Space-Habitat Illuminators with Non-Imaging Optics

Bill Parkyn, Space Fan (lparkyn@pacbell.net)

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Abstract

The strongest known material, carbon nanotube, has inspired designs of spinning space habitats reaching radii of 1000 km. Known as the Space Ring, a cylinder of such radius, with a 'short' 500 km length, has an 'open sky' geometry that only self-occludes a third of the view of the stars, as they spin around twice per hour. Sunlight is unsuitable for illuminating the Ring interior because it cannot be turned off. Instead, the Ring axis is sideways to the sun, and solar-cell concentrator troughs cover its exterior to provide power for a central illuminator. Because the inside living space is π times the projected cell area, illumination effectiveness is at a premium, even if the electrical efficiency of the cells is 50%., and enormous storage capacity accounts for 'night-time' sunlight. Only a quarter of the light output of a central isotropic emitter would fall on the Ring, so that nonimaging optics is called for. Overall luminaire size (and cost) is reduced by increased emitter luminance, but considerations of eye safety oppose this. An ideal CPC of revolution would produce a rectangular 'sun' with 4:1 aspect ratio, fixed overhead in a blue sky, unable to generate rainbows, sunrises, or sunsets.

Keywords: space habitats, artificial sun, megastructures, equatorial illuminators, solar concentrators, future history.

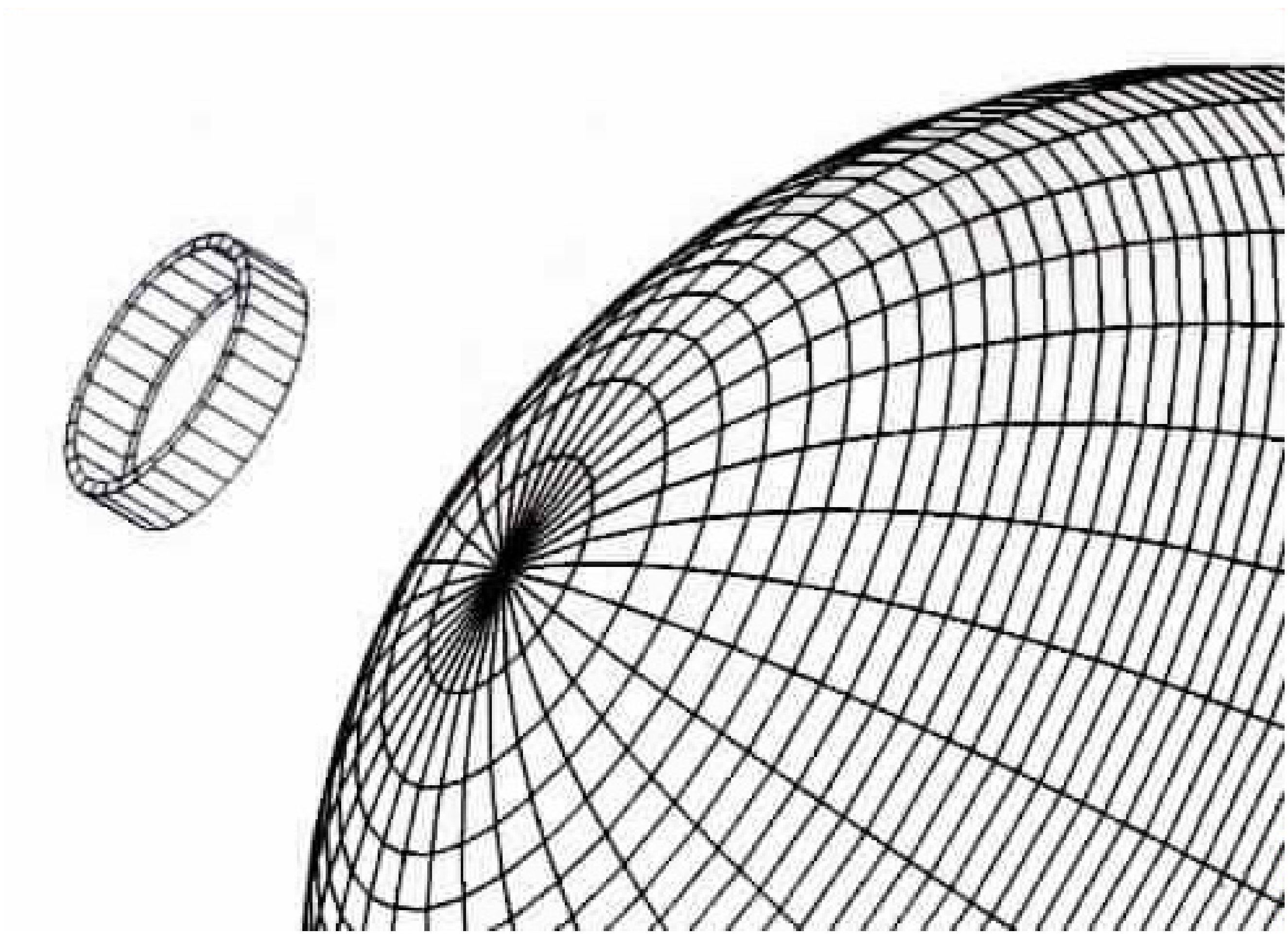


Figure 1. The Space Ring, the ultimate artificial habitat in space. At 2,000 km diameter, its size is shown in comparison with the Earth's size. Its 500 km width gives it an interior 'land' area equal to that of India. Sidewalls hold the atmosphere against the one earth-gravity provided by two revolutions per hour. Of course, such objects would never be brought so close to Earth. They would be constructed and eco-stocked at the Solar L1 point, a million miles sunward from Earth, then moved by ion rockets into nearby resonant co-orbits.

1. THE SPACE RING

1.1 Space habitats

Originally proposed by O'Neill[1] in the '70s, space habitats are large-scale orbital installations that seek to produce an 'outdoors' experience with open volumes of pressurized air, typically inside a spinning cylinder at least 100 meters across, up to many kilometers. A simple Lambertian emitter would suffice as a centralized tubular illuminator even for diameters of tens of kilometers, because of the 100% enclosure of the habitation surface. Hoop-stress limits of conventional metals kept the maximum feasible diameter under 50 kilometers, and a 200-kilometer length. As discovered with the very first U.S. satellite, Explorer I, spinning cylinders much greater aspect ratio than this soon transform their rotation into an end-over-end tumbling mode. So, conventional materials spell a maximum habitat 'land' area of a few tens of thousands of square kilometers, sufficient for a million people. Without a perpetual haze, the daunting prospect of a 'sky full of land' may deter many people who would otherwise emigrate from Earth. In addition, suburban population densities would be required. It would not feel like 'another world', but merely being in a larger container than a space station.

1.2 Ultimate limits

More recently, the discovery of carbon nanotubes offers prospects of unprecedented cable strength. Space habitats already proposed would be much easier and less costly to build. Moreover, nanotubes offer enough cable strength for a thousand-kilometer radius at one gravity: an enormous scale-up. A single such megastructure could easily accommodate entire nations at rural population densities. Here we examine a particular proposed architecture, by Forrest Bishop of the Foresight Institute[2], that does feel like a world, because it is only one-third enclosed, and two-thirds open to space.

Herein called the Space Ring, this simple architecture is shown in Figure 1 on the left, its huge size scaled by the Earth on the right. The 100-km high sidewalls are just visible in the Figure, holding in the atmosphere. Figure 2 shows the Space Ring's scale compared to Sri Lanka. The water in Halley's comet would cover the entire Ring interior to 10m depth.

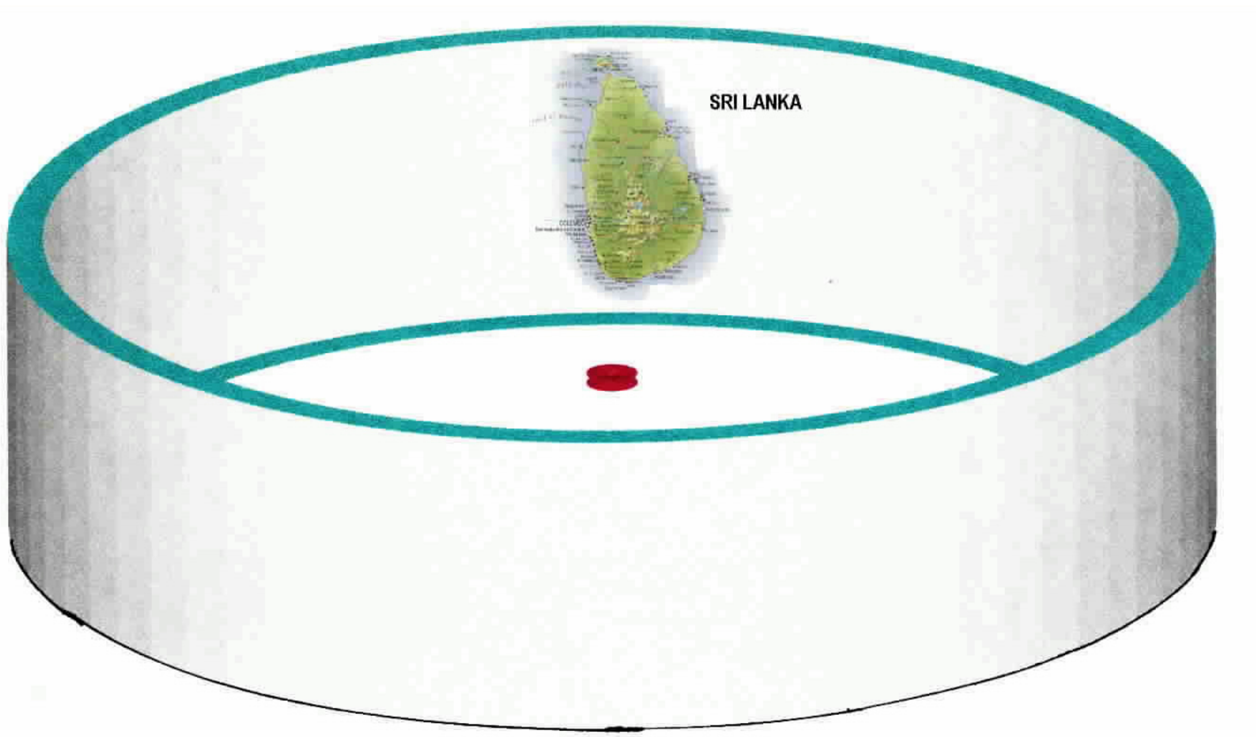


Figure 2. The Space Ring and its central 'sun', a toroidal CPC that restricts light output to the Ring inner surface. The Ring spins twice an hour for Earth gravity. The 100 km walls hold an Earth-normal atmosphere. The Ring is oriented in the plane of the solar system (Ecliptic) so that the exterior solar cells can be one-dimensional concentrators. The Space Ring is 2,000 km across and 500 km wide, with an interior surface equal to the area of India. Its relatively thin structure requires the disassembly of a medium-sized asteroid, of which the Solar System has tens of thousands, enabling there to be enormously more people than could ever live on Earth.

On either side of the overarching Ring (±7° at zenith) would be open sky (60% of 2π steradians), rotating twice per hour for one gee. Figure 3 shows a flattened-hemisphere graph of half the sky from the SpaceRing floor. Because there is as much air mass as on Earth, the stars would be no brighter than in the darkest skies here, and cosmic rays would be no worse.

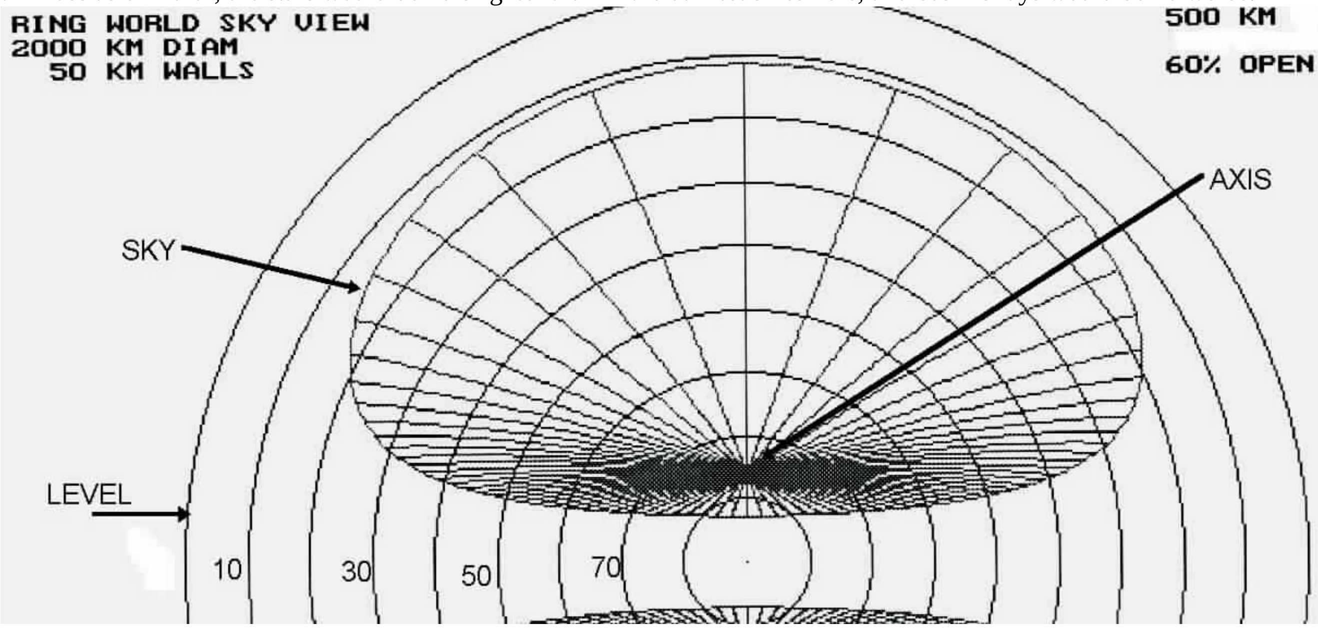


Figure 3. View from SpaceRing floor. The opposite side is at zenith, the center of the circles, which represent 10° intervals.

With two-thirds of the sky open to space, control over illumination dictates that the sun not be visible. This is possible only if the gyroscopically fixed Space-Ring rotation axis is normal to the plane of the Ecliptic.

1.3 Power budget

With such a 'side-on' orientation to the sun, the Space Ring presents a projected area of a million square kilometers, while its interior surface is π times this much. With such an orientation, one-dimensional concentration is possible, as much as n/sin 0.25° ~ 200n for cell immersion in a medium (undoubtedly diamond) of index n. System efficiency over half is plausible with nanoscale technology. With 1350 W/m^2, total electric power would be ~7E14 watts, a thousand times that of the United States today. Conveying that much power to a central illuminator would require superconducting cables, of which carbon nanotube itself is an eligible candidate. They would have to be small enough to be invisible from a distance.

The entire purpose of an axially located illuminator would be to establish a day-night cycle. An energy-storage system (undoubtedly antimatter) would be required for the solar electricity collected during the night cycle. Unlike the sun, this light would remain overhead, with no sunrises or sunsets in the blue sky, or any rainbows, except from aircraft. An important factor is its luminance. The higher the luminance, the smaller the luminaire, but the greater the eye danger.

Assume 80% storage efficiency and luminaire efficacy of 100 lumens per watt. Illuminance will be about 40,000 lux, 40% of a noonday sun, well within normal experience, and quite suitable for most crops. Lower radiance will not mean lower temperature, because the external solar cells will be heat sources as well. Lower irradiance will mean a milder hydrologic cycle, utilizing evaporation from the relatively shallow (10m) bodies of water allowed as loads on the Space-Rings carbon nanotube skeleton. Presumably wave machines could provide a more oceanic ambiance, although large cetaceans may find such lack of depth disagreeable.

2. THE LUMINAIRE

Bishop[2] proposed light sources suspended just above the atmosphere, but this gives highly nonuniform illumination on the Ring floor, unless the source is suitably tailored with an elaborate luminaire. A central luminaire on the Ring Axis can illuminate the entire Ring floor with uniform illumination, while simultaneously preventing light from going into space.

The central light source must have its angular output restricted to the 28° subtended by the Ring. A simple reflective design for a Lambertian cylindrical source is a rotated CPC. With an 0.25 numerical aperture, skewness is small and efficiency high, but from the Ring floor an unmoving 4:1 rectangular 'sun' is seen at the zenith.

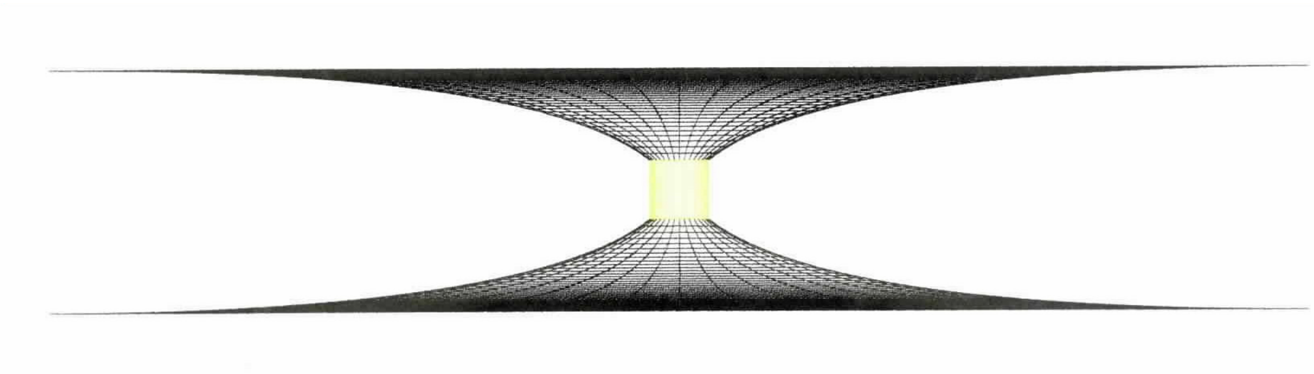


Figure 4. Axially revolved CPC with 14° acceptance angle. 1E8 cd/m^2 Lambertian cylindrical source is 10 km across.

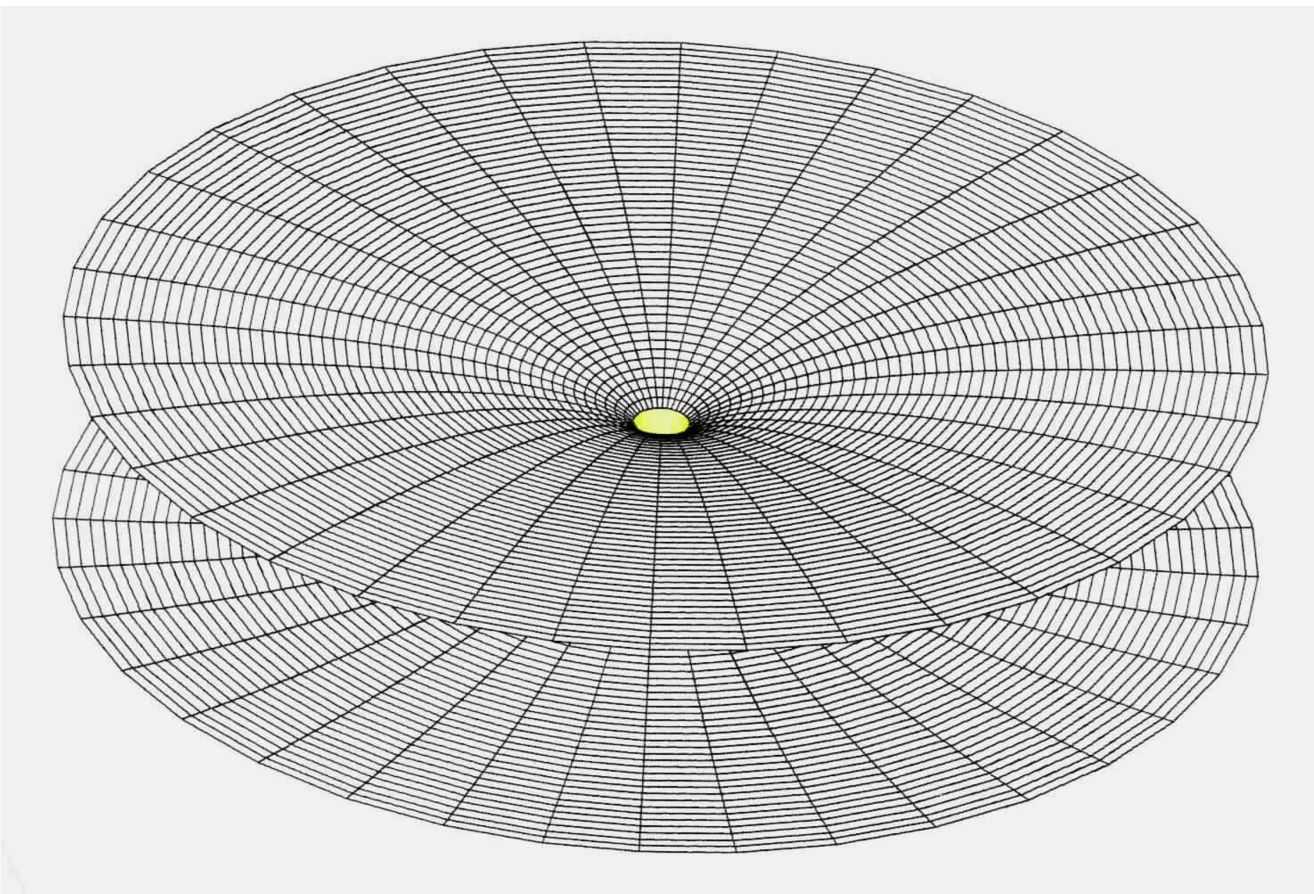


Figure 5. Toroidal symmetry of CPC. Source would not actually be visible from this angle, due to presence of other installations.

Here on Earth, the sun subtends a half a degree, or 8.7 milliradians, and its luminance is over a billion candela/m^2. At a tenfold lower level, the abovementioned 40,000 lux of illuminance gives a source solid angle of 1/2500th steradian, or 1.3$^{\circ 2}$. A 4:1 rectangular solid angle of that size would be a little wider than our sun, but much 'longer'. As shown in the edge-on view of Figure 4, the full CPC shape could be significantly truncated with little reduction of illuminance. The source is 10 km in both diameter and length. This toroidal CPC has a 40 km aperture width, and a diameter of 210 km. Such a low-mass thin-film structure is within the realm of solar-sail technology.

3. HUMANITY'S FUTURE IN SPACE

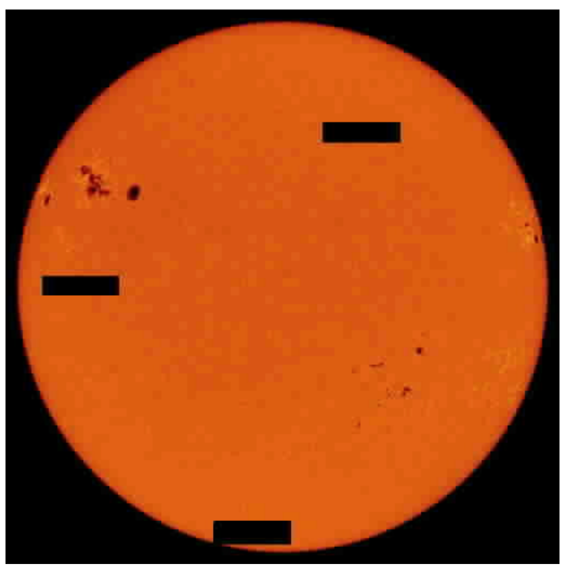
Both futurists and most of science fiction implicitly assume humanity's future will be on planets. But the terraforming of Mars is, I think, impossible because of Mars' immense dust load, while terraforming Venus would require both the removal of most of its atmosphere and some kind of sun-shade, as well as somehow making the planet spin faster. Ironically, there is enough carbon dioxide in Venus' atmosphere to provide the carbon nanotubes for many thousands of Space Rings, and the specific energy of the Venus gravity well requires far more energy than removing the oxygen from the carbon.

Earth is so vulnerable to civilization-destroying impact hazards that humanity's large-scale presence in space is an absolute necessity for world-society's long-term survival. Also, with a static world population, there will be no place of escape from poverty, war, or oppression, no frontier where new societies can form, where ethnic populations can isolate themselves from those who hate them. To move billions off of Earth, a large-scale Space Elevator will be required as well, and a transportation infrastructure far beyond that depicted in the movie '2001'. Equally challenging will be establishing sufficient ecological knowledge to stock an entire sub-continent's worth of 'land' with topsoil and vegetation. All these will take centuries to accomplish, far too late for anyone alive today, but the only way the human race can expand beyond Earth's limits.

A Space Ring would require the consumption of an asteroid tens of kilometers in diameter. Such lethal-sized objects would be brought no closer to Earth than the solar libration point L1, a million miles sunward. From here on Earth a completed Ring could be seen against the Sun, subtending about a milliradian, looking like a rectangular sunspot. Once ecologically stocked and populated, the Ring would be moved (via peripheral ion rockets) to resonantly librating co-orbits[3] that basically share Earth's orbit at safe distances from it.

The fundamental advantage of the Space Ring is its lack of a gravity well. Although its peripheral speed of 3 km/s is comparable to the Moon's gravity well, arrivals and departures from the Ring Axis require minimal velocity. Not only is a Space Ring much easier to move than a planet, its immense electrical power can be used for lasers as well as lighting. Indeed, Space Rings will be militarily much more secure than a planet could ever be. Unlike the SF clichés of colonies oppressed by Earth, the future will see the Earth as a quaint tourist backwater where a tiny minority of humanity tends to the remnants of the past, while trillions live throughout the inner Solar System, on thousands of independent worlds. Given that the Earth may be unique in all the Galaxy[4], then Space Rings are the way all other star systems will be settled someday, FTL (faster-than-light travel) or not[5].

Lebensraum in outer space:
View from Earth of
Space Rings under construction
At Solar L1, from captured asteroids



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[3] F. Namouni, AA. Christou, & C.D. Murray, 'New coorbital dynamics in the solar system', astro-ph/9904016, 1-Apr 1999
[4] Peter Ward & Donald Brownlee, *Rare Earth*, Copernicus, New York, 2000
[5] Bill Parkyn, 'Supersense: The Sidereal Eye', *Sky & Telescope*, June 1994, Vol 87 #6, pp. 30-34