate with Earth. There have also been proposals to place robotic aerostats in the upper atmospheres of the gas giant planets for exploration and possibly mining of helium-3, which could have a very high value per unit mass as a thermonuclear fuel.

The Jovian system

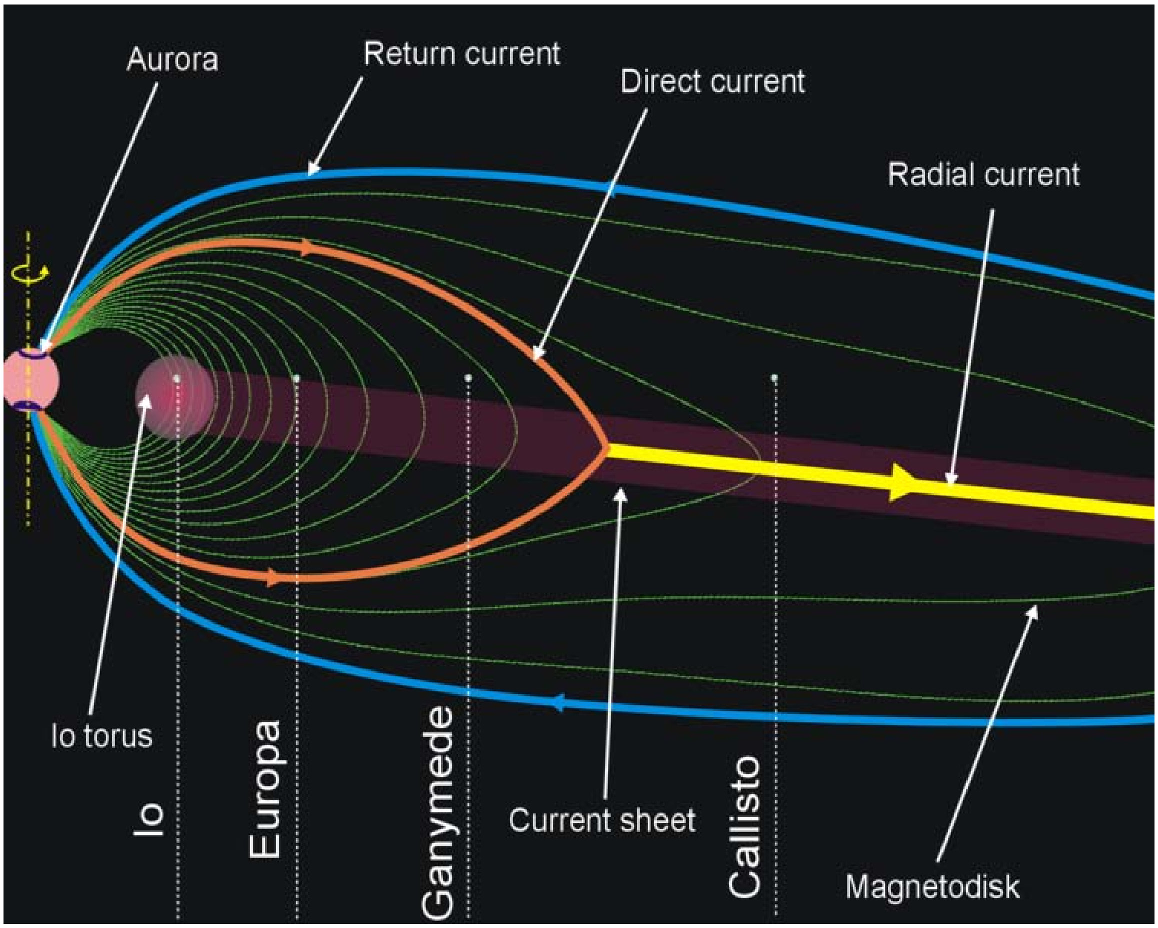
The Jovian system in general poses particular disadvantages for colonizing because of its severe radiation environment and its particularly deep gravity well. Its radiation would deliver about 3,600 rems per day to unshielded colonists at Io and about 540 rems per day to unshielded colonists at Europa. Exposure of approximately 75 rems over a period of a few days is enough to cause radiation poisoning, and about 500 rems over a few days is fatal.

Jupiter

Orbiting colonies could exist around Jupiter, as around any body in the solar system, but artificial gravity (such as through rotation of the structure) would need to be employed. These bases would also need to withstand radiation from all angles. This type of structure could also serve as a dock for ships visiting other parts of the Jovian system. Additionally, science fiction writers have sometimes proposed that Jupiter could be the site of airborne colonies such as floating cities, assuming the radiation and gravity issues in traveling to and from the atmosphere are properly addressed. So far no serious proposals or studies have been made of such a colony within Jupiter's atmosphere. However, there does exist a depth within Jupiter's atmosphere at which the pressure is the same as Earth's at sea level, and where there is a blue sky, although it is colder than on Earth; further down, there is a location that has the same average temperature as the surface of the Earth, although the pressure is about five bars.

One significant challenge to overcome in colonizing Jupiter would be the intense radiation in the planet's magnetosphere.

Europa



The magnetic field of Jupiter and co–rotation enforcing currents

The Artemis Project designed a plan to colonize Europa. Scientists are to inhabit igloos and drill down into the Europan ice crust, exploring any sub-surface ocean. It also discusses use of air pockets for human inhabitation.

Ganymede

Ganymede is the largest moon in the Solar System. Ganymede is the only moon with a magnetosphere but it is overshadowed by Jupiter's magnetic field. Ganymede receives about 8 rem of radiation per day. Callisto being further from Jupiter's powerful radiation belt is subject to only 0.01 rem a day.

Callisto

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.

Trojan asteroids

The 2006 announcement by the Keck Observatory that the binary Trojan asteroid 617 Patroclus, and possibly large numbers of other Trojan objects in Jupiter's orbit, are likely composed of water ice, with a layer of dust, suggests that mining water and other volatiles in this region and transporting them elsewhere in the Solar system, perhaps via the proposed Interplanetary Transport Network, may be feasible in the not-so-distant future. This could make colonization of the Moon, Mercury and main-belt asteroids more practical.

The Saturnian system

Robert Zubrin identified Saturn, Uranus and Neptune as "the Persian Gulf of the solar system", as the largest sources of deuterium and helium-3 to drive the pending fusion economy, with Saturn the most important and most valuable of the three, because of its relative proximity, low radiation, and excellent system of moons.

Titan

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 colonization, and saying "In certain ways, Titan is the most hospitable extraterrestrial world within our solar system for human colonization." A widely published expert on terraforming, Christopher McKay, is also a co-investigator on the Huygens probe that landed on Titan in January 2005.

The surface of Titan is mostly uncratered and thus inferred to be very young and active, and probably composed of mostly water ice, and lakes of liquid hydrocarbons (methane/ethane) in its polar regions. While the temperature is cryogenic (95 K) it should be able to support a base, but more information regarding Titan's surface and the activities on it is necessary. The thick atmosphere and the weather, such as potential flash floods, are also factors to consider.

Enceladus

On March 9th, 2006, NASA's Cassini space probe found possible evidence of liquid water on Enceladus. According to that article, "pockets of liquid water may be no more than tens of meters below the surface." If these findings are confirmed, it would mean liquid water could be collected much more easily on Enceladus than on, for instance, Europa (see above). Discovery of water, especially liquid water, generally improves a celestial body's consideration for colonization dramatically. An alternative model of Enceladus' activity is the decomposition of methane/water clathrates - a process requiring lower temperatures than liquid water eruptions. The higher density of Enceladus indicates a larger than Saturnian average silicate core that should provide materials for base operations.

Uranus

Because Uranus has the lowest escape velocity of the four gas giants, it has been proposed as a mining site for helium-3. If human supervision of the robotic activity proved necessary, one of Uranus' natural satellites might serve as a base. An alternative is to place floating cities in its atmosphere, as its surface gravity is only 90% of Earth's. Saturn and Neptune could be suitable as well, but Jupiter would likely not be, due to its high gravity, escape velocity, and radiation.

Neptune

It's hypothesized that one of Neptune's satellites could be used for colonization - Triton's surface shows signs of extensive geological activity implying a sub-surface ocean, perhaps of ammonia/water. If technology advanced to the point that tapping such geothermal energy was possible, it could make colonizing a cryogenic world like Triton feasible, supplemented by nuclear fusion power.

Kuiper Belt and Oort Cloud

The noted physicist Freeman Dyson identified comets, rather than planets, as the major potential *habitat* of life in space.

Challenges

There are various difficulties in colonizing the outer solar system. They include:

- Distance from Earth: The outer planets are much further from Earth than inner planets, and would therefore be harder and more time-consuming to reach.
- Planetary conditions: The outer planets have no surface to land on, so any habitation would have to use floating colonies, increasing complexity and decreasing reliability. The moons/comets do not have this problem, although some have specific problems (e.g., Europa is in Jupiter's intense radiation bands).
- Power: Solar power is generally considered unsuitable because of the large distance from the sun. Nuclear power is believed to be the only suitable power source for the colonies.

Chapter- 10

Colonization of Europa and Titan

Colonization of Europa

Europa, the fourth-largest moon of Jupiter, is a subject in both science fiction and scientific speculation for future human colonization. Europa's geophysical features, including a possible subglacial water ocean, make it a strong possibility that human life could be sustained on or beneath the surface.

Feasibility

Europa as a target for human colonization has several benefits compared to other bodies in the outer solar system, but is not without challenges.

Possible advantages

Europa is thought to have a liquid water ocean underneath its icy exterior. The access to this liquid water ocean is a major difficulty. But the abundance of water on Europa is a benefit to any considerations for colonization. Not only can water provide for colonists' drinking needs, it also can be broken down to provide breathable oxygen. Oxygen is also believed to have accumulated from the radiolysis of the ice on the surface that has been convected into the subsurface ocean and may prove sufficient for oxygen-using marine life.

Possible problems

The colonization of Europa presents numerous difficulties. One is the high level of radiation from Jupiter's radiation belt, which is about 10 times as strong as Earth's Van Allen radiation belts. As Europa receives 540 rem of radiation per day (500 rem is a fatal dose), a human would not survive at or near the surface of Europa for long without significant radiation shielding. Colonists on Europa would have to descend beneath the surface when Europa is not protected by Jupiter's magnetotail, and stay in subsurface habitats. This would allow colonists to use Europa's ice sheet to shield themselves from radiation.

Another problem is that the surface temperature of Europa normally rests at −170 °C (103 K) (-275°F). However, the fact that liquid water is believed to exist below Europa's icy surface, along with the fact that colonists would spend much of their time under the ice sheet in order to shield themselves from radiation, may somewhat mitigate the problems associated with low surface temperatures.

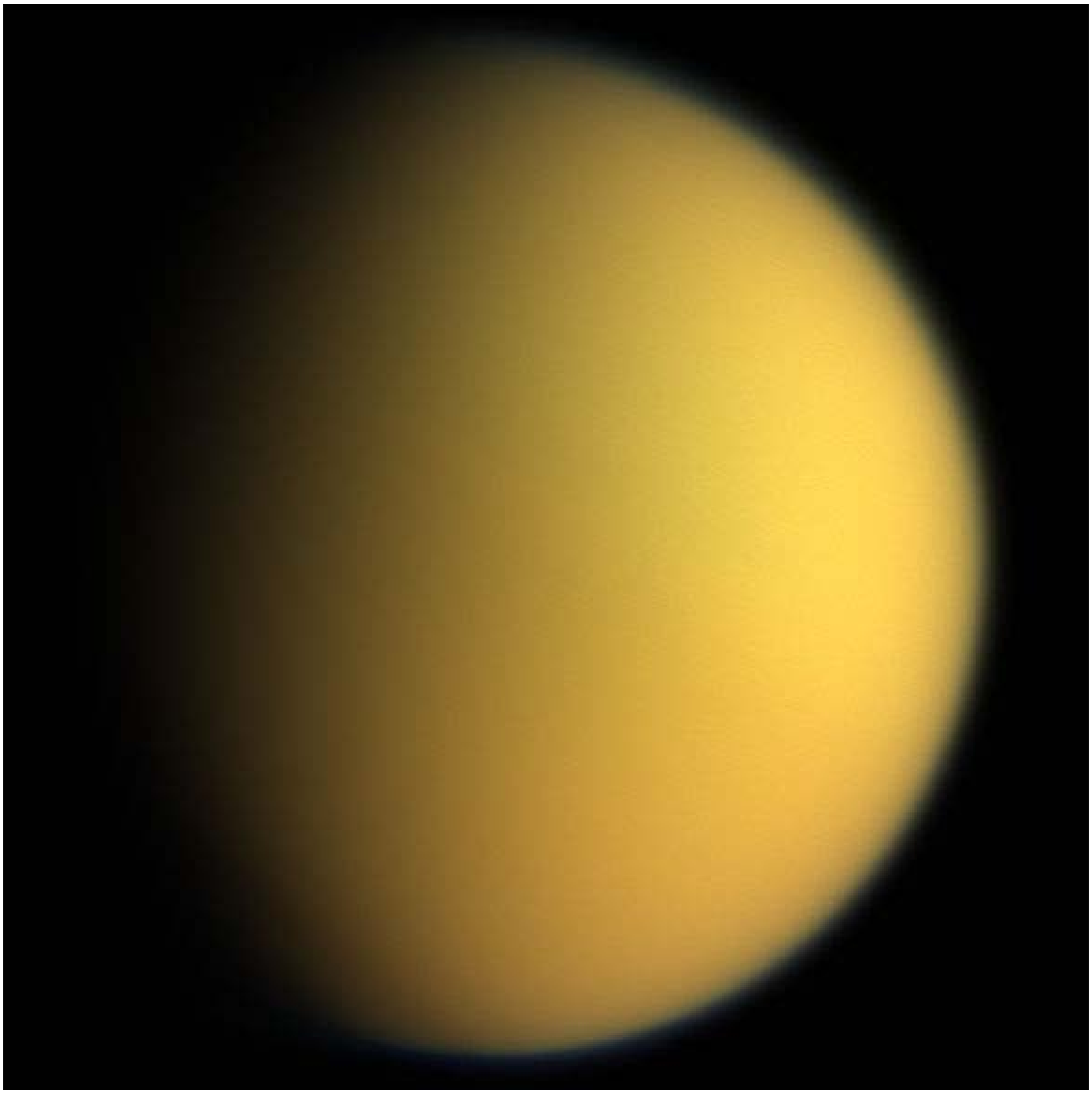
The low gravity of Europa may also present challenges to colonization efforts. The effects of low gravity on human health are still an active field of study, but can include symptoms such as loss of bone density, loss of muscle density, and a weakened immune system. Astronauts in Earth orbit have remained in microgravity for up to a year and more at a time. Effective countermeasures for the negative effects of low gravity are well-established, particularly an aggressive regimen of daily physical exercise. The variation in the negative effects of low gravity as a function of different levels of low gravity are not known, since all research in this area is restricted to humans in zero gravity. The same goes for the potential effects of low gravity on fetal and pediatric development. It has been hypothesized that children born and raised in low gravity would not be well adapted for life under the higher gravity of Earth.

It is also speculated that alien organisms may exist on Europa, possibly in the water underlying the moon's ice shell. If this is true, human colonists may come into conflict with harmful microbes, or aggressive native life forms. More recent studies have indicated that the action of solar radiation on the surface of Europa might produce oxygen, which could be pulled down into the subsurface ocean by upwellings of the interior. If this process occurs, Europa's subsurface ocean could have an oxygen content equal to or greater than that of the Earth's, possibly providing a home to more complex life, which could create additional problems. Regardless of the form of life (if any) that is found on Europa, human colonization raises ethical questions of ecocide.

Artemis Project Colonization Plan

In 1997, the Artemis Project produced a plan to colonize Europa. According to this plan, explorers would first establish a small base on the surface. From there, they would drill down into the Europan ice crust, entering the postulated subsurface ocean. The colonists would then create (or, possibly, find) a pocket between the icy surface and the liquid interior in which to establish a base. This location would be protected from radiation by the ice overhead, and would be at a more reasonable temperature than the surface, as indicated by the presence of liquid water.

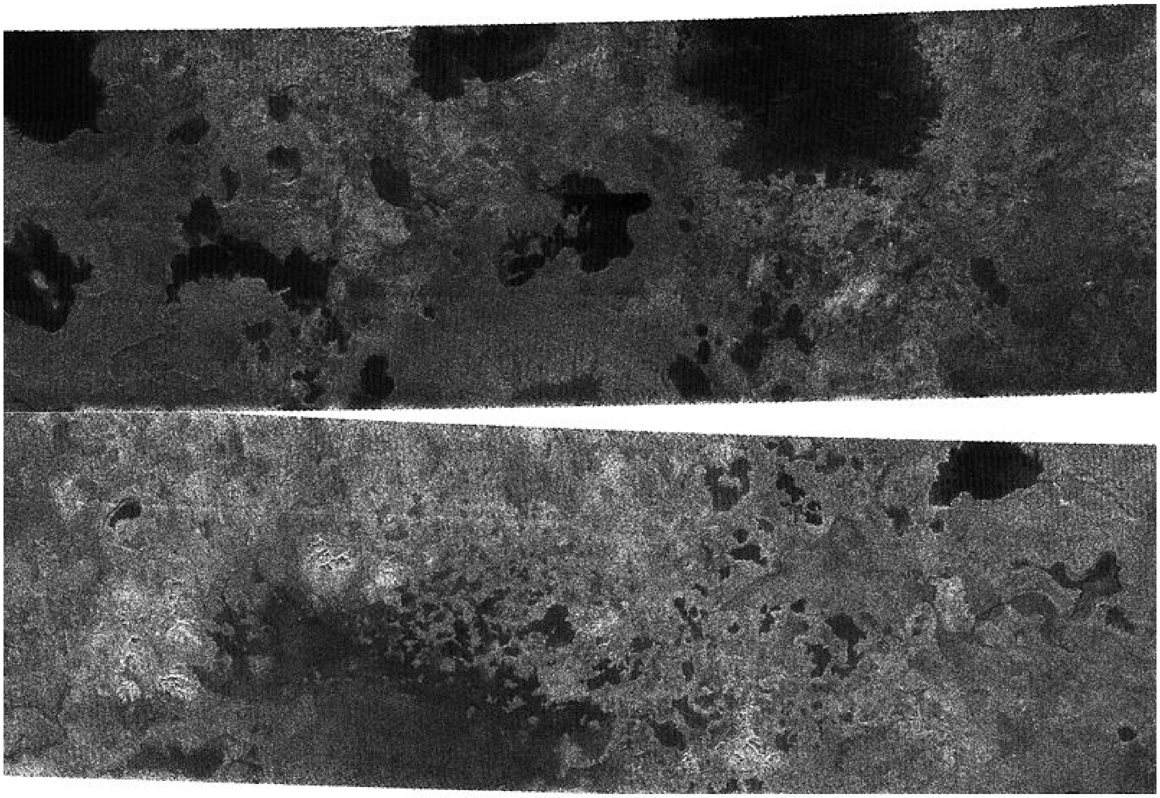
Colonization of Titan



Saturn's moon Titan in natural color.

Saturn’s orange moon Titan is one of several candidates for a possible future colonization of the outer planets in the solar system. There are many possible reasons for colonization, one of which is mining or collecting hydrocarbons which drive Earth's machines.

Natural resources



Lakes of Titan

According to Cassini data from 2008 Titan has hundreds of times more liquid hydrocarbons than all the known oil and natural gas reserves on Earth. These hydrocarbons rain from the sky and collect in vast deposits that form lakes and dunes. "Titan is just covered in carbon-bearing material—it’s a giant factory of organic chemicals," said Ralph Lorenz, who leads the study of Titan based on radar data from Cassini. “This vast carbon inventory is an important window into the geology and climate history of Titan.” Several hundred lakes and seas have been observed, with each of several dozen estimated to contain more hydrocarbon liquid than Earth's oil and gas reserves. The dark dunes that run along the equator contain a volume of organics several hundred times larger than Earth's coal reserves.

Titan 'sea' (left) compared at scale to Lake Superior (right)

Radar images obtained on July 21, 2006 appear to show lakes of liquid hydrocarbon (such as methane and ethane) in Titan's northern latitudes. This is the first discovery of currently-existing lakes anywhere besides Earth. The lakes range in size from about a kilometer to one which is one hundred kilometers across.

On March 13, 2007, JPL announced that it found strong evidence of seas of methane and ethane in the northern hemisphere. At least one of these is larger than any of the Great Lakes in North America.

Suitability

The Jovian system is the least likely to be developed for collecting resources from a gas giant, because of its extraordinary radiation belt. The American aerospace engineer and author Robert Zubrin identified Saturn as the most important and most valuable of the three other gas giants, because of its relative proximity, low radiation, and excellent system of moons. He also named Titan as the most important moon on which to establish a base to develop the resources of the Saturn system.

Habitability

Robert Zubrin has pointed out that Titan possesses an abundance of all the elements necessary to support life, saying "In certain ways, Titan is the most hospitable extraterrestrial world within our solar system for human colonization." The atmosphere contains plentiful nitrogen and methane, and strong evidence indicates that liquid methane is on the surface and, liquid water, and ammonia are present under the surface and are often delivered to the surface by volcanic activity. Water can easily be used to generate breathable oxygen. Nitrogen is ideal to add buffer gas partial pressure to breathable air; indeed, nitrogen forms about 78% of Earth's atmosphere. Nitrogen, methane and ammonia can all be used to produce fertilizer for growing food.

Atmosphere

Additionally, Titan has an atmospheric pressure one and a half times that of Earth. This means that the interior air pressure of landing craft and habitats could be set equal or close to the exterior pressure, reducing the difficulty and complexity of structural engineering for landing craft and habitats compared with low or zero pressure environments such as on the Moon, Mars, or the asteroids. The thick atmosphere would also make radiation a non-issue, unlike on the Moon, Mars, or the asteroids. While Titan's atmosphere contains trace amounts of hydrogen cyanide, in the event of pressure suit breach, the concentration would not inflict more than a slight headache.

Gravity

Titan has a surface gravity of 0.14 *g*, slightly less than that of the Moon. Managing long-term effects of low gravity on human health would therefore be a significant issue for long-term occupation of Titan, more so than on Mars. These effects are still an active field of study. They can include symptoms such as loss of bone density, loss of muscle density, and a weakened immune system. Astronauts in Earth orbit have remained in microgravity for up to a year and more at a time. Effective countermeasures for the negative effects of low gravity are well-established, particularly an aggressive regime of daily physical exercise. The variation in the negative effects of low gravity as a function of different levels of low gravity are not known, since all research in this area is restricted to humans in zero gravity. The same goes for the potential effects of low gravity on fetal and pediatric development. It has been hypothesized that children born and raised in low gravity such as on Titan would not be well adapted for life under the higher gravity of Earth.

Temperature

The temperature on Titan is about 94 K (−179 °C, or −290.2 °F), so insulation and heat generation and management would be significant concerns. Although the air pressure at the surface is about 1.5 times that of Earth sea level, because of the colder temperature, the density of the air is about 4.5 times that of Earth sea level. This substantial density should moderate shifts in temperature over time and from one locale to another, to a fraction of the types of temperature changes familiar from the day/night cycle, the seasons, and weather on Earth. The corresponding narrow range of temperature variation further reduces the difficulties in structural engineering.

Relative thickness of the atmosphere combined with extreme cold makes additional troubles for human habitation. Unlike vacuum, the high atmospheric density makes thermoinsulation a significant engineering problem.

Flight on Titan

The very high ratio of atmospheric density to surface gravity also greatly reduces the wingspan needed for an aircraft to maintain lift, so much so that a human would be able to strap on wings and easily fly through the atmosphere.