INTERNATIONAL ACADEMY OF ASTRONAUTICS

Missions to the outer solar system and beyond

SEVENTH IAA SYMPOSIUM ON REALISTIC NEAR-TERM ADVANCED SCIENTIFIC SPACE MISSIONS

Aosta, Italy, July 11-14, 2011

SHELL WORLDS

1. Kenneth I. Roy, PE; 2. Robert G Kennedy, PE; 3. David E. Fields, Ph.D.

1,2. The Ultimax Group Inc., 112 Mason Lane, Oak Ridge, TN, USA, 37830;

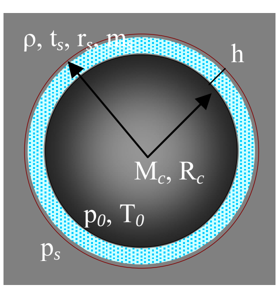
3. Tamke-Allan Observatory, 3818 Guinn Road, Knoxville, TN, USA, 37931

1. kiroy@att.net; 2. robot@ultimax.com, 3. fieldsde@aol.com

ABSTRACT

The traditional concept of terraforming assumes ready availability of candidate planets with acceptable qualities: orbiting a star in its "Goldilocks zone", liquid water, enough mass, years longer than days, magnetic field, etc. But even stipulating affordable interstellar travel, we still might never find a good candidate elsewhere. Whatever we found likely would require centuries of heavy terraforming, just as Mars or Venus would here. Our increasing appreciation of the ubiquity of life suggests that any *terra nova* would already possess it. We would then face the dilemma of introducing alien life forms (us, our microbes) into another living world. Instead, we propose a novel method to create habitable environments for humanity by enclosing airless, sterile, otherwise useless planets, moons, and even large asteroids within engineered shells, which avoids the conundrum. These shells are subject to two opposing internal stresses: compression due to the primary's gravity, and tension from atmospheric pressure contained inside. By careful design, these two cancel each other out resulting in zero net shell stress. Beneath the shell an earthlike environment could be created similar in almost all respects to that of Home except for gravity, regardless of the distance to the sun or other star. Englobing a small planet, moon, or even a dwarf planet like Ceres, would require astronomical amounts of material (quadrillions of tons) and energy, plus a great deal of time. It would be a quantum leap in difficulty over building Dyson Dots or industrializing our solar system, perhaps comparable to a mission across interstellar space with a living crew within their lifetime. But when accomplished, these constructs would be complete (albeit small) worlds, not merely large habitats. They could be stable across historic timescales, possibly geologic. Each would contain a full, self-sustaining ecology, which might evolve in curious directions over time. This has interesting implications for SETI as well.

Keywords: circumstellar habitable zone; geoengineering; megastructure; SETI; space colonization; terraforming



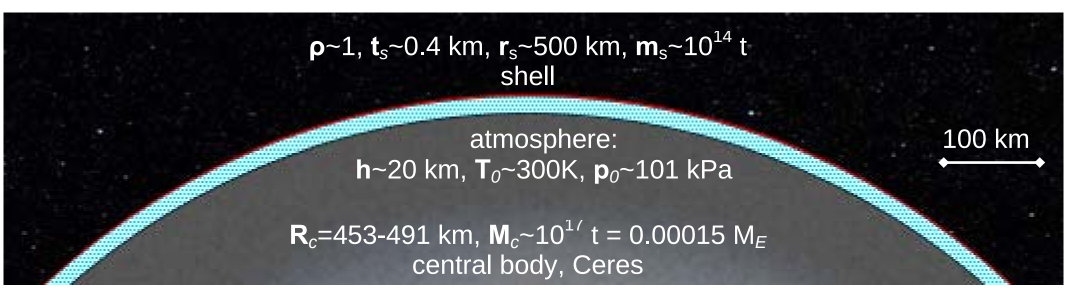


Fig. 1. Diagram of notional shell -- not to scale (*left*) **Fig. 2. Side-view of enshelled Ceres -- to scale** (*right*)

NOMENCLATURE

G = universal gravitational constant, 6.67 E-11 [N m^2 kg^{-2}]

M_c = mass of central body [kg]

p_s = atmospheric pressure @ shell altitude, [N m^{-2}]

p_0 = atmospheric pressure @ "sea level", [N m^{-2}]
MW = molecular weight of atmosphere [kg mol^{-1}]
t_s = shell thickness (stress-bearing), [m]
r_s = shell radius from barycenter, [m]
R_c = radius of central body [m]
R = ideal gas constant
T_0 = air temperature [K]
h = atmospheric height, [m]
ρ = shell density, [kg m^{-3}]
m_s = mass of shell [kg]

INTRODUCTION

Imagine a starship which has finally arrived at its destination after a long voyage of perhaps generations. Now the colonists, distant descendants of the ones who sallied forth, are faced with life in a new home outside the ship. Where to live? How will they raise their children to know what it is to be fully human? Our heritage and culture evolved over millions of years living on this planet; we cannot just put that aside. The descendants of far travelers will have the choice of either adapting themselves to new conditions, perhaps by genetic engineering, or the other way 'round -- creating Earth-like conditions so unmodified people can start new lives around alien stars. Where the first path will lead is an open-ended imponderable. Let us consider the second.

1. LOTS OF PLANETS BUT NOT ENOUGH HOMEWORLDS

Planets appear to be plentiful in our galaxy. More worlds, more types of worlds, as well as a bewildering variety of entire solar systems, are discovered almost every day. As we venture into space it would be nice to find countless Earth-like planets having breathable air, lots of liquid water, and no allergens, toxins, or pathogens. Moderate temperature, reasonable gravity, low background radiation, polite neighbors, etc., would all be nice, too. A colony would land and live happily ever after. But as time goes on, we increasingly appreciate the ubiquity, tenacity, and protean nature of life, which suggests that any *terra nova* would already have it, as well as a complex ecology, but probably incompatible or even toxic to us, due to the vast number of random directions evolution can take. Bad interactions with unexpected results have occurred, both ways, right here on *terra firma*.

At the dawn of the Space Age, Stephen Dole of the Rand Corporation estimated in his 1962 classic *Habitable Planets for Man* that 1 in about 200 stars has a *habitable planet*.[2] Space explorers would have to look through a spherical volume 25 light-years in radius to have a good chance of finding just one such world. Other estimates put the necessary search radius at 100 to 1000 light years, while the discovery this year of over a thousand possible extrasolar planets by the Kepler Space Observatory, including a half-dozen potentially habitable candidates, suggests just the opposite. Habitable planets may not be not as common as we would like, or if they were, by definition already possess life, which may not react well to alien invaders (us), or the other way 'round.

In *Islands in the Sky*, Martyn Fogg defines two more types of planets that our spacefaring descendants would seek.[3] The second is a "*biocompatible planet*". This possesses the necessary physical parameters for life to flourish on its surface, but is initially lifeless. With the introduction of Tellurian biota, it could host a complex ecology without heavy-duty geoengineering. The third is an "*easily terraformable planet*", which could be rendered biocompatible, and ultimately habitable, maintained with modest geoengineering techniques. All of these must lie within, or at least very close to, a star's circumstellar habitable zone.[4] This "Goldilocks Zone" is a fairly thin shell around a star where the stellar output maintains a planet's temperature above freezing but below the boiling point of water. In our solar system, Venus and Mars are just outside the habitable zone. Earth (with Luna) sit comfortably in the middle of it (but we need the greenhouse effect nevertheless). None of the other hundred or so worlds of our sun (Mercury, gas giants' moons, minor planets, and plutoids) are in the Zone.

According to Dole, stars smaller than 0.72 solar masses don't have a habitable zone at all, because a planet close enough to such a star to be warm enough, quickly gets tidally locked around that star. A day becomes a year. One hemisphere always stares at the star (like the Man in the Moon to us) and broils, as well as being bombarded by frequent flares common to small suns; the other faces the dark 2.7K universe and freezes. Only the terminator, a band of perpetual twilight, might support some kind of tough crepuscular life. Dole also argues that any planet must be greater than 0.4 Earth-masses (M_E) in order to hold on to enough atmosphere to become habitable. This criterion lets out Mercury but also eliminates Mars.

So the problem with planets which we can live on is that there do not appear to be enough of them. Many stars will have none at all. Ones we do find are probably going to require a lot of work before we can move in.

2. THE TROUBLE WITH CLASSICAL DOMES, AND TUBES

The domed city on an airless world is a staple of science fiction literature. It looks impressive on the silver screen and provides a controllable atmosphere with reasonable gravity (which saves a lot of money on the special effects budget). Domes can be fitted out as tolerable, even pleasant, places to live and work, with all the material and energy resources that a whole world has to offer, just outside the airlock. The problem arises from the fact that even a small pressure over a large surface results in huge forces and stresses. Just a modest dome of 300-meter (m) radius containing Earth-normal pressure requires steel walls 10cm thick, with no windows and no safety factor! Since the equation for wall stress in a pressure vessel is linear, a dome *twice* as big will need *twice* the wall thickness (0.2m!) to hold the *same* internal air pressure. Barring the discovery of *unobtanium*, *balonium*, or *wishalloy*, or some other outlandish material which is also transparent, actual domes on airless worlds will be small and dark -- suitable for outposts or research stations, but not long-term homes for people.

Things are no better offworld. An O'Neill-style space colony is a pressurized tube rotating in space. The spin generates centrifugal acceleration which serves as artificial gravity. For several reasons, such as avoiding motion sickness, the rotation rate should not exceed 2 rpm.[7] To generate Earth-normal gravity, this condition constrains the radius to 225m. If the spin is halved to 1 rpm, the radius quadruples to 900m, and so does the stress! Bernal's eponymous sphere, a stronger, more efficient shape than a cylinder, suffers from the same basic material problem, and would only have full gavity at its equator anyway. Even with very high-strength material, say titanium instead of steel, the walls of space habitat would be thicker than a modern tank's armor or a submarine's pressure hull. With windows, the situation would be much more dangerous due to stress concentration.

This is not to say that O'Neill-style space habitats are impossible. We can change design parameters, or use stronger stuff to make them work. But, like most other materials, metals under significant stress for long periods of time creep and eventually fail. How long would a typical habitat last before rupture? Centuries? Perhaps. Millennia? Probably not. How many lives are we willing to bet on the answer? Absent amazing new materials, habitats may be adequate temporary housing for space construction workers, but not for permanent occupation.

3. THE SHELL WORLD APPROACH

If we could build a rigid shell of matter around a world to contain an atmosphere, keep out radiation, and regulate heat, many of the limitations discussed in the previous two sections disappear. Suddenly Mercury, Mars, Luna, the bigger moons around the gas giants, and even some plutoids and minor planets become candidates for future homes for humanity. Applying the Copernican Principle, worlds like these must also be fairly common around other suns, even the numerous small stars under 0.72 solar masses.

This megastructure would be a rigid hollow sphere, as shown in Figure 1. The tensile stress in a pressure vessel the size of a planet, floating freely by itself in space, would be far too great to be borne by any material we know of today. But, when wrapped around a planet, a *second force* enters the picture: *gravity*. A mass in the middle of a hollow sphere would pull on that sphere, causing compression. If the central mass was just a small planet, the compression due to gravity would still be huge; even a thick armor-steel shell would crumple like foil or wet tissue paper. If we are clever, we can make the two forces cancel out, resulting in as close to zero net shell stress as we care to achieve. Think about that for a minute. The world within would have an Earth-normal atmosphere, securely contained, which will never leak away. The shell that holds it is under little if any stress and could survive for millennia. Add a little heat and you could comfortably walk the surface of any world in the solar system without a spacesuit. Granted, it would be pitch dark under there, but we will come to that.

Setting compressive stress, $\boldsymbol{C}$, (on the left) equal to tensile stress, $\boldsymbol{T}$, (on the right) in Equation (1) below, it has been shown that the necessary density of the shell, $\boldsymbol{\rho}$, [kg m^{-3}] is directly proportional to the atmospheric pressure contained within, while the required thickness of the shell, $\boldsymbol{t_s}$, is proportional to the major radius squared.[8]

$$C = \frac{GM_c\rho}{2r_s} = \frac{p_s r_s}{2t_s} = T \tag{1}$$

The smaller the central world, the more massive, hence thicker, the shell must be, in order for that world's weaker pull of gravity to induce enough compression in the shell to counteract the tension from the fixed atmospheric pressure within. Enough mass must be provided to hold the internal pressure at the high end of the internal temperature range, while the rigid shell must yet be flexible enough to allow for normal expansion and contraction due to internal temperature cycles. Markedly asymmetric central bodies, such as the large asteroid 4 Vesta, or the Kuiper belt object Haumea, might not be suitable for englobing, due to the resulting nonuniform distribution of stress in the shell. (The limits of this symmetry parameter will be explored in a future paper.) Basic parameters for several familiar bodies in our solar system are shown below in Table 1. Mercury tends to buck the trend of progression because it is denser than anything except Earth. The dwarf planet 1 Ceres (bottom row in the table), is depicted approximately to scale with its atmosphere and shell in Figure 2 on page 1.

	avg $\mathbf{R_c}$ [km]	$\mathbf{t_s}$, if steel [m]	shell mass, m_s [tonne]	sectional density [tonne m^{-2}]
super-Earth (~3 M_E)	*~8,000*	0.87	7.01 E+15	6.9
Earth, M_E	6,378	1.31	5.28 E+15	10.4
Mars (~0.1 M_E)	3,393	3.49	3.98 E+15	27.6
Mercury (~0.05 M_E)	2,439	3.48	2.05 E+15	27.5
Luna (~0.01 M_E)	1,738	8.05	2.43 E+15	63.6
Ceres (~0.00015 M_E)	472	45.2	1.24 E+15	357.2

Table 1. Parameters of Notional Steel Shell around Various Central Bodies

Because the shell is under such low stress it is possible to make it out of almost anything. Most of the mass is dead weight, needed to give the central body something to tug on to induce compression. In the case of our moon, a steel shell 1m thick with about 60m of regolith (lunar "dirt") dumped on top of it would have the same mass and wall stress as a solid steel shell 8m thick. Infinite combinations of metal, ice, dirt, and rocks are possible; but whatever mix of building material is selected, it must be airtight and the mass must be evenly distributed.

4. ORDERS OF STABILITY?

A shell around a world as described above has previously been shown to be statically stable, i.e., stable to the zeroth order.[8] We demonstrate with thought experiments that it is dynamically stable to the first order as well.

A ring around a star, if disturbed, has no restoring force. Positive feedback and the inverse square law will progressively pull the closer edge into the star, leading to an exciting but ultimately sad doom for any denizens of the ring. The author of the *Ringworld* series handled this problem by having his Engineers install control jets.[6]

There is no gravitational potential across the inside of an isolated, hollow, spherically symmetric shell.[5] But it can be shown that potential for a restoring force does exist in a *two*-body concentric system in which $\mathbf{M_c} \gg \mathbf{m_s}$. (In Table 1 above, the smallest world, Ceres has the most massive shell with respect to its central body, yet the $\mathbf{M_c}$:$\mathbf{m_s}$ ratio is still over 1000:1.) The central world's gravipotential field is superposed on the shell's. This force, which is just a few percent of the central body's total pull on the shell and linear with displacement, resists disturbance of the shell off the system's barycenter, acting to restore symmetry in a negative feedback loop.

Another independent restoring force also exists. It is an effect of scale height and differential air pressure which also acts, internally, to resist displacement of the shell off the system's barycenter.

$$p(h) = p_0 Exp\left[\frac{GM_c MW}{RT_0}\left(\frac{1}{r(h)} - \frac{1}{R_c}\right)\right] \tag{2}$$

Atmospheric pressure falls off exponentially with height, per (2) above. Imagine displacing the central body in Figure 1 to the left by $\boldsymbol{h}$, so that the shell's ceiling just grazes the ground. The inside surface of the left-hand side of the shell now feels the maximum air pressure (p_0), which pushes to the left against the shell. The shell on the opposite right-hand side feels much less air pressure ($p_{(h)}$), since pressure falls off with height, which is now $2\boldsymbol{h}$. The leftward push overcomes the rightward push, resulting in net force, and motion, to the left, thus restoring the shell's symmetry around the system's barycenter. The shell then oscillates back-and-forth in simple harmonic motion, but the atmosphere's friction and viscosity would eventually damp this out like a shock absorber.

5. LIFE INSIDE A SHELL

The mass and size of the celestial body will determine the gravity and surface area of the new world. Large terrestrial worlds like Venus and Earth already have atmospheres. Englobing them with shells would be difficult and redundant, but not impossible. They are at the upper end of the probable size range for shell worlds, since traditional terraforming is adequate for large planets already inside their star's ecosphere.

The dwarf planet 1 Ceres, just 0.00015 M_E, and 0.08 R_E, represents perhaps the smallest world that could be englobed. The shell would be very thick, carrying 36 kg of mass for every square centimeter of shell area. This is a lot of mass, hundreds of meters thick, but it would be an effective thermal insulator and absorb radiant energy in either direction. It would make such a fine shield protecting the dwellers within from large does of hard radiation that they would survive a nearby supernova better than their relatives back on Earth. Smaller bodies such as Ceres also offer the prospect of subterranean galleries and mine shafts that could be utilized for living space or industrial facilities after resource extraction. If all of Ceres was occupied – half a billion cubic km – it would be equivalent in volume to a 1-km high building covering the entire surface of Earth, including oceans!

Shell height above the surface of the world is a design choice, limited only by the amount of gas available to import. It needs to be high enough to accommodate the maximum difference between the equatorial and polar radii of the central body, as well as the maximum temperature variation inside. Ceiling features must be far up enough clear any tall ground features, with some safety margin, because the shell will freely rotate with respect to the central body, which will also retain its Original Spin. Pressures other than 101 kPa, and compositions other than 21% O_2-79% N_2 are possible. On a world with light gravity, extra thick air, and maybe a little extra pO_2, human-powered flight would be possible -- an amazing way to stay fit.

Area and depth of waterbodies is another design choice. Once an atmosphere exists, the presence of water will lead in short order to lakes, seas, and maybe oceans, even on low-gravity worlds. Large bodies of open water are indispensible for regulating / moderating temperature and vital to life. Climate can be a choice as well. The entire world can be temperate, or it can be configured to have frozen poles and a tropical equator with resulting weather patterns. It can be a hot desert, or a cold iceball.

There is no reason structures cannot be attached to the underside ("ceiling") of the shell provided that enough dead weight outside over that point is removed to compensate. Inverted cities and hanging gardens would be sights to see; their view would change every day due to the two superposed rotations of the shell and central body. The entire ceiling might be utilized for living space effectively doubling the useful land area of the shell world. Heavy industry could be located outside on the "roof" for ready access to vacuum and space transportation.

However, everything beneath the shell would be in total darkness without artificial lighting. Penetrations must be minimized as they are the likeliest points to fail over the long run. Large windows are likewise out of the question, barring some new material. But artificial lighting, color, intensity, and patterns in time and space provides an infinite palette of choice. People need light to see but plants need light to live. Terrestrial plants only use about a sixth (250 W/m^2) out of the 1400 W/m^2 streaming in at Earth orbit from the sun -- mainly in the blue-violet and orange-red ends of the spectrum. This much is the bare necessity. UV can shine over beaches for essential tanning, while IR could control sensible temperature. The lights could always stay on in some places with eternal night in others, or cycle sequentially like Home, or turn on/off worldwide all at once. Heating and cooling comes in two flavors: If the shell world is too close to a star, e.g., Mercury, the challenge is to minimize heat gain while maximizing ways to dump excess heat. Far out in the Oort Cloud, it is the other way round.

Any space settlement must consider acceptable limits for radiation exposure.[1] On Earth, the average person absorbs 30 millirem (mrem) annually from space radiation, out of a 360 mrem total annual dose. Most of that is from terrestrial sources such as radon, because most charged particles are deflected by Earth's magnetic field, or to some extent, the Sun's. But gamma rays and some relativistic heavy ions get through and are attenuated only by our atmosphere. Moderate doses do elevate cancer risk, and even without that, high doses of radiation can kill.

These are all engineering problems. Answers will no doubt depend on access to large amounts of power, but a civilization that can build a shell probably has the ability to accomplish any goal which can be stated logically. Construction of a shell world requires energy and material inputs, plus fabrication and transport around the solar system, on literally astronomical scales. Only by an advanced civilization capable of making and using large quantities of antimatter could pull off this feat, for that is likely the only energy source dense enough for the job.

6. MAKING A SHELL -- EASY AS 1-2-3

Take Luna. We could just as well choose Mercury or Pluto but assume we have somehow obtained rights to Earth's moon. The designers specify an atmosphere 20 km thick. They also want an ocean which covers a fourth of the surface to an average depth of 100 m. City sites and future forests are laid out. Rough landscaping is done with kinetic energy: rocks from space notch crater rims to connect future seas and lakes, raze or raise mountains as desired, level plains. Fine sculpting is done by robot dozers. Ice comes from gas giants such as Jupiter, or diverted from the Oort cloud where countless comets have waited billions of years for something like this to happen. About 1 quadrillion tonnes of it is delivered and stored in the future ocean basins. The 20-km blanket of air masses another petatonne. Oxygen can be made on the Moon by roasting regolith, or imported from Venus (leaving behind an amazing amount of carbon black). 200 trillion tonnes (teratonnes) of O_2 is needed. Nitrogen can come from Titan or the Kuiper belt. Over three times as much of N_2 is needed, 800 teratonnes. Add a pinch of argon to make our air truly Earth like, a mere dekateratonne or so – all in a century's work.

Automated factories now start rolling out meter-thick carbon-based fabric, perhaps nanotubes made of carbon recycled from Venus. This textile is stronger than steel, airtight, and corrosion resistant, yet flexible enough to stretch about 1 percent to cope with temperature fluctuations. (Why so little? Even if the volume of the thin shell of air doubled, the shell's radius is about the same as the central world's; hence the change in linear dimensions in only a few percent. See Figure 2.) We drape the entire surface of the moon with it and seal up the seams. Drop steel armor over it, meter-thick plates fabricated from a smallish nickel-iron asteroid, connected in a geodesic pattern to flex with the fabric underneath. Atop all, 50m of regolith gets dumped to reach a total loading of 64 [t/m^2]. Large structures, hanging inside or standing outside, are sometimes substituted for regolith mass.

Now we slowly release the oxygen, nitrogen and argon under the shell and heat it (perhaps with Dyson Dots!) The shell levitates off Luna. The pressure underneath remains 101 [kPa]. More gas is released, the shell eventually reaching 20 km above the lunar surface. Next, we melt the ice for oceans. All the *maria* get filled with water of course, at long last living up to their ancient misnomer. (The *aqua nova* near side would be quite beautiful from Earth, if only the Terrans had X-ray vision to peer through the shell.) Lights and communications are hung inside the ceiling, all run by power plants located on the outside of the shell.

Now comes the hard part. We introduce life from Earth to its new home and tenderly nurture what once was a sterile world into a vibrant living ecosystem. It will have been a long and expensive enterprise, but at the end we will have a new home and all the other forms of life that shared Earth with us will, too. Except perhaps certain pests and parasites. Could we not do without fleas and mosquitoes?

THE INTERSTELLAR PERSPECTIVE

Shell worlds could be constructed at any star that has something larger than Ceres, but smaller than Earth, revolving in it. The type of star doesn't matter. The extent or even existence of the star's habitable zone doesn't matter. The radiation environment does matter but can be dealt with. In high radiation fields we want smaller bodies, for thicker, more massive shells. Such shell worlds could last for many millennia, and with proper maintenance and gradual improvements could go longer, perhaps for geologic time.

The most common type of star in our Galaxy is the small, unassuming, red dwarf – the multitudinous M-class stars massing less than 0.45 of Sol's. Until now SETI and world hunters have overlooked them. This may be a mistake. Such stars probably have many bodies suitable for transformation into shell worlds. They have trillion-year life spans -- many times longer than our sun.

There are probably even more brown dwarfs (or failed stars) in our Galaxy than red dwarfs, not to mention rogue planets. Many probably have satellites suitable for shells. Indeed, it is possible that an advanced but introverted civilization may come to prefer small red stars and brown dwarfs as quiet places to get away from it all. If the universe is a dangerous place, and we have no reason to think it isn't, then a shell could be covered with regolith that is carefully re-sculpted to mimic the original surface of the moon or planet. It would have a slightly greater radius but otherwise could look exactly the same. Explorers, space pirates, xenophobes and would-be xenocides might overlook such a camouflaged world entirely.

Shell worlds offer the chance to convert virtually any solar system with some orbital debris into a cozy home for life. When we finally head to the stars, we won't be limited to looking only for the rare precious jewels -- habitable worlds -- and taking them away from somebody else. We will transform lifeless planets and other junk of the cosmos into living Earth-like environments. Surely, the elder races can't fault us for that.

ACKNOWLEDGMENTS

The authors acknowledge the following persons who contributed to or reviewed the "Shell Worlds" concept over the years: David Bowman Ph.D.; B. Derk Bruins Ph.D.; Dwayne A. Day Ph.D.; H.Keith Henson; Les Johnson; Michael R. Johnson; Greg Matloff Ph.D.; Amarak Panya, John Wharton; and David Woolsey.

REFERENCES

1. Corliss, WR, *Space Radiation* (U.S. Energy Research and Development Administration, Washington: 1968)
2. Dole, SR, *Habitable Planets for Man* (Blaisdell Publishing, New York: 1962)
3. Fogg, MJ, *Terraforming: Engineering Planetary Environments* (Society of Automotive Engineers: 1995)
4. Fogg, MJ, "A Planet Dweller's Dreams", *Islands in the Sky* eds. Schmidt & Zubrin (Wiley, New York: 1996)
5. Newton, IS, *Philosophiæ Naturalis Principia Mathematica*, (S.Pepys, London: 1687)
6. Niven, L, *The Ringworld Engineers* (Holt Rinehart & Winston, New York: 1980)
7. O'Neill, GK, *The High Frontier: Human Colonies in Space* (William Morrow & Co., New York: 1977)
8. Roy, KI; Kennedy III, RG; Fields, DE; "Shell Worlds: An Approach To Terraforming Moons, Small Planets And Plutoids", *Journal of the British Interplanetary Society*, January 2009, vol.62, no.1, p.32-38.