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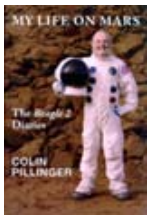

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SHELL WORLDS: AN APPROACH TO TERRAFORMING MOONS, SMALL PLANETS AND PLUTOIDS

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One big problem with the traditional terraforming approach is finding planets with workable initial parameters: large enough, temperate enough, wet enough, axial spin not too fast or too slow, a magnetic field, etc. A novel method to creating habitable environments for humanity by enclosing airless and otherwise useless sterile planets, moons, and even large asteroids within engineered shells is proposed. These shells are subjected to two primary opposing internal forces: compression caused by gravity and tension caused by atmospheric pressure. By careful design, these two forces can cancel each other out resulting in a net stress on the shell of zero. Beneath the shell an earthlike environment could be created similar in almost all respects to that of Earth except for gravity, regardless of the distance to the sun or other star. These would be small worlds, not merely large habitats, possibly stable across historic timescales. Each would contain a full, self-sustaining ecology, which might evolve in interesting directions over time.

Keywords: Shell worlds, terraforming, ecology, atmosphere, minor planets, moons, SETI, radiation, advanced civilizations

1. INTRODUCTION

There is no other Earth in our solar system. Venus and Mars are sometimes suggested as possible candidates for terraforming but each would require many generations of effort and literally astronomical amounts of energy and resources in order to transform either into a new Earth [1]. Early work in this field was reviewed in [2]. It is entirely possible that we may not find another habitable planet elsewhere even after visiting hundreds of other star systems. It is likely that whatever extrasolar planets we do find, would, like Mars or Venus, also require centuries of terraforming. Suppose we did manage to find a second Earth. It would already have life and a complex ecology. If its life wasn't incompatible or even toxic to us due to the vast number of seemingly random directions that evolution can take, we would face the very real ethical issue of introducing alien life forms (us, our pets, our plants, and our microbes) into another living world with unpredictable consequences.

If we assume that we're not going to find a ready-made world, once we start traveling among the stars, we're forced to conclude that we're going to have to build it. Finding sterile planets similar to Earth in size, spin, temperature, composition, and all the other parameters necessary for a second Earth seems like a long shot. However, planets the size of Mars, or even the Earth's moon, must be fairly common. We already have a fair number of those, plus many more minor planets, in our own solar system. If the requirement that they exist within a star's habitable zone is removed, the number of candidates goes way up, by an order of magnitude or more.

The problems of making a small body habitable are significant. Simply dumping an earth-like atmosphere onto a small planet or moon wouldn't work for long. Such an atmosphere would be stripped away over short timescales due to the slight gravity, solar wind, and ultraviolet (UV) dissociation [3, 4]. Even if the atmosphere could be maintained or continually replenished, without a magnetic field, space radiation could make the surface unpleasant at best and downright hostile at worst. If not located at just the right distance from the star, it would be either frozen solid or would be so hot that the oceans would boil off.

But, if a spherical shell of matter could be constructed around a planet or large moon so as to totally enclose the world then the shell could contain the atmosphere, shield the occupants from space radiation, and moot the parameter of distance from the star(s), or even type of star(s). An earth-like environment could be created under the shell with artificial lighting and temperature control. The gravity would depend on the moon or planet selected for enclosure and might be only a fraction of Earth's. Otherwise, all other qualities could be as earthlike as desired. These "shell worlds" would not merely be large habitats, but complete worlds engineered for human habitability and stability across historic timescales. Each would contain fully functioning, self-sustaining ecologies, based on Earth's.

2. GRAVITATIONALLY-INDUCED COMPRESSION OF A SHELL AROUND A POINT MASS

Consider a small planet or large moon. Assume that this mass can be represented by a point source at the origin of a Cartesian coordinate system. Assume a spherical shell constructed around this point source. If this shell is sliced exactly in half at every point where y = 0, then the total gravitational force **F** in the y direction is represented by Equation (1).

$$F = \int_0^r \frac{\sin(\theta) GM\ \rho s 2\pi r dy}{r^2} = GM\ \rho s \pi \qquad (1)$$

Where:

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

M = mass of small planet or large moon (assume point source), [kg]

ρ = average density of shell, [kg m^{-3}]

s = total shell thickness, [m]

r = radius of shell from barycenter, [m]

$Sin(\theta) = y/r$

With this total force in the y direction divided by the area of shell supporting this force, we get the gravitational induced compression stress on the shell, **C**, as shown in Equation (2).

$$C = \frac{GM\ \rho s\pi}{2\pi rd} = \frac{GM\ \rho s}{2rd} \tag{2}$$

Where:

C = gravitationally-induced compressive stress in a shell, [N m^{-2}]

d = thickness of load-bearing portion of shell, [m]

Note that where the load-bearing portion of the shell constitutes the entire shell then **s** would equal **d** and the two terms would cancel out in equation (2). Using this equation, it turns out that building a shell 20 kilometers above the surface of Mars requires a material 70 times stronger than steel [5]. A shell above Mercury requires a material 50 times stronger (not to mention thermal considerations); a shell above the Earth's moon, only 15 times stronger. Maybe we can develop such materials in the future. But in this case we don't have to.

3. ATMOSPHERIC-INDUCED TENSION OF A SHELL

Assuming that the objective is to contain an Earth-normal atmosphere of 14.7 psi, then the shell will experience pressure-induced tension, similar to a balloon. Given one atmosphere of pressure at the underside of the shell and vacuum above the shell, and assuming a "thin" rather than "thick" shell, the induced tension **T** from the contained atmospheric pressure is shown in Equation (3).

$$T = \frac{ar}{2d} \tag{3}$$

Where:

T = atmospheric pressure-induced tension in a shell, [N m^{-2}]

a = atmospheric pressure at the underside of the shell, [N m^{-2}]

r = radius of shell from barycenter, [m]

d = thickness of stress-bearing portion of the shell, [m]

4. NET SHELL STRESS

It is possible to choose the thickness so that the gravity-induced compressive stress exactly cancels out the atmosphere-induced tensile stress in the shell. **C** would equal **T**. In the case of a shell made completely of steel (sp.gr.=7.9, or 7900 kg/m^3) constructed 20 kilometers above the surface, with one atmosphere of pressure at the underside of the shell and no pressure on the outer side of the shell, several solutions are listed for various bodies within our solar system as shown in Table 1 [6].

Note that there are two entries for Ceres based on two assumed mass values. There is some uncertainty as to its current mass [7]. In addition, if Ceres was actually going to be terraformed, neighboring asteroids would probably be nudged in such a manner as to join Ceres, so the final shell world mass would probably be closer to the larger value.

Because the shell material is under almost no stress it is possible, in theory, to build it out of almost anything. Most of the shell mass is necessary to create compressive force in opposition to the atmosphere-induced tensile stress and can be mere dead weight. In the case of the Earth's moon, a steel shell of one-meter-thickness will work, provided that it has about 62 meters of dry dirt (regolith) on top of it. Using average densities of lunar soil [8], this gives the necessary 63.6 tonnes-per-square-meter (6.36 kg/cm^2) average shell loading to result in no net shell stress. Infinite combinations of steel, ice, dirt, and rocks are possible. It is not actually necessary to use a metal such as iron or steel. Stony materials such as concrete can handle a lot of compression. A strong fabric material that is airtight and in slight tension could be used to support the mass of the shell, which could be mainly rocks and dirt.

Stress due to self-gravitation of the shell is minimal: Entering the shell's own parameters from row (7 - Ceres) of Table 1 into Equation (2) yields a maximum stress of a mere 1,200 kilopascals (180 psi) [9]. This effect would slightly reduce the size of the shell but is ignored herein. If the candidate world for englobement was a satellite very close to a massive primary, say Ganymede around Jupiter or Titan around Saturn, then tidally-induced flexing would have to be considered in the shell's design. If the shell were to rotate then centrifugal accelerations would have to be addressed.

If the completed shell is comprised principally of dirt dumped on a strong inner balloon, then the exterior shell surface could

TABLE 1: *Example Steel Shell Parameters*.

	Thickness of steel shell [m]	Total mass of shell [T]	Mass per unit area [T/m^2]
super-Earth (~3 M_E)	0.87	7.01E+15	6.9
Earth	1.31	5.28E+15	10.4
Mars (~0.1 M_E)	3.49	3.98E+15	27.6
Mercury (~0.05 M_E)	3.48	2.05E+15	27.5
Earth's Moon (~0.01 M_E)	8.05	2.43E+15	63.6
Ceres (if ~0.0002 M_E)	45.2	1.24E+15	357.2
Ceres (if ~0.0001 M_E)	90.4	2.49E+15	714.3

be arbitrarily contoured, within certain broad limits, i.e. without excessive concentrations of mass, or *mascons*. The dirt could even be re-sculpted to mimic the original surface of the celestial body. Who's to know? This camouflage option opens up a whole avenue of speculation.

While it will not be demonstrated in this paper, it is possible to prove that a shell having mass equally distributed across the surface of the shell will be stable with respect to a much more massive object located at the center of the shell. If the central mass is displaced a given distance inside the shell, gravity will act to restore the shell's original position with respect to that body. Such is not true for a ring. If there were no way to damp the movement, the shell would oscillate back and forth. A viscous atmosphere will tend to dampen oscillations until the mass center is once again congruent with the center of the shell.

5. DESIGN CONSIDERATIONS

The size of the celestial body chosen will determine the gravity and the surface area of the new world. Small worlds inversely require much more mass per unit area in the shell, because they have less gravity to pull the shell in to contain the atmosphere. A world as large as Earth only requires a mere kilogram-per-square-centimeter shell loading (coincidentally, precisely the same areal density as Earth's atmosphere itself). However both Earth and Venus already have atmospheres, as a consequence of their considerable mass, which makes construction of a shell difficult, but not impossible. An airless Earth-sized planetary body would have the advantage that it would already have Earth-normal gravity. With the addition of a shell and an earth-normal atmosphere and lighting it could be very earthlike indeed.

The maximum gravity which humans might be able to tolerate for extended periods is 1.5 gee [10, 11]. A world that is about three times as massive as Earth, and ~40% larger radius plus the 20-km air gap, would require a shell loading of only 0.69 kg/cm^2 to contain one atmosphere of pressure. This is equivalent to a steel shell only 87 cm thick, but this would provide only limited radiation protection. With gravity roughly 50% greater than that of Earth, such a world could hold onto its atmosphere without a shell. The shell would allow the regulation of temperatures and lighting to earth-normal conditions and provide protection from UV light and some protection from hard radiation. A shell also minimizes the amount of atmosphere that must be imported. Thus a frigid superterrestroid on the edge of a solar system, comparable to one of our plutoids of the Kuiper Belt, or even a putative rocky rogue of the Oort Cloud, could become a possible human-inhabited world. (Though the heating bill might be as stiff as the exterior landscape, they'd have good ice cream.)

The asteroid Ceres, with a mass only 0.0001-0.0002 that of Earth and having a radius of 0.08 that of Earth represents the other end of the mass range that could be suitable for human habitation. A shell around Ceres would require up to 71 kg/cm^2 of mass to hold in an Earth-normal atmosphere. Compared to the super-Earth's thin shell, the thick blanket around Ceres would provide more than enough shielding to survive even a nearby supernova. If half of the terraformed Ceres is ocean, spotted with archipelagoes perhaps, then the dry land area would still be roughly the size of Indonesia. Gravity would be only 1.5% that of Earth – midocean waves on Ceres might touch the ceiling under the right conditions! At this point, it is unknown what long-term exposure to a microgravity might do to humans or if there is some treatment to deal with these consequences. This information could restrict the minimum size for an acceptable shell world.

The height of the shell above the surface can be almost any arbitrary value. The higher the shell, the more room for high mountains, the better the view, and the better the opportunity for natural weather patterns. However, the higher the shell, the greater the amount of air that must be imported. Unlike an atmosphere with a free unbound surface in space, the vertical pressure distribution in a shell world would be nearly uniform – thus more height means more air. Shells from 1 to 200 kilometers above the surface are feasible.

Although in this paper it is assumed that the atmosphere will need to be very similar in composition and pressure to that on Earth, it is noted that other atmospheres with different compositions and pressures are certainly possible.

The ocean is the most significant surface feature of our world. Many life forms can only survive in an ocean. Thus some ocean will probably be desirable on a shell world. Due to water's amazing thermodynamic properties, large bodies of it are vital for moderating temperature extremes. Ocean basins provide a place into which salts from the soil can be washed. Algae would contribute oxygen to the environment. One important decision is how much of the shell world is to be ocean and how deep it is to be. Oxygen and hydrogen are common enough, but an artificial ocean would require a lot of these elements. An intriguing possibility is a shell world with no solid surface or core at all – a water drop world. Imagine a multimegameter globule populated by benthic behemoths - denizens of the deep languidly swimming in near-microgravity, feeding on marine snow falling through the stygian gloom, growing with no upper size limit. This may happen anyway over long enough timescales if we englobe certain ice worlds in the outer system and they subsequently warm up.

Climate can be a design variable. The entire world can be temperate, or it can be configured to have frozen poles and a tropical equator with the resulting weather patterns or vice versa. The atmosphere could be either cooled or heated at the shell to create winds and weather. Rain would probably be generated by condensing water vapor out of the atmosphere via machines located on the outer surface of the shell and piping liquid to portions of the shell located over regions that require rainfall. Such precipitation could be scheduled, the quantity specified. The shell would have to be resilient enough to respond to global temperature variations while maintaining more-or-less constant pressure. Since the atmosphere is rather thin in scale compared to the central body, a flexing capability of just a few percent should be sufficient to accommodate any conceivable range of air temperatures.

The ecology inside a shell world would be designed to support a specific human population level. The underside of the shell itself could be a location of light industry, residential housing, transportation systems, and offices all having breathtaking (in every sense of the word) vistas of the ground below. Gardens would literally hang. The exterior surface of the shell world would be ideal for heavy, dirty industry, and even power plants producing radiation and radioactive waste. The interior surface of the world could be left unoccupied as a farm or park, or even a wildlife preserve.

With light gravity and normal atmospheric pressures, hu-

man-powered flight would be possible. This would not only be an amazing experience but would also serve as a means to get exercise sufficient to maintain muscle and bone mass.

In addition, the subterranean zones of small celestial bodies would offer vast - virtually unlimited - cubic for support functions and resource extraction. Consider that the interior of Ceres - half a billion cubic kilometers - could contain almost exactly the same working volume as a world-spanning city which packed the entire surface of Earth, oceans included, with billions of 1 km high skyscrapers, each the rival of Burj Dubai. In the light gravity of Ceres, every bit of that volume would be easily reachable and cheaply exploitable, unlike the deep wells and mines of Earth. A shell world might well be the richest planet in its solar system, once the huge cost of englobement was paid off.

6. LIGHTING A SHELL WORLD

The environment under the shell will be pitch black without some provision for either artificial lighting or use of natural sunlight. Structural penetrations in the shell, such as the large windows characteristic of O'Neill colonies, are dangerous, even if made with meter-thick fused quartz, because of inevitable stress concentration at the transitions, and the necessary absence of the thick blanket of regolith over the glass to absorb small meteor strikes. Lighting, in all likelihood, will be artificial. If the shell world is near a sun, solar energy can be converted to electricity to power the lights, or sunlight can be concentrated and piped in via giant fiber optics. If the shell world exists far from a sun, it will need lots of power plants to keep the lights on.

Fortunately, the state of illumination technology is progressing rapidly. We could duplicate the solar constant (1353 W/m^2) [7] by installing full-spectrum artificial lighting on the ceiling and flipping it on and off for the day/night cycle. Shell worlds from Mercury to the Kuiper Belt could have an earthlike insolation, ecology and diurnal cycle. An alternative is to reduce this by a factor of 4 (ratio of total surface area of globe:cross-sectional area facing the sun) to ~350 W/m^2 on the shell and leave the lights on permanently, all over the shell. The net energy input into the world would be the same. The human eye is marvelously adaptable across an enormous range of intensities and should function very well at these reduced levels. There would be no night, just continual crepuscular twilight.

Existing electro-luminescent displays (ELD) only provide about 1-2 W/m^2 of radiant energy in various colors from red to blue-green, but their state of the art (brightness, efficiency, cost) is rapidly advancing [12, 13]. Since ELD materials are presently available in all three primary colors and can be subdivided into addressable segments, we can imagine a pixelated ceiling of video wallpaper simulating the natural sky of Earth (clouds, sunsets, stars, etc.) or generating any arbitrary scene. The postindustrial motto "everything is media" means art can reach its fullest expression in the canvas of a shell world.

Humans need to see but plants need light to live. Photosynthesis utilizes less than 250 W/m^2 out of the 1353 W/m^2 of total radiant energy in the white light from Sol. The chlorophyll-A and chlorophyll-B molecules each have major absorption peaks, in the blue-violet and orange-red regions of the spectrum, respectively [14]. The band of wavelengths in which Sol peaks, yellow-green, is rejected completely! Evolutionary luck-of-the-draw has given us a remarkably inefficient plant economy. Therefore, the full requirement for growing Earth plants could be provided by the underside of the shell radiating a soft magenta light at an average of 60 W/m^2 continuously. The shell surface over agricultural areas could radiate at precisely those frequencies and intensities needed by the crops below, providing what the plants need with little wasted energy.

There would be no harmful UV radiation, since that tail of the solar spectrum would be truncated, therefore no need for ozone (O_3) to block UV. However, some useful UV light may be required for biological considerations and could be provided, for example over beaches at sufficient intensity to cause tanning and vitamin-D synthesis. The infrared (IR) light at the other end of the spectrum would only be necessary as a way to control sensible temperature. The day/night cycle could be manipulated - some areas of the surface left in permanent darkness, others in permanent brightness. Morning could come at the same instant for everybody or sequentially as on Earth.

7. RADIATION PROTECTION

Any space settlement concept must confront the question of space radiation [15]. For the type of worlds under consideration here, this hazard breaks down into two major components: the solar wind, and cosmic rays. The solar system is protected, in part by the solar magnetic field. Earth's magnetic field also helps deflect charged particles but neutrons, gamma rays, and high-energy particles (usually from cosmic sources) are stopped, in part, only by our atmosphere. The typical human on Earth receives 30 millirem (mrem) annually from space radiation [16]. This is a small portion of the total average dose of some 360 mrem from all sources.

On a shell world, the question of space radiation becomes important. If we assume that background, medical, and cultural sources remain constant, can we keep the annual space-based component below 30 mrem per year? A shell over Earth's moon, for example, would have a sectional density of 6.4 kg/cm^2, or over six times the areal mass density - thus protection - provided by Earth's atmosphere. This would effectively stop all of the hard solar radiation and even most of the cosmic radiation. However, heavy ions coming in at relativistic speeds present a special problem. Some cosmic rays are iron atoms fully stripped of their electrons and coming in with a speed 95% that of light. The secondary radiation from such particles will be attenuated differently than on Earth. Mesonic secondary radiation is attenuated partly as a function of travel time between the primary cosmic ray impact point and the target. Thus on earth we benefit from a great distance between this point (perhaps at 30 km altitude) and the surface of the planet. A shell, even if located as far as two kilometers above the lunar surface, would afford significantly less protection.

A correct calculation of attenuation vs. distance requires accounting for the relativistic time dilation from the near-light-speed particle velocity. It is for this reason on Earth, where electron and proton doses peak at about 20 km altitude, that muon- and pion-meson tissue dose rates rise from about 5 microrad/hour at 25 km altitude to about 15 microrad/hour at 15 km altitude, then diminish. Neutrons resulting from relativistic heavy-ion-impact also represent something of an unknown.

However, cosmogenic mesonic radiation is not necessarily lethal. If a cure for cancer were to be developed that was both simple and reliable then allowable radiation doses for individu-

als might be significantly increased. Or, a secondary shell, say to principally serve as a solar energy collector, could be constructed above the primary shell to provide an additional function as a heavy ion trap. It would be stationed many kilometers above the primary shell and would be high enough to allow for meson decay before the particles reach the primary shell. A secondary shell provides yet another beneficial function – a sacrificial ablator—vaporizing very high-speed meteorites before they reach the primary shell.

The radiation protection issue needs further study as with any space habitation proposal, but radiation is not a showstopper with respect to shell worlds.

8 FAILURE MODES

Earth is not a benign place to live. Aside from large asteroid impacts, supervolcanoes, tsunamis, earthquakes, ozone layer failure, massive solar flares, and global climate change, there are a number of other events, both known and unknown, that could terminate our civilization and maybe even our species. Shell worlds offer some protection from most of these potential disasters. We can choose or build worlds with no volcanoes and no plate tectonics. The ozone layer is unnecessary. Solar flares, even nearby supernovae, would have little effect on a shell world's inhabitants. The weather is controlled, and hurricanes and tornadoes would not exist, except where created.

Perhaps the major threat to a shell world is a shell rupture. If gone uncorrected, the carefully created atmosphere would escape into space and quite literally the sky would fall. The shell should be engineered to deflate slowly, allowing time for repairs to stop the leak. If the leak is not repaired, the shell will slowly lower itself to the surface with the pressure remaining at earth normal until it reached the surface. It would be engineered so that it would not pop like a balloon. Such a disaster could result from asteroid impact, material failure, design failure, space transportation accident, sabotage or military action.

Asteroids represent a very significant hazard to a shell world. They also are a very real threat to natural worlds. A small shell world would enjoy the advantage of a much shallower gravity well compared to Earth (the biggest densest planet in the inner system) and thus much less likely to draw in an errant bolide in the first place. However, it is not unreasonable to assume that a civilization that could construct shell worlds could also map out and either utilize or deflect all the asteroids within a given solar system. The inhabitants of a shell world would have every reason to get the design and materials fabrication for a shell right. Indeed it would probably be an ongoing effort to improve the shell, and perhaps its camouflage, with ever-advancing science and technology. No doubt some impressive military defenses will be installed on the shell surface to destroy any threat to the shell world, either natural or artificial.

One important failure mode to recognize is the possibility that the ecosystem could fail. But then, that risk already exists on mother Earth herself. There have been efforts to design, build, and maintain artificial, closed-cycle ecologies here on Earth but to date, they have all failed. Hopefully in the future, our enterprising descendants will know more than we do and will be able to make and enjoy efficent, stable closed-cycle ecosystems.

9. ONE POSSIBLE CONSTRUCTION SCENARIO

To build a shell around a small planet or a large moon will require energy and material fabrication on a large scale. One likely approach would be to, in essence, construct the shell on the surface of the moon or planet and then blow it up, like a balloon. Let's discuss the Earth's moon and how such a shell might be made and then deployed. While this discussion is specific to the Moon, the basic approach could be used on any planetary body large enough to provide sufficient gravity. It is recognized that future nano-technologies could make construction of shell-worlds possible and perhaps easy, but exactly how is unclear at this point.

To begin with, the proper raw materials would have to be brought to the Moon. Table 2 identifies what and how much is needed, what it would be used for, and from where it might come. This "modest" scenario assumes that the shell will be located a mere 2 kilometers above the surface and that the Moon's new oceans will only cover one quarter of the body just to 100 meters in depth. Nitrogen is perhaps the major problem. It is available in Jupiter's atmosphere and on Saturn's moon Titan. Titan can also provide us with the argon needed to duplicate Earth's atmosphere. CO_2 is of course available at Venus in any quantity needed. The transportation needed to move this much mass around the solar system will require an unprecedented capability. For instance, the delta-vee of a minimum-energy Hohmann transfer orbit from Titan to Luna is on the order of 40 km/sec [7, 17]. Thus the energy required to simply move the quantities of terraforming material tabulated below – roughly 1 quadrillion tonnes – is many millions of times greater than all the current nuclear arsenals put together. Significant advances in energy production and space transportation over what is available today will be required.

While the offworld materials are being collected and transported, the future ocean basins would be carved out of the moon's surface using carefully guided kinetic energy weapons or the icy asteroids intended for the future oceans. High mountains would have to be leveled. The future landscape inside would be sculpted with either an artistic or naturalistic touch, depending on the builders' whim; the exterior surface as well could be either high techno-art or a perfect mimicry of nature, depending on their paranoia. The new atmosphere would be stored in liquid form at various depots on the moon. Oceans of water would be stored as ice in the newly carved ocean basins. Large fabrication plants on the Lunar surface would begin to manufacture a carbon-based fabric, perhaps using carbon nanotubes. This fabric would be laid out on the moon's surface as one continuous sheet. This fabric would be composed of multiple layers and eventually reach a thickness of 25 cm [5]. It would of course be airtight and designed to withstand high-tensile loads. Because it is made on the surface, but intended to be lifted to a high altitude, hence greater diameter, it must be able to stretch. If the shell is to be 2 kilometers above the Moon's surface, it must be able to stretch 0.11% (11 cm for every 100 meters of fabric); a 20 km air height means the shell would need ~1% stretch. This fabric will have numerous hooks attached to the bottom side. To provide a safety feature, large hexagonal steel plates, each 50 cm thick and face-hardened, are laid on top of the fabric. This armor plate is intended to distribute surface loads, protect the fabric beneath, and serve as a warning to anyone working on top of the shell that what is beneath should not be disturbed. Each plate would be connected to adjacent plates but in such a way that the required expansion is permitted. On top of the armor plate is now distributed rock and dust to reach a target

TABLE 2: *Lunar Shell Material Requirements*.

Material	Quantity Needed (Million Metric Tonnes)	Possible Source
OXYGEN	22,150,000 (atmosphere)	Moon, Venus
NITROGEN	72,016,000 (atmosphere)	Jupiter or Titan
CARBON	5,873,840 (shell fabric)	Moon, Venus
ARGON	1,317,000 (atmosphere)	Jupiter or Titan
IRON	73,922,300 (shell's armor plate)	Moon
WATER	848,149,000 (oceans and rivers)	Jupiter's moons

loading of 6.4 kilograms per square centimeter. Assuming average densities, this requires rock and dirt about 60 meters deep on top of the steel plate. Industrial facilities intended for vacuum operation are sometimes substituted for the dirt.

Airlocks have been provided in the fabric and armor to allow material, machines, and people to move through the shell. These airlocks are now closed and the atmosphere is slowly released under the shell. If all goes well, the shell will begin to levitate off the surface of the moon when the pressure reaches 1 atmosphere. Extra atmospheric component mass must be provided to account for absorption by the moon itself. Once the shell is some 50 meters above the surface, the expansion will be halted. Some redistribution of the mass on the shell is probably going to be required. Also, the underside of the shell begins to see significant construction as a superconducting power grid is installed. This grid is powered by stations located on the surface of the shell. These power plants are of an advanced design probably using antimatter to induce hydrogen fusion, or perhaps just large solar collectors or both. This grid supplies the lighting and radiant heating fixtures, also being installed. Heat is provided to begin to melt the ice that will eventually form oceans. At least there won't be a lack of thermal heat sinks for heavy industry – it will be a long time before the subterranean realms will be comfortable to bare skin. But the human workers on the surface under the shell can now go about their tasks in their shirtsleeves instead of spacesuits.

Structures can be attached to the underside of the shell. Hanging cities (as well as gardens of course) are possible; in fact, their presence will diminish the required surface loading by inert material. The underside of the shell represents an area equal to some four times the area of the United States. This is a lot of real estate with an interesting view. Now more and more atmosphere is released. The pressure does not increase; instead, the shell height increases. Once the design height is reached only enough atmosphere is released to maintain the proper altitude. The lights are on, the heat is on, and the air is breathable at earth-normal pressures.

Now comes the difficult part of the project. Dehumidifiers, either a few big ones or many small ones, hung from the underside of the shell begin to suck water out of the air. This collected water is dumped at carefully selected locations. The rains have started. With the rains come microorganisms and nutrients. Earth life is slowly introduced to its new home. Salts are washed out of the lunar soil and into the new oceans. Oxygen levels begin to fall as lunar rocks and soil begin to oxidize. Additional oxygen is released to replace that which is lost. Ocean algae begin to establish themselves and release oxygen. The biologists and ecologists will be busy for a long time but eventually, humanity and all the other life that has shared our planet with us will have a new home. Except, perhaps, for certain parasites. Would anyone willingly release pathogens or pests into this new world?

10. CONCLUSIONS

The idea of an atmosphere constraining shell around a large moon or planet is feasible. It provides both a means to hold an atmosphere and shield the interior from most space radiation. Its underside offers an ideal location to support artificial lights that can effectively simulate Earth's sun, regardless of the actual distance of the world to its sun. Temperature control is required and possible. The airless, outer surface of the shell is an ideal location for many industrial facilities such as power plants and manufacturing facilities. The underside of the shell represents an interesting location for possible urban construction. The surface of this new world could be made as earth-like as we care to make it, except for gravity. Hanging cities and human powered flight are possible in low gravity worlds.

The construction of the shell, the atmosphere, and the biosphere (including oceans) is going to be very challenging and time consuming. The project could well take hundreds or even thousands of years. The energy costs alone would be literally astronomical compared to anything humanity has done to date and would probably require production of large quantities of cheap anti-matter. Building and managing a shell world in our own solar system would provide valuable experience toward constructing stable reliable generation ships for true interstellar voyages, assuming we will remain limited to the propulsion physics we know about.

Despite the cost, at completion, all of earth's life would have a new home, here or there. With proper care and maintenance, this new home could endure for many thousands of years. Future technologies could extend the life of the shell well beyond this.

Such worlds could be constructed just about anywhere a suitable planet or large moon is located. The presence of a sun or star is not necessary. Many candidate bodies probably circle small red dwarf stars, which are by far the most common type. Such stars are long lived – on the order of a trillion years – and their solar systems fairly quiet and peaceful places, and perhaps most appealing, utterly unremarkable, save for the occasional flare. An advanced civilization might like such a neighborhood and may have already constructed shell worlds there. Brown dwarfs (failed stars) are probably more common that red dwarfs

and offer many of the same advantages and for introverted types, are even more difficult to find. They probably possess a fair complement of plutoids and small planets suitable for shell worlds.

Shell worlds offer the possibility of converting virtually any solar system containing enough orbital debris into a habitable star system. The ethical questions associated with interfering, or contaminating another planet that has developed any kind of life can be avoided. Indeed, it is logical to conclude that any advanced civilization may come to prefer constructed shell worlds to natural worlds because of their stability, safety, and adaptability. SETI researchers would do well to consider such a possibility.

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