Space Settlement Should Use 1 g Shielded Space Platforms, Not the 1/6 or 1/3 g, Radiation Exposed Moon or Mars

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Previous missions have subjected astronauts to confined space, weightlessness, and increased radiation. These impair astronaut comfort, performance, and future health. The exploration and future settlement of space will depend on the long term presence of individual humans. This requires the development of space platforms where humans can work and live in health for many years, perhaps generations. A livable space platform must provide adequate volume, gravity, and radiation shielding. This seems easier to do in deep space or Low Earth Orbit (LEO) than on the surface of the moon or Mars. Permanently habitable deep space platforms will enable scientific and technical research, space tourism, space mission preparation, space industry development, and military surveillance and operations. The first fully habitable space station would probably be located in LEO for convenience and lower cost.

Nomenclature

ELEO	=	Equatorial Low Earth Orbit
EVA	=	ExtraVehicular Activity
GEO	=	Geosynchronous Earth Orbit
ISS	=	International Space Station
LEO	=	Low Earth Orbit
SAA	=	South-Atlantic Anomaly
SPE	=	Solar Particle Event

I. Introduction

THIS paper suggests an approach for human expansion in space based on providing the best possible human environment in space. All previous human space missions have been designed to accomplish specific goals that required astronaut assistance, and the astronauts' comfort and health have necessarily been somewhat compromised. Previous missions have subjected astronauts to confined space, weightlessness, and increased radiation. These can damage astronaut comfort, performance, and future health.

The difficult human effort of space exploration is justified by great mission accomplishments including Earth orbits, moon landings, Hubble repair, and space station research and technology development. Developing Apollo, the space shuttle, and the space station are fantastic engineering accomplishments in themselves, even without the political, scientific, and technical goals that they achieved. However, if a permanent space station operates in microgravity and high radiation, humans cannot be long term occupants.

A key NASA objective, and a major goal in public perception, is to establish a permanent and growing human presence in space. This requires a fully habitable space platform, one where humans can live in health for many years, perhaps for their entire lives and over several generations. A habitable space platform would provide sufficient habitable volume, artificial gravity, and radiation shielding.

The first fully habitable space station would not be a self-sufficient Earth-independent ecosystem, but rather a well-connected and integrated outpost supporting human expansion into the Earth-moon system and beyond into the solar system. It would probably be located in Low Earth Orbit (LEO) for convenience and lower cost. Future human space platforms would expand into deep space, either in far Earth orbit, orbiting the Earth-Moon system, or even orbiting the sun at approximately Earth distance. They would almost certainly not be located on a planetary surface.

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II. Suitable locations for human expansion into space

The reasons to have the first fully habitable space platform located in LEO are the benefits of closeness to Earth. Nearly all human activity occurs on the surface of the Earth and closeness to the surface enhances the platform's ability to provide many services. Higher orbits require additional rocket boost, so the cost per kilogram is higher for the required mass for artificial gravity and radiation shielding. The lightspeed communications delay is noticeable in conversations relayed from Geosynchronous Earth Orbit (GEO) and would hinder some services and operations. Astronauts in LEO experience slightly increased levels of radiation due to electrons and protons trapped in the Van Allen belts near the Earth and by solar flares and galactic cosmic rays. However, beyond the Van Allen belts the radiation protection by the Earth's magnetic field is lost, the radiation from solar flares and galactic cosmic rays is much greater, and shielding would be needed for long term individual habitation.

Future platforms for solar system exploration would be needed in deep space beyond LEO. Platforms orbiting the sun at approximately Earth distance would receive the same solar intensity as Earth and would tend to have the same average temperature. Planetary surfaces, the moon or Mars, provide living area, gravity, and material, but these locations have limitations when compared to deep space platforms.

A. Surface area

The amount of surface area provided by the moon or Mars is not very large compared to Earth's surface area. Table 1 shows surface areas for Earth, Mars, and the moon.

Table 1. Planetary surface areas

Planet location	Surface area, millions of square miles	Relative area
Earth	196.9	1.00
Earth water surface	139.7	0.71
Earth land surface	57.2	0.29
Mars	55.9	0.28
Earth habitable land[1]	40.2	0.20
Asia	17.2	0.09
Earth barren land and glaciers[1]	17.1	0.09
Moon	14.6	0.07

Earth's surface is 71% water and 29% land. The surface of Mars is slightly smaller than Earth's land surface. Earth's habitable land is only 20% of the total surface area, since 9% is barren land or glaciers.[1] However, the total of the barren land plus glaciers on Earth is somewhat larger than the surface of the moon and would be much easier to inhabit.

If the moon surface could be settled, the area available to humans would increase about 26%. If the Mars surface was made accessible, the area available to humans would increase about 98%. These are incremental additive gains, but the area available for space platforms is vastly greater. Table 2 shows surface areas for spheres centered on and surrounding the Earth or sun.

Table 2. Space sphere surface areas

Sphere	Surface area, millions of square miles	Relative area
Earth	196.9	1.00
LEO, 200 miles above Earth's surface	217.3	1.10
GEO, 22,236 miles above Earth's surface	8,622.7	43.79
Earth-moon radius sphere, 240 thousand miles	7.17.E+05	3,642.47
Earth-sun radius sphere, 93 million miles	1.09E+11	5.52E+08

A sphere in space centered on the Earth at LEO height would have a 10% larger surface area than the Earth. A sphere in space centered on the Earth at GEO height would have a 44 times larger surface area than the Earth. A sphere in space centered on the Earth at the moon's distance would have a 3,642 times larger surface area than the Earth. A sphere in space centered on the sun with an Earth distance radius would have a 552 million times larger surface area than the Earth.

Malthus observed long ago that the human population can increase exponentially, while the arable farmland needed to support humans can be increased only additively. If the human population is ultimately limited by habitable area and grows proportionally to the area it occupies, fully colonizing the moon and Mars would allow only about double the population supportable on Earth. Providing habitable space platforms in the Earth-moon system would allow the occupied area to increase by tens, hundreds, and thousands. Providing habitable space platforms in the solar system at Earth distance from the sun would allow the occupied area to increase by hundreds of millions. Solar space is not limitless, but it is vastly larger than Earth and the planets.

B. Surface resources

The surface areas of Earth, the moon, Mars, and deep space provide various resources to support human habitation. The most important resource is the energy of solar radiation, which is available everywhere but decreases as the square of the distance from the sum. Mars is about 1.5 times the Earth's distance from the sun, so it receives about 43% of the Earth's solar power in Watts per square meter. Mars is therefore cooler. Earth, the moon, and Mars rotate, with the surface areas having day and night. Earth and Mars have roughly the same one day rotation period, but the moon rotates once a month as it keeps the same face toward Earth. Therefore the moon has much greater temperature extremes. The total radiation received by the Earth, moon, and Mars is not equal to the solar radiation times their total spherical surface area, but rather what falls on the area of a circle with the planetary radius. The LEO, GEO, and Earth-moon radius spheres also have a light and dark side. However, an Earth-sun radius sphere centered on the sun would be continually illuminated on its inner surface and, if a fully closed sphere, would capture all of the sun's radiation.

The main difference between deep space and surfaces of the Earth, moon, and Mars is that the planets provide material resources. Construction of deep space platforms would require materials from Earth or other planets, asteroids, or comets. Robotic mining and transport could provide them. Alternately, platform components could be manufactured on planetary surfaces or at asteroids. Developing space habitats would require efficient use and recycling of materials.

The material resources provided by the Earth are much different from those on the moon and Mars, and much more conducive to human habitation. Even an Antarctic glacier has Earth normal atmosphere, water, Earth normal gravity, and seasonally varying Earth normal solar radiation. The main challenge is cold temperature, but there is a permanent human habitation at the South pole. The surfaces of the moon and Mars are extremely inhospitable, without water or suitable atmosphere and with more challenging temperature extremes. The moon surface has difficult dust and the Mars surface has reactive chemicals. It seems probable that suitable atmosphere, water, temperature, and dust and chemical protection can be provided on the moon and Mars, but Earth normal gravity cannot. The moon has about 1/6 Earth gravity and Mars about 1/3. The long term effects of partial gravity are not well known and may discourage permanent individual human habitation on the moon and Mars. If we require permanent human habitations in space, it seems that we will have to build them.

C. Is there enough mass and orbital clearance for large space spheres?

It can be questioned that there is enough material in the solar system to construct a sphere with a radius equal to the Earth's distance from the sun or that swarms of independently orbiting space habitats can avoid colliding, but advocates assert that there is enough mass and space. A fundamental contributor, Freeman Dyson, in his first paper on what are now called Dyson spheres, stated "(T)he mass of Jupiter, if distributed in a spherical shell revolving around the sun at twice the Earth's distance from it, would have a thickness such that … (it) could be made comfortably habitable."[2] A more detailed analysis considered the masses of the inner planets and the rocky cores of the outer planets. "The inner system contains enough usable material for a Dyson sphere." And "With the extra material from the outer system, we get … enough for a quite heavy sphere."[3]

The problem of collisions is also thought to be avoidable. "In a type I Dyson Sphere all the structures orbit independently around the star, and their orbits are normal keplerian elliptic or circular orbits. … And if two orbits intersect, they can be adjusted by using solar sails, ion engines, magsails or similar low-energy devices."[3]

III. Adequate habitable volume

The habitable volume of a deep space platform intended for permanent occupancy should be of adequate size. The International Space Station (ISS) pressurized volume is 915.6 cubic meters. For the long term maximum number of six astronauts, this is 152.6 cubic meters each, but much of the volume is filled with equipment and materials.

The average size of a new house in the United States is about 2,500 square feet and recently 9 foot ceilings have become more common than 8 foot. Thus the average volume of a new house is 22,500 cu ft or 637.1 cu meters. For an average household of 2.5 people, this provides 254.8 cubic meters per person. Based on these numbers, 200 cubic meters per person seems a reasonable volume for one person.

This is much larger than the habitable volume NASA plans for exploration missions. NASA experts recommended a minimum acceptable habitable volume of 25 cubic meters per person.[4]

Depending the situation, much smaller volumes can be acceptable. The average Eskimo igloo is 3 or 4 meters in diameter and can house 5 adults. The volume of a half sphere with a radius of 2 meters is 18.2 cubic meters, giving 3.6 cubic meters per person.[5] An igloo is more a survival shelter than an adequate habitation.

The International Committee of the Red Cross recommends that shared prison cells or prison dormitories provide a minimum area of 3.4 square meters per person, roughly 8 cubic meters. However, they recommend a total space requirement for shared accessible areas of 20 to 30 square meters per person, roughly 50 to 75 cubic meters.[6] Future space settlers would probably not be confined to one habitat, but visit other habitats and platforms.

IV. Artificial gravity

Rotating spacecraft producing artificial gravity have been proposed many times, beginning with Tsiolkovsky in 1903. Most early designs for space stations assumed artificial gravity. Examples include the von Braun wheel, the Stanford torus, the O'Neil cylinder, and Zubrin's Mars Direct, discussed in the Appndix. Rotating spacecraft are the only way to provide artificial gravity in space and so are necessary for permanent human habitation. However, despite the obvious need and past plans, a rotating space habitat has not been built. The needed technology is available. Nearly all structural engineering has occurred in one g and the materials and the techniques are well known. Artificial gravity human spacecraft have not been built largely because of their much greater mass and launch cost. Other reasons are that zero gravity is tolerable for short periods, that zero gravity counter measures such as exercise have some effect, and that zero gravity is interesting for scientific and engineering research.

A. Problems of zero and partial gravity

Astronauts who spend many weeks or months in space in zero g suffer serious health problems including muscle atrophy, cardiovascular deconditioning, bone calcium loss, impaired vision, and immune system change.[7] Extensive exercise does not prevent these problems. The physical ability of astronauts to explore Mars after a more than year in zero gravity is questionable.

Clément and Bukley[8] discuss human performance in artificial gravity. The debilitating effects of weightlessness were first demonstrated on the longer Skylab, Salyut, and Mir missions, but it was mistakenly believed that in-flight exercise and resistance training would solve the problem. Being in microgravity or partial gravity can disturb postural balance, locomotion, eye-hand coordination, and spatial orientation. Short parabolic flight tests have shown that manual task performance at 0.2 g was much better than for 0.1 g, while 0.5 g seemed as good as 1 g. Long term artificial gravity may benefit the musculoskeletal and cardiovascular systems. Using artificial gravity produced by a centrifuge improves the orthostatic tolerance of both healthy and deconditioned persons. Orthostatic tolerance is the ability to prevent low blood pressure and dizziness when standing up. The improvement is due to improved heart stroke volume and was greater in those who exercised while under artificial gravity. Artificial gravity improves the post-flight orthostatic tolerance of astronauts, but cardiovascular deconditioning in space flight is not overcome by current countermeasures. However the use of small radius centrifuges can have negative side effects on the neurovestibular system. Coriolis forces can cause spatial disorientation, loss of coordination, and motion sickness. [8]

A systematic review by Richter et al. summarized "the different effects of partial gravity (0.1–0.4 g) on the human musculoskeletal, cardiovascular and respiratory systems."[9] They found that, "Partial gravity exposure below 0.4 g seems to be insufficient to maintain musculoskeletal and cardiopulmonary properties in the long-term. To compensate for the anticipated lack of mechanical and metabolic stimuli some form of exercise countermeasure appears to be necessary in order to maintain reasonable astronauts' health."[9] Some of their reviewed studies showed a strong correlation between heart rate, oxygen consumption, net metabolic rate and 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."[9]

Another reviewed model predicted a weekly loss of 0.39% in bone mineral density for the moon and a loss of 0.22% on Mars. "Provided the mathematical modeling is accurate, it appears that planetary stay times could be extended from ~100 weeks on Moon to 3 years on Mars (based on the assumption that until then a reduction of 66% in strength is attained) before a weakened skeleton could create serious hazards during the stresses of re-entry and returning to terrestrial gravity."[9]

The review concludes, "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."[9]

B. Rotating spacecraft design concepts

Different designs to provide artificial gravity have been proposed. The simplest is a single cable with a mass at each end, either both human habitats or one habitat and a module providing power, processing, storage, and other support. The most well-known design is a wheel or torus. A cylinder is probably the most advantageous, as it is easy to build and to expand, by extending the cylinder or adding concentric cylinders at different g levels.[5]

Split designs, with both rotating and non-rotating sections, have been suggested for transit missions. Rotation is a problem for directionally fixed functions, such as propulsion, communications, and solar power arrays. However, split rotating/non-rotating designs are complex, with large rotating joints to connect the sections and transfer people, material, power, and communications. An all rotating design is structurally simple and saves mass and reduces risk.[10]

C. Required radius and spin rate

Artificial gravity for long term human habitation is expected to be set at a Earth normal 1 g. Other g levels can be provided for processing and research. Increasing the force of artificial gravity produced by rotation requires increasing either the radius of rotation or the rotation rate. The usually assumed maximum spin rate of 4 rotations per minute (rpm) determines a minimum habitat radius of 56 meters.

The formula for the centripetal acceleration due to rotation is acceleration (m/s^2) = radius of rotation (m) * (2π 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 cylinder producing 1 g on the inner surface would be 112 meters.

The maximum rotation rate of 4 rpm is set to limit human susceptibility to the Coriolis effect, an apparent force felt in a rotating system. If someone in a rotating cylinder moves closer to the axis of rotation, they will feel a force pushing them in the direction of spin. The force acts on the inner ear and can produce disorientation and motion sickness.[6]

The maximum 4 rpm rotation rate sets the large minimum diameter of 112 meters to achieve 1 g. The desire to produce artificial gravity in smaller exploration spacecraft has led to investigations of higher spin rates. "Preliminary results suggest that in a few days, individuals can increase the spin rate at which the (Coriolis) illusion is imperceptible (e.g. 10 RPM)." [11] For 10 rpm, rotation producing 1 g can be achieved with a radius of 8.9 meters and a diameter of 17.8 meters.

D. Problems implementing artificial gravity

Despite long standing interest and the obvious need, artificial gravity has had relatively little engineering development. There are many possible reasons, including uncertain gravity level and rotation rate requirements, negative impact on necessary spacecraft functions such as propulsion, communications, and solar power collection, and the hope of developing more effective zero gravity countermeasures. Zero gravity itself has been seen as a resource for specialized manufacturing, and one purpose of the ISS is to exploit zero gravity. The greatest barrier to implementing artificial gravity has probably been its expected high launch mass and consequent high cost.[6]

E. Further advantages of 1 g artificial gravity

Earth-like gravity provides advantages for habitation equipment and human activity, essentially by establishing a wide commonality and synergism with terrestrial activities and by eliminating the special challenges of zero gravity.

Human activities that must be provided for on a spacecraft include food preparation, dining, waste handling, personal hygiene, clothing, waste handling, recreation, exercise, medical treatment, housekeeping, storage, maintenance, and sleep accommodations. The cost of developing and testing equipment for all these activities for Earth normal gravity is much less than for zero gravity and the risk of a mistake or oversight is much lower. Showers and sinks will not need vacuums to control free-floating debris. Food preparation can be modeled on an Earth-based kitchen and use similar appliances and cooking techniques. The 1 g environment will allow the use of beds, chairs, desks, and other familiar furniture.[6]

A 1 g system operating environment would allow designers to base their systems on Earth-based analogs. Similar or identical appliances and procedures can be used. New designs can be tested on Earth, decreasing the cost and allowing reliability to be easily improved, tracking Earth advances.[6]

Human physical activities can be much better understood, planned, and conducted in 1 g. Work, exercise, and sports at low spin rates can proceed as on Earth. Perceptions of difference, strangeness, and disorientation would be reduced by the inclusion of familiar objects and activities.

V. Radiation shielding

Earth is largely shielded from radiation by its magnetosphere, but cosmic background radiation and solar flares can be harmful to humans in deep space, and even on the moon and Mars, which lack magnetic fields. The Earth's magnetosphere creates the Van Allen belts of trapped particle radiation, which can also be harmful to space travelers.

Radiation consists of high energy particles such as electrons, protons, neutrons, and atomic nuclei and of photon or wave radiation including gamma rays and X-rays. Charged particles can damage humans and electronics by ionizing their atoms. Radiation is measured by particle flux (particles/cm^2/sec) and by particle energy in mega-electron volts (Mev).

A. Van Allen radiation belts

The Van Allen belts consist of trapped high energy electrons and protons. The particles originate in the solar wind or by cosmic ray radiation hitting the upper atmosphere. The electrons are found in two donut shaped regions above the Earth's equator, with the inner belt strongest at 2 Earth radii and the outer belt at 5 Earth radii. The protons peak near 3.5 Earth radii.[12 13]

Van Allen belt radiation is a minor exposure for astronauts crossing to deep space, but can be serious in Earth orbits. For the electrons and protons found in the Van Allen belts, the effective radiation dose depends directly on the particle flux and is less affected by any variations in the particle energy above 0.1 Mev. The Earth's magnetic North pole is offset from the true rotational North pole by about 12 degrees, and this creates a region with a weak magnetic field and high intensity Van Allen radiation called the South-Atlantic Anomaly (SAA). The charged particle flux can be 100 times greater than average in the SAA, which can be as low as 200 km above the Earth's surface. Reduced EVA and increased shielding are suggested for space platforms traversing the SAA.[12 13]

B. Solar radiation

The solar wind is a high density flow of electrons and protons that produces the Van Allen belts but is not itself hazardous because the particle energy is low, typically less than 0.01 Mev. The major radiation hazard in space is due to Solar Particle Events (SPEs), which are sometimes referred to as solar flares or solar storms. SPEs produce radiation at frequencies from radio to X-rays and particles including electrons, protons, and heavy nuclei. They are associated with ejections of coronal mass. The particles move in all directions, nearly always away from Earth. Solar flares are unpredictable but are more likely near the maximum of the 11 year sunspot cycle.[8, 9]

Smaller flares are frequent but dangerously large flares are rare. Particle energies can reach 1,000 Mev and the radiation dose can increase a thousand times in minutes. During the Apollo program in August 1972, an SPE was big enough to have induced radiation sickness in an astronaut on the moon's surface, if one had been present. SPEs can build up in minutes and last for hours. Attempts are being made to observe their occurrence and provide some minutes of warning. Very heavy shielding of the entire space platform or of a storm cellar are reasonable SPE mitigations for habitats beyond the Van Allen belts.[8, 9, 14]

C. 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. Cosmic rays are reduced by a factor of two during the solar sunspot maximum, when the solar magnetic field is strongest.[8, 9]

Even though galactic cosmic rays have high energy, they cause relatively little radiation damage compared to solar flares because of their low flux density compared to solar flares. It has been considered impractical to shield a spacecraft on a Mars mission against cosmic rays. A solar flare presents a vastly greater risk. A typical solar flare would increase the background cosmic ray energy by factor of ten, and a 10% worst case solar flare would increase it by a factor of nearly a million. The August 1972 event was another factor of ten larger, producing ten million times the energy of the cosmic back ground radiation.[12 13]

Nevertheless, minimally shielded galactic cosmic rays over a long period would very greatly increase cancer mortality. With typical aluminum spacecraft shielding, the deep space cosmic radiation is about 1.5 mSv per day during the solar minimum and about half that, 0.8 mSv per day during the solar maximum.[15] In one year in deep space an astronaut would accumulate 0.30 to 0.55 Sv of cosmic radiation.[15,16] Predictions of the increased cancer risk of cosmic radiation are very uncertain.[16] A rule of thumb is that 0.2 Sv increases the risk of a fatal cancer by 1%.[11] This suggest that cancer risk would increase by 1.5 to 2.8% per year of exposure. Another estimate suggests 2.4% per year but ranging up to several times higher.[16]

Men in the US have a 40% chance of developing cancer in their life time and a 22% chance of dying from it.[17] Persons spending most of their lives on a minimally shielded permanently inhabited space platform would have reduced lifespans due to the very high risk of cancer. Only the other mortality risks and early deaths would keep the cancer risk significantly less than 100%. Without significant medical advances, a permanently inhabited deep space platform will require cosmic ray shielding.

D. Shielding mass and cost

Shielding is required to protect astronauts from brief but potentially life threatening solar flares and from constant low level but damaging galactic cosmic rays. Passive bulk shielding is the only realistic approach, but it requires high mass for adequate protection.

Aluminum is used in spacecraft walls, typically with a mass of a few grams per cm^2, but this is insufficient. Lighter elements such as hydrogen, oxygen, and carbon provide more shielding per unit mass, so water and plastic can be used.[13] Water used for life support and oxygen, hydrogen, and other propulsion fuel can be used for shielding.[10]4

The August 1972 solar flare would have subjected an astronaut in space or on the moon to 1.3 Sv, creating a 25% chance of radiation sickness. One design of a safe haven for solar flares is a 2 meter diameter aluminum sphere with 7.5 cm thick walls, weighing 20 g/cm^2 and a total of 2.5 metric tons (MT).[13] [14] The safe haven volume is 4.2 m^3, the size of a single person igloo but tolerable for several people for a few hours. Since the solar flare rays proceed directly from the sun, a flat plate shield would be more mass-effective. At the current projected low launch cost of $1 k/kg, or $1 M/MT, this safe haven would cost $2.5 M to launch to LEO.

Reducing galactic cosmic ray exposure is more difficult. Since galactic cosmic rays are constant and omnidirectional, any habitation volume where the crew spends more than a little time 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.[10] A spherical habitable volume of 200 m^3, adequate for one crewmember, would have a total surface area of 165 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 82 MT. At the cost of launch to LEO of $1 M/MT, these shields would cost $13 M and $82 M per crew member to launch to LEO.

VI. Providing shielding and 1 g on Mars

The two major challenges to establishing a permanent base on Mars, as elsewhere in space, are providing shielding from occasionally intense solar radiation and countering the effects of partial gravity. One idea for shielding is to create underground habitats with Martian regolith, which is freely available in unlimited quantities. “Other possibilities include excavating subterranean spaces, or sealing the ends of an existing lava tube.”[18] In general, most Mars habitat designs consider radiation shielding but few consider artificial gravity.

An interesting idea for creating 1g on Mars is a large rotating underground wheel. “(T)he outer wall of the wheel (the floor where people walk) must be tilted to give an effective 1g gravity 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.” The wheel diameter and rotational speed are adjusted to provide 1g, and the angle of the floor is set to be perpendicular to the 1g force. Other possibilities include an exercise regime or personal centrifuges used for several hours a day. [18]

VII. Long term expansion into the solar system using permanent deep space stations

It is reasonably hoped that humans can expand from Earth into the solar system, capturing much of the sun’s energy to support a solar civilization. This will require permanent deep space habitats with artificial gravity and radiation shielding. The metal for rotating habitat construction could be obtained from planets and asteroids, while hydrogen, oxygen, and carbon for shielding, propulsion, and life support could be obtained from comets and the outer gas giant planets and their satellites. Scientific and technical productivity seems to increase with the number of interacting individuals and their ability to cooperate and specialize.[19] Human expansion into the solar system would make possible scientific, technical, economic, political, and social advances that are now unimaginable.

This vision of the future differs from the conventionally accepted expectation of human settlements on the moon, Mars, and possibly the asteroid belt and outer planets’ moons. In this view, transparent domes will provide atmosphere and partial gravity and radiation are not problems. Advances in space exploration have shown that these earlier ideas are implausible. The moon lacks an atmosphere and magnetic field, and so would require the same radiation shielding as deep space. Although it has not been determined, the moon's weak 1/6 gravity is not likely to fully counteract the effect of zero gravity weightlessness. If it was acceptable, artificial gravity at 1/6 g would be much easier to provide than 1 g in a deep space platform. The moon's month long solar cycle and consequent extreme temperatures are additional problems not found in deep space.

Mars has a thin atmosphere and no magnetic field, but the solar wind interacts with the atmosphere to create a magnetosphere. The Mars atmosphere 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.[13] Mars gravity at about 1/3 g is stronger than the moon's, but 1/3 g is clearly insufficient to eliminate the serious health problems caused by zero gravity.[9] Solar light radiation is lower at Mars' distance from the sun and temperatures are much colder.

Operations in the asteroid belt or near comets would require platforms similar to those needed for deep space. Visiting the outer planets or their moons would also require artificial gravity and radiation shielding.

Combining the moon, Mars, and asteroids, the extent of potential human expansion on planetary bodies is not much larger than that provided by the Earth alone. Large scale expansion and exponential human growth require expansion into the empty solar system using habitable space platforms.

VIII. A near term permanent space platform in low Earth orbit

Although permanent human habitations in deep space will require both artificial gravity and radiation shielding, a permanent station in LEO can avoid high radiation and the need for shielding. A location in LEO provides easier access, quick communications, and the potential for many Earth-oriented applications.

A permanent station in LEO has recently been proposed.[20] [21] The planners modify the two fundamental decisions about rotation rate and shielding mass that were made in "The High Frontier," O'Neil's 1970's space colony concept. That design assumed that a low rotation rate of 2 rpm was required to prevent motion sickness. Since then a rotation rate of 4 rpm has usually been considered acceptable, and current studies may allow higher rotation rates. The 1970's design assumed the space colony would be in deep space and so require massive radiation shielding. The proposed new permanent station will be in Equatorial Low Earth Orbit (ELEO), at about 500 kilometers high, in an orbit avoiding the South Atlantic Anomaly. The required radiation shielding would be a few g/cm^2, no more than in typical spacecraft construction.

IX. Conclusion

The human future in space will not be what has usually been thought. Permanent deep space stations with artificial Earth normal gravity and heavy radiation shielding will fill the solar system. The colonization of the moon and Mars would require similar radiation shielding and may be fundamentally infeasible if their partial gravity is insufficient for human health. The additional living space obtainable on the moon and Mars is not large compared to the uninhabited space on Earth, while space is vastly more extensive. Permanent space stations can be developed in two stages. Artificial gravity stations without radiation shielding can be deployed in LEO. Radiation shielding can be added in permanent human habitats for deep space.

Appendix: Proposed Artificial Gravity Space Habitats

Rotating spacecraft producing artificial gravity have been proposed many times. The major concepts for a rotating artificial gravity habitat are a wheel or torus, a sphere, a cylinder, and a habitat and other mass joined by a tether. The better known historical concepts are listed in Table A.1.

Table A1: Proposed artificial gravity space habitats.

Year	Author	Concept	Reference
1903	Konstantin Tsiolkovsky	Spinning space vehicle. Concept 1888, publication 1956.[8, 22, 23]	B 1 C
1929	Hermann Noordung (Herman Potočnik)	Rotating wheel with 30 meter diameter.[22, 8]	
1929	John Bernal	A hollow nonrotating spherical shell with a 10 mile diameter. [24, 25, 8]	2 B 3
1952	Werner von Braun	Rotating wheel, 76 meter diameter, 0.3 g for Mars transit. [26]	4 C
1977	Gerard O'Neil	Rotating Bernal sphere, 1,800 meter diameter. [27, 28] O'Neil rotating cylinder, five mile diameter, 20 miles long. [29]	5 6 7
1977	Johnson and Holbrow	Stanford torus,1.1 mile diameter rotating wheel. Larger version of von Braun's wheel. [30]	8
1990	Robert Zubrin	Rotating tethered booster and habitat for Mars transit.[23, 31]	9 C

Noordung, von Braun, and Zubrin propose smaller habitats for interplanetary travel, the latter two specifically for Mars transit. Bernal, O'Neil, and Johnson and Holbrow with the Stanford torus propose larger habitats with dimensions of miles for permanent human settlement in space.

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