Long Term Human Presence in Space Requires Artificial Gravity and Radiation Shielding

Harry W. Jones[1]
NASA Ames Research Center, Moffett Field, CA, 94035-0001, USA

Astronauts who spend many months in microgravity suffer serious health problems including muscle atrophy, cardiovascular deconditioning, bone calcium loss, impaired vision, and immune system changes. Exercise countermeasures have been insufficient to maintain normal human performance. Similar problems can be expected in the partial gravity of the Moon and Mars. Achieving the long-term presence of healthy humans in space requires providing artificial Earth level gravity. This can be done on the Moon and Mars by using horizontally rotating habitats with angled floors, but it is easier in space habitats. Astronauts travelling beyond the protection of the Earth's magnetic field can suffer harm from cosmic background radiation and occasional strong solar flares. Supporting healthy long-term human lives will require radiation shielding on the Moon and Mars as well as in space. Human space settlement will probably begin with artificial rotating space habitats in Low Earth Orbit (LEO) where they will be shielded from radiation. The earlier anticipated human communities in pressurized domes on the Moon or Mars appear unrealistic because of the now known problems of partial gravity and radiation.

I. Introduction

The ultimate objective of space research and exploration is to establish a permanent and growing human presence in space. This requires the development of fully habitable space platforms where humans can live in health for their entire lives and be followed by successive generations in space. All past and currently anticipated human space missions require astronauts to endure weightlessness and increased radiation that impair their health and performance. This difficult human effort has been rewarded by great accomplishments including Moon landings, Hubble repair, and building the International Space Station (ISS), and it is expected to continue a return to the Moon and expedition to Mars. However, humans cannot remain healthy in an environment of partial gravity and high radiation. A habitable long term space platform must provide artificial gravity and radiation shielding.

Humans become severely impaired when they spend long periods in microgravity. The debilitating effects of weightlessness were seen on the first long missions. It was initially hoped that countermeasures such as exercise and resistance training would moderate musculoskeletal and cardiopulmonary deconditioning, but these countermeasures are clearly insufficient. Similar impairments can be expected in the reduced gravity of the Moon and Mars. There appears to be a correlation between heart rate, oxygen consumption, and net metabolic rate with a simulated level of gravity from 0 to 1 g. Living in partial gravity will probably cause less severe physiological deconditioning than microgravity, but as in microgravity, exercise countermeasures will probably be insufficient to maintain human physiological systems.

Humans can easily be harmed by radiation in space. The Earth is shielded by its magnetosphere, but cosmic background radiation and solar flares can be harmful to humans in deep space. The major radiation hazard in space is Solar Particle Events (SPEs), often called solar flares. Smaller flares are frequent but dangerously large flares are rare. They are unpredictable but are more likely near the maximum of the sunspot cycle. Galactic cosmic rays are emitted by distant stars and galaxies and arrive uniformly from all directions. They consist of extremely high energy particles and over the long term they can greatly increase cancer mortality. Cosmic rays and solar flares also cause problems on the Moon and Mars, which lack magnetic fields.

A permanent expanding human presence in space can best be achieved by developing space habitats with artificial gravity and radiation shielding, not by building surface bases on the Moon or Mars. The first such space habitats should probably be in Low Earth Orbit (LEO) for convenience, lower launch cost, short communications delay, and

---

[1] Systems Engineer, Bioengineering Branch, AIAA Member.

Earth's radiation shielding. They can support scientific and technical research and commercial and military observation, communication, and control. Future human habitats could be in far Earth orbit, orbit the Earth-Moon system, or even orbit the sun. The Moon and Mars have insufficient gravity and radiation shielding for long term human habitation and they also require the artificial gravity and radiation shielding needed for deep space habitats. The surface areas of the Moon and Mars are not large compared to the uninhabited area on Earth and it is unlikely that they will be extensively inhabited. The human future in space will probably be different than what has been expected. Space habitats with artificial Earth normal gravity, heavy radiation shielding, and solar power will expand into the solar system. Space habitats using nuclear rather than solar power could travel to the stars.

II. The Damaging Effects of Microgravity

Astronauts who spend months in space undergo bone calcium loss, muscle atrophy, cardiovascular deconditioning, sensory and motor deconditioning, and regulatory physiology disruption. [1] [2] [3] [4] [5]

A. Bone Calcium Loss and Osteoporosis

Maintaining bone mass and strength requires the loads and impacts of walking in Earth's gravity. In microgravity, "the major bones that support body weight begin to deteriorate, and a net loss of body calcium occurs, independent of the amount taken in with food or supplements." [3] In microgravity, "Calcium is lost at a rate of about 1% per month, and the losses are reflected in the density and mass of weight-bearing bones. The rate of calcium loss is not reduced by vigorous exercise." [3] Calcium loss can continue at a high rate indefinitely.

B. Muscle Atrophy

Maintaining muscle mass and strength requires supporting the body's weight in Earth's gravity. In microgravity, "Very significant losses of muscle strength, muscle volume, and total body weight are noted." [3] Two weeks of zero gravity can atrophy muscle fibers by 30%. Using an exercise bike or running on a treadmill reduces muscle atrophy, "Yet despite rigorous exercise, astronauts return to Earth shockingly weaker than when they left. Exercise alone has not prevented muscle wasting during spaceflight." [3]

C. Cardiovascular Deconditioning

Microgravity causes many changes that reduce cardiovascular fitness. Blood and other fluids rise from the lower to the upper body, so the face swells and the legs shrink. Body fluid, blood plasma, and red and white blood cells are lost. Microgravity causes increased heart rate, irregular heart rhythm, briefer pulse duration, and decreased heart chamber volume, which explain the astronauts reduced ability to work and exercise. Returning astronauts can feel lightheaded and can faint when standing. [3]

D. Sensory and Motor Deconditioning

Microgravity causes sensory-motor deconditioning because of the loss of signals to the inner ear and to the internal body sensors of motion and position. These systems help control spatial orientation, posture, movement, and coordination. Initial space motion sickness is common and spatial disorientation often occurs throughout a mission. Most returned astronauts experience postural imbalance, uncoordinated locomotion, and vertigo and nausea for months. [3]

E. Regulatory Physiology Disruption

"The physiology of humans is composed of a totally integrated set of complex subsystems that maintain critical physiological parameters (e.g., temperature, fluid balance, biological rhythms, and electrolyte levels) at relative stable levels, a function called homeostasis. Operational observations and spaceflight experiments have demonstrated changes in these physiological parameters and processes. For example, changes in electrolyte balance, blood cell mass, hormone synthesis, and hormone action have been observed during spaceflight." [3] Information from the inner ear vestibular system influences heart rate, blood pressure, and circadian rhythms. Microgravity also suppresses the cell-mediated immune system, reducing the ability to fight infection. [3]

F. Microgravity Exercise Countermeasures Are Unsatisfactory

Exercise is a reasonable countermeasure for microgravity bone loss, muscle atrophy, and cardiovascular deconditioning, if not for sensory-motor deconditioning or regulatory physiology disruption. Unfortunately, "Extensive exercise does not prevent these (biomechanical and cardiopulmonary) problems." [2] "After a long-duration mission, it is not uncommon for crewmembers to be unable to lift their arms to remove the belt restraint. After flight lasting six months or more, they have to be physically removed from the vehicles on litters." [3]

G. The Expected Effects of Partial Gravity on the Moon and Mars

Richter et al. summarized "the different effects of partial gravity (0.1–0.4 g) on the human musculoskeletal, cardiovascular and respiratory systems." [2] They found that, "Partial gravity exposure below 0.4 g seems to be insufficient to maintain musculoskeletal and cardiopulmonary properties in the long-term." [2] Some studies show that heart rate, oxygen consumption, and net metabolic rate are correlated with simulated gravity from 0 to 1 g. "Therefore, exposure to Moon and Mars gravities might be less severe compared to physiological deconditioning as experienced in μg." [2] A model predicts loss of 0.39% per week in bone mineral density for the Moon and 0.22% per week on Mars. "It can be anticipated that partial gravity environments as present on the Moon or on Mars are not sufficient to preserve all physiological systems to a 1 g standard if not addressed through adequate countermeasures." [3] However, currently used countermeasures do not seem adequate.

III. Artificial Gravity by Rotating Spacecraft

Most historical and more recent proposals for space stations suggest artificial gravity. The main ideas for a rotating artificial gravity habitat are a wheel or torus, a cylinder, and a habitat with a balancing mass joined by a tether. Konstantin Tsiolkovsky suggested a spinning space vehicle in 1903. [6] [3] [7] Hermann Noordung in 1929 proposed a rotating wheel with a 30-meter diameter. [6] [3] Werner von Braun in 1952 suggested a rotating wheel with a 76-meter diameter to provide 0.3 g for a Mars transit. [8] Gerard O'Neil in 1977 proposed a rotating cylinder with a five-mile diameter that would be 20 miles long. [9] [10] Johnson and Holbrow the same year proposed the Stanford torus, a 1.1-mile diameter rotating wheel. [11] Robert Zubrin in 1990 proposed a tethered rotating booster and habitat for Mars transit. [12] Von Braun and Zubrin proposed small habitats for Mars transit. O'Neil and Johnson and Holbrow proposed larger habitats with dimensions of miles for permanent human habitation in space.

Rotating spacecraft are the only way to provide artificial gravity in space. They seem necessary for permanent human habitation. Rotating artificial gravity space habitats have not been built or planned in detail, probably because of their much greater mass and launch cost. The recent great reduction in launch cost makes rotating habitats more feasible. [13]

A. Spin Rate and Spacecraft Radius

The level of artificial gravity should probably be an Earth normal 1 g for long term human habitation. The force of artificial gravity produced by rotation increases with the rotation rate and the radius of rotation. The maximum spin rate humans can tolerate is about 4 rotations per minute (rpm), which requires a habitat radius of 56 meters to produce 1 g.

A maximum rotation rate of 4 rpm is suggested to limit the Coriolis effect felt in a rotating system. When someone in a rotating cylinder moves closer to the axis of rotation, they feel a force pushing them in the direction of spin. This force can produce disorientation and motion sickness. [14]

The centripetal acceleration due to rotation is acceleration (m/s^2) = radius of rotation (m) * $(2 \pi \text{ rpm}/60)^2$, where rpm is rotations per minute. For 4 rpm, producing 1 g = 9.81 m/s^2 requires r = 56 m. The diameter of a rotating wheel or cylinder producing 1 g on the inner surface would be 112 meters. Very large diameter space habitats would rotate very slowly.

B. Advantages and Disadvantages of Rotating Spacecraft

Providing Earth-level gravity by rotating a spacecraft will establish commonality and synergism between space and terrestrial systems and processes. Human activities in a space habitat include food preparation, dining, personal hygiene, clothing, waste handling, recreation, exercise, medical treatment, housekeeping, storage, maintenance, and sleep. If Earth-level gravity is provided, all these activities can be conducted using the same systems as on Earth. Work, exercise, and other physical activities can be carried out as on Earth. Any new systems needed for a space habitat can be confidently developed and tested on Earth without concern for microgravity or partial gravity effects. Innovative systems developed in space can be directly used on Earth, and Earth developments applied in space, establishing a shared technical basis and avoiding the high cost of systems specialized for partial gravity.

The rotation needed to produce artificial gravity will make external interaction and observation more difficult. Propulsion, communication with Earth and other human habitats, solar power collection, and Earth and astronomical observation all require orientation in a fixed direction. A split habitat with a rotating and non-rotating section is possible but would be complex with a large rotating joint to transfer people and material and connect power and communications. A rotating space habitat will probably have greater mass and development cost than a nonrotating one, but this seems necessary to provide a fully habitable space platform.

IV. The Damaging Effects of Space Radiation

Solar and cosmic radiation can be harmful to humans in deep space and on the Moon and Mars. Earth is largely shielded from radiation by its magnetosphere, but the Moon and Mars lack magnetic fields. Radiation damages humans by ionizing atoms in their bodies. Radiation includes high energy particles including electrons, protons, neutrons, and atomic nuclei as well as photon or wave radiation including gamma rays and X-rays.

A. Solar Particle Radiation

The major radiation hazard in space is Solar Particle Events (SPEs), also called solar flares. SPEs produce radiation from lower radio frequencies up through the spectrum to X-rays and charged particles. Solar flares ejection coronal mass in all directions away from the sun. Solar flares are unpredictable but occur more frequently near the maximum of the 11-year sunspot cycle. [3] [2] Dangerously large solar flares are rare. SPEs can build up in minutes and last for hours. Particle energies can reach 1,000 Mev and the radiation dose can increase by factors of thousands to millions. [15] [16] [17]

B. Galactic Cosmic Radiation

Galactic cosmic rays are emitted by distant stars and galaxies and arrive in the solar system uniformly from all directions. They consist of extremely high energy particles including electrons, protons, and heavy nuclei. Even though galactic cosmic ray particles have high energy, they cause less health damage than solar flares because of their lower particle flux density. Solar flares are the greater risk. A typical solar flare would exceed the background cosmic ray energy by factor of ten, and a 10% worst case solar flare would exceed it by a factor of nearly a million. An SPE in 1972 produced ten million times the energy of the cosmic background radiation. It would have caused radiation sickness if any Apollo astronauts had been in space. [15] [16]

The background cosmic rays can cause serious harm despite their relatively low level. Exposure to galactic cosmic rays over a long period would greatly increase cancer incidence and mortality. With typical aluminum spacecraft shielding, the deep space cosmic radiation dose is about 1.5 mSv per day during the solar minimum and about half that, 0.8 mSv per day during the solar maximum. [18] In one year in deep space an astronaut would accumulate 0.30 to 0.55 Sv of cosmic radiation. [18] [19] Predictions of the increased cancer risk due to cosmic rays are uncertain. [19] A rule of thumb is that 0.2 Sv increases the risk of a fatal cancer by 1%. [18] This suggest that fatal cancer risk would increase by 1.5% to 2.8% per year of exposure. Another estimate suggests a 2.4% increase per year but it could be several times higher [19]

Men in the US have a 40% chance of developing cancer in their lifetime and a 22% chance of dying from it. [20] People spending their lives in a minimally shielded space habitat would have a several times higher risk of developing cancer and dying from it. It would be highly desirable for a permanently inhabited deep space platform to have substantial cosmic ray shielding.

V. Radiation shielding

Radiation shielding is required to protect space dwellers from brief solar particle radiation that can cause acute radiation sickness and from constant low level galactic cosmic rays that can cause cancer. Passive bulk material shielding is currently the only realistic approach, but it requires high mass for adequate protection. Spacecraft walls are usually aluminum, typically with a mass of only a few grams per cm^2, which does not provide significant shielding. Lighter elements such as hydrogen, oxygen, and carbon provide more shielding per unit mass, so water or organic material can be effective shielding. [16] The water and oxygen used for life support and the oxygen and hydrogen or other propulsion fuel can be used. [17]

A suggested design for a safe haven from solar flares uses a 2-meter diameter aluminum sphere with 7.5 cm thick walls, weighing 20 g/cm^2 for a total of 2.5 metric tons (MT). [16] [17] The safe haven's volume is 4.2 m^3, room for one or two people but only one-third the volume of a phone booth.

Adequately reducing galactic cosmic ray exposure requires much more shielding. Since galactic cosmic rays are constant and omnidirectional, the entire crew living volume must be shielded. Reducing the galactic radiation to about half, to 0.25 Sv/year, requires an 8 g/cm^2 shield, and reducing it to one-quarter requires 50 g/cm^2. 17] A reasonable living space for one crewmember would have a volume of 100 m^3. [21] This could be a square room with height 2 meters and area 50 m^2. The total surface area, top, sides, and bottom would be 157 m^2. The total mass of its shielding per crewmember at 8 g/cm^2 would be 13 MT and at 50 g/cm^2 would be 78 MT. Cosmic ray shielding for all of a crewmember's living space will be more than thirty times as massive as a safe haven for solar flares.

The mass needed for radiation shielding appears to be prohibitively large, but this is a significant problem only for small spacecraft with few crew members. The mass per crewmember for radiation shielding will be much smaller for future large space habitats with thousands or millions of inhabitants. This is because the surface area of the space habitat increases at a slower rate than the interior volume increases. The shielding mass (covering the surface) increases at a slower rate than the number of inhabitants (filling the interior). For example, a sphere of radius r has volume $v = 4/3\ \pi\ r^3$ and surface area $s = 4\ \pi\ r^2$. The volume of the habitat is proportional to the number of crew, N. The shielding mass, M, is proportional to the surface area of the habitat. The ratio of shielding mass to number of crew is $M/N = (4\ \pi\ r^2)/(4/3\ \pi\ r^3) = 3/r$. The ratio M/N decreases as r^{-1} as M increases more slowly than N. Since volume is proportional to N, and volume $v = 4/3\ \pi\ r^3$, so N is proportional to r^3 and inversely, r is proportional to $N^{1/3}$. The shielding mass per crewmember, $M/N = 3/r$, decreases with the number of crew as $M/N \sim N^{-1/3}$. If there are 1,000 crew, M/N decreases roughly as $N^{-1/3}$, by a factor of 10. For each crewmember having a volume of 100 m^3, the total mass of shielding per crewmember at 8 g/cm^2 would be 1.0 MT and at 50 g/cm^2 would be 6.5 MT. For one million crew, M/N decreases roughly by a factor of 100. The total mass of shielding per crewmember at 8 g/cm^2 would be 100 kg and at 50 g/cm^2 would be 646 kg. The metal structure and mass contents of the habitat may provide much of the required shielding.

VI. Mars Bases Also Need Artificial Gravity and Radiation Shielding

The Martian atmosphere is thin. It attenuates galactic cosmic rays with a shielding value of about 16 - 22 g/cm^2, but solar flare and galactic cosmic ray shielding would still be required. [16] Most Mars habitat designs include radiation shielding. One common suggestion for shielding is to cover surface habitats with Martian regolith. Others are to excavate a subterranean space or seal the ends of some existing lava tube. [22]

Mars gravity is about 1/3 the Earth's, but it is probably insufficient to eliminate the serious health problems caused by zero gravity. [3] Only a few Mars habitat designs include artificial gravity. One way to create artificial Earth gravity on Mars is to use a large rotating underground wheel. "(T)he outer wall of the wheel (the floor where people walk) must be tilted to give an effective 1 g gravity acting on a person standing inside the wheel. The centrifugal force caused by the gravity wheel rotation causes an outward force on a person that is horizontal to the Mars surface. But the Mars native gravitational force pulls vertically downward on a person. So a person standing in the gravity wheel has both forces acting on him or her simultaneously." [22] The wheel diameter and rotational speed are adjusted to provide a combined 1 g, and the angle of the rotating floor is set to be perpendicular to the 1 g force.

Mars presents the other unique difficulties of cold temperature and toxic surface dust. The sun's light energy per square meter is only half that of Earth's at Mars' distance from the sun, so Mars' surface temperatures are much colder than Earth's. Space habitats at the Earth's distance from the sun receive the same energy per square meter as the Earth and naturally have the same average temperature. The strongly oxidizing chemical perchlorate occurs Martian soils at concentrations from 0.5 to 1%. It is toxic in very dilute concentrations and is a serious hazard for astronauts. [23]

VII. A Next Step Space Habitat in Low Earth Orbit

A near term rotating space habitat in LEO can avoid high radiation and the need for shielding. A space habitat in LEO has easier access from Earth, a short communications delay, and can provide close support for observation and control of Earth surface and orbital systems.

A permanent space station in LEO has been proposed. [24] [25] They reevaluate the earlier decisions about rotation rate and shielding mass that were made in the O'Neil cylinder space habitat concept. [8] The cylinder design assumed that a low rotation rate of 2 rpm was required to prevent motion sickness due to the Coriolis effect. Currently a rotation rate of 4 rpm is usually considered acceptable and astronaut acclimation may allow higher rotation rates. The O'Neil design assumed space colonies would be in deep space and need massive radiation shielding. The proposed new permanent station will be in Equatorial Low Earth Orbit (ELEO), at about 500 kilometers high. Its orbit would avoid the South Atlantic Anomaly, a high radiation area due to a gap the van Allen belts. The required radiation shielding would be only a few g/cm^2, no more than provided in typical spacecraft construction.

VIII. Human Expansion into the Solar System and Galaxy

In the future it is possible that humans will expand from Earth into the solar system, ultimately capturing much of the sun's radiant energy to create a system wide civilization. This will require the development of many permanent deep space habitats that have artificial gravity and radiation shielding. The metal for habitat construction must be obtained from the Earth, other rocky planets, and asteroids, while hydrogen, oxygen, and carbon for shielding, propulsion, and life support could also be obtained from comets and the outer planets and their moons. Science, technology, material productivity, and social systems seem to advance more rapidly as the number of interacting individuals and groups increases. [26] Human establishment of a solar-system-wide civilization would lead to scientific, technical, economic, political, and social advances that are now unimaginable.

The potential increase in human population from one limited to Earth to one filling the solar system strains the imagination. The surface area of the Earth is 197 million square miles. A sphere in space centered on the sun at Earth distance would have a surface area of 1.09 * 10^{11} million square miles. The ratio of potential space habitat area at Earth distance from the sun to Earth's sunlight area is roughly $10^{11}/10^{2} = 10^{9}$. There is enough sunlight surface at Earth distance in the solar system to allow one billion new Earths. It also appears that there is sufficient mass and orbital clearance space in the solar system to allow that many independently orbiting space stations. [27] [28] [21]

How long might it take for humans to expand from Earth to fill the solar system, with a population increase of a billion times? It could be quite rapid. An increase of one billion times, 10^{9}, is about 2^{30}, 30 doublings of solar power area and human population. If a human population that is not resource constrained doubles every 25 years, as on the American frontier, 30 doublings would require only 750 years. The ultimate population of the solar system would be a billion times Earth's current nearly 10 billion, so 10 billion billion or 10^{19}. Such a human expansion into the solar system would take about a thousand years, a long time compared to the recent rate of technical and social change, but only a very brief time, one millionth of the time, of the billions of years needed for biological evolution, geologic change, and the formation of stars, planets, and galaxies.

A solar civilization will be based on the sun's power, which is limited even if a billion times greater than the Earth's portion of solar power. Our galaxy contains 100 to 500 billion stars and is a spiral disk about 100 thousand light years in diameter and one thousand light years thick. The typical distance between stars is a few light years. Humans can travel to the stars and establish further star centered civilizations using space habitats that are nuclear powered. If the speed of interstellar travel is between 1% and 10% of light speed, and if the distance between stars is between 1 and 10 light years, the time to travel between stars is between 10 and 1,000 years. Suppose a space habitat with one million people is sent to a neighboring star and the trip takes 1,000 years. Increasing the population from the original one million, 10^{6}, to 10^{19}, a star system filling population, would be about 40 doublings and take about another 1,000 years. The number of human inhabited star systems in the galaxy could then double every 2,000 years. Going from one solar civilization to 500 billion would require 39 doublings and take about 78,000 years, but the physical shape of the galaxy would prevent this. The far side of our spiral galaxy is nearly 100 thousand light years away and travelling that distance at 10% or 1% of light speed would take one million to ten million years. Filling the solar system with human habitats will take thousands of years, enough time for substantial cultural changes that could be limited by communication and trade. Filling the galaxy with human inhabited star systems will take hundreds of thousands to millions of years, which would permit drastic cultural changes and even biological divergence. Two-way communications at light speed would take tens to hundreds of thousands of years and exchanging populations and trading material artefacts would take thousands to millions of years. [29]

IX. Conclusion

Establishing continued human presence off Earth should begin by building space habitats with artificial gravity and radiation shielding. Previous missions have subjected astronauts to microgravity and sometimes higher radiation. Weightlessness and radiation damage astronaut health and impair performance. Artificial gravity and radiation shielding are needed so humans can live, work, and raise families in a healthful space environment.

Permanently inhabited domes on the surface of the Moon and Mars are implausible because their partial gravity is insufficient to maintain human conditioning and health and because a high level of cosmic radiation would cause a high incidence of cancer. Like space habitats, bases on the Moon and Mars will require rotational artificial gravity and radiation shielding.

The first rotating artificial gravity space habitat could be in LEO, where radiation shielding is not needed. Another near term possibility is an artificial gravity Mars transit vehicle. The limited duration of the Mars mission could allow reduced radiation shielding. Permanent space habitats with artificial gravity and radiation shielding can enable human expansion into the Earth-moon system and beyond into the solar system. Nuclear powered habitats can take us to the stars.

References

[1] Goyal, R., Bryant, T., Majjiy, M., Skelton, R. E., and Longman, A., “Design and Control of Growth Adaptable Artificial Gravity Space Habitats,” AIAA SPACE Forum, 10.2514/6.2017-5141, 12 - 14 Sep 2017, Orlando, FL.

[2] Richter, C., Braunstein, B., Winnard, A., Nasser, M., and Weber, T., “Human biomechanical and cardiopulmonary responses to partial gravity - A systematic review,” Front. Physiol. 8:583, https://www.frontiersin.org/articles/10.3389/fphys.2017.00583/full, 2017, accessed July 1, 2020.

[3] Clément, G., and Bukley, A., (eds), Artificial Gravity, Berlin, Springer, 2007.

[4] Daga, A. W., Daga, M. A., Wendel, W. R., “Evolving concepts of lunar architecture: The potential of subselene development,” The Second Conference on Lunar Bases and Space Activities of the 21st Century, 1988 conference, NASA Conference Publication 3166, 1992.

[5] Young, L. R., “Artificial Gravity Considerations for a Mars Exploration Mission,” Annals of the New York Academy of Sciences, 871: 367–378, 1999.

[6] Noordung, H., The Problem of Space Travel: The Rocket Motor, Stuhlinger, E, Hunley, JD, Garland, J (eds) US Government Printing office, Washington DC, NASA SP-4026, 1995. (Potočnik, H., The Problem of Space Travel, 1929.)

[7] Wikipedia, Rotating Wheel Space Station, https://en.wikipedia.org/wiki/Rotating_wheel_space_station, accessed Oct 11, 2018.

[8] Braun, W., “Crossing the Final Frontier,” Colliers, March 22, 1952.

[9] O'Neil, G. K., The High Frontier, William Morrow & Co., 1977.

[10] Wikipedia, O’Neil cylinder, https://en.wikipedia.org/wiki/Bernal_sphere, accessed July 5, 2020.

[11] Johnson, R. D., and Holbrow, C., (eds), Space Settlements: A Design Study, NASA Washington, DC, NASA SP-413, 1977.

[12] Wikipedia, Artificial Gravity, https://en.wikipedia.org/wiki/Artificial_gravity, accessed July 3, 2020.

[13] Jones, H., “The Recent Large Reduction in Space Launch Cost,” ICES-2018-81, 48th International Conference on Environmental Systems, 8-12 July 2018, Albuquerque, New Mexico.

[14] Joosten, B. K., Preliminary Assessment of Artificial Gravity Impacts to Deep-Space Vehicle Design, NASA JSC-63743, February 2007.

[15] Tribble, A. C., “The Space Environment-Hazards and Effects,” in W. K. Larson, and L. K. Pranke, eds., Human Spaceflight: Mission Analysis and Design, McGraw-Hill, New York, 2000.

[16] Eckart, P., Spaceflight Life Support and Biospherics, Kluwer Academic, Dordrecht, 1996.

[17] Reed, R. D., and Coulter, G. R., “Physiology of Spaceflight,” in W. K. Larson, and L. K. Pranke, eds., Human Spaceflight: Mission Analysis and Design, McGraw-Hill, New York, 2000.

[18] Turner, R., The Radiation Threat to “the Martian,” ANSER, 2015, www.anser.org/docs/the_radiation_threat_to_the_martian.pdf, downloaded Dec. 10, 2018.

[19] Cucinotta, F. A., and Durante, M., “Cancer risk from exposure to galactic cosmic rays: implications for space exploration by human beings,” Lancet Oncol 7, pp. 431–35, 2006.

[20] American Cancer Society, Lifetime Risk of Developing or Dying from Cancer, https://www.cancer.org/cancer/cancer-basics/lifetime-probability-of-developing-or-dying-from-cancer.html, accessed December 6, 2018.

[21] Jones, H., “Space Habitats Should Be 1 g Shielded Space Platforms, Not on Low Gravity, Radiation Exposed Moon or Mars,” INCOSE International Symposium 2022, June 25, 2022.

[22] Sommariva, A., The Political Economy of the Space Age: How Science and Technology Shape the Evolution of Human Society, Vernon Press, Wilmington, Delaware, US, 2018.

[23] Davila, A.F., Willson, D., Coates, J.D. and McKay, C.P., “Perchlorate on Mars: a chemical hazard and a resource for humans,”. International Journal of Astrobiology, 12(4), pp.321-325, 2013.

[24] Marotta, T., and Globus, A., The High Frontier: An Easier Way, Amazon Digital Services, 2018.

[25] Globus, A., Covey, S., and Faber, D., Space Settlement, an Easier way, NSS Space Settlement Journal, Issue #2, July 2017.

[26] Turchin, P., Currie, T. E., Whitehouse, H., François, P., Feeney, K., Mullins, D., Hoyer, D., Collins, C., Grohmann, S., and Savage, P., “Quantitative historical analysis uncovers a single dimension of complexity that structures global variation in human social organization.” Proceedings of the National Academy of Sciences, 2018. 115 (2):E144-E151.

[27] Dyson, F. J., “Search for Artificial Stellar Sources of Infrared Radiation,” Science, 03 Jun 1960, Vol. 131, Issue 3414, pp. 1667-1668.

[28] Sandberg, A, “Dyson Sphere FAQ,” https://www.aleph.se/Nada/dysonFAQ.html#ENOUGH, nd, accessed June 30, 2020.

[29] Jones, H., “Technical Civilizations in the Galaxy,” SAE 2006-01-2005, 36th International Conference on Environmental Systems, 2006.