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SKYLIFE

FIRST THERE was a flying island.

Then there was a brick moon.

The inventors, Jonathan Swift (Gulliver's Travels, 1726) and Edward Everett Hale (grandson of Nathan), were not entirely serious. Still, the significance of their visions reached well beyond the engineering inventions of the eighteenth and nineteenth centuries. In Hale's alternative to living on Earth, "The Brick Moon" (1869) and its sequel, "Life on the Brick Moon" (1870), people set up housekeeping inside Earth's first artificial satellite and did quite well. Hale's artificial satellite, the first known presentation of the idea, called attention to a technological innovation implicit in our observations of the Earth-Moon system and that of the other planets that possess moons.

What nature could do, we might also do.

We, the third type of chimpanzee, fresh out of Africa and swinging in trees, thought of lofty havens.

For Hale, the artificial satellite meant not only a technological feat but also the expansion of human possibilities, a vision of social experimentation beyond the confines of Earth. Space exploration has ever since carried the hope of a social and cultural renaissance springing beyond the planetary cradle.

Such visions increased toward the end of the nineteenth century and throughout the twentieth, as if humanity were trying on one after another. Now the United States is launching the parts for the greatest skylife hostel yet -- to mixed reviews. Understanding the transparently foolhardy enterprise demands some historical perspective. Living in space is in the end about more than a hotel room in the sky.

It does not seem strange in hindsight that the idea of space colonies should have become so prominent in the United States, a nation that has itself been described as a science fictional experiment. The American attempt at a dynamic, self-adjusting utopian vision based on a constitutional separation of powers and the intended, orderly struggle of those powers with one another as a way to deal with a quarrelsome human nature -- is still in progress. But it is also held back by the limits of planetary life.

The first major twentieth-century vision of humanity in space was set down in all seriousness, and with extraordinary thoroughness, by the deaf Russian schoolteacher Konstantin Tsiolkovsky (18571935). He did not try to match Jules Verne and H. G. Wells as a writer of stories, but his fiction and nonfiction set out with great imagination and technical lucidity the scientific and engineering principles for leaving Earth, and presented nearly all the reasons, cultural and economic, for expanding human capabilities beyond Earth. He saw that the entire sunspace was rich in resources and energy and could be occupied. Every step from space capsule to moonship was itself a small habitat, a way of taking a bit of our home world, its air and food, with us into the cosmos.

For many years the concept of space habitats lived mostly in science fiction stories. Olaf Stapledon's Star Maker (1937) described the use of whole worlds, natural and artificial, for interstellar travel and warfare. Edward E. "Doc" Smith, today called the father of the Star Wars movie saga, used planets similarly in his Skylark and Lensman series of the 1920s, '30s, and '40s. Isaac Asimov, in his Foundation stories of the 1940s, showed us Trantor, an artificial city-planet that rules the Galaxy. Don Wilcox's "The Voyage that Lasted Six Hundred Years" (1940) introduced the idea of using generation starships to reach the stars, in the form that was to be often imitated, one year before Robert A. Heinlein's more famous story "Universe" and its forgotten sequel "Common Sense" -- gritty realistic dramas of travelers aboard a space ark who learn, in the manner of a Copernican-Galilean revolution, that their world is a ship.

The uneasy familiarity of generation starship stories springs from our seeing the Earth as a ship, the stars as other suns. We glimpse how our view of the universe changed in the last thousand years. Earth is a giant biological ark circling its sun. As in Heinlein's "Universe," the dispelling of illusion and misconception lays the groundwork for surprising hopes and the expansion of human horizons.

Behind the science fiction stories stood visionary nonfiction such as J. D. Bernal's 1929 The World, the Flesh, and the Devil, which pictures an urban ring of worlds around the Earth. In the 1950s, Arthur C. Clarke and Wernher von Braun envisioned space stations as giant wheels spinning to maintain centrifugal "gravity." They thought that such stations would orbit the Earth to observe weather, refuel interplanetary spaceships, and train astronauts who would later set up bases on the Moon and Mars conservative proposals that even today we have not fully exploited.

Engineer Dandridge Cole, in his bold and comprehensive visions of the early 1960s, called space settlements "Macro-Life." These might be new habitats constructed from advanced materials, or nestled inside captured asteroids, hollowed out by mining their metals. Isaac Asimov described the same concept as "multiorganismic life" and coined his own term, "spome," as the space home for such a way of life. Cole envisioned Macro-Life as the ultimate human society, because of its open-ended adaptability, and delved into its sociology. Asimov proposed the scattering of spomes as insurance for the survival of humankind.

Both thinkers saw space settlements as a natural step, as important as life's emergence from the sea. As amphibians would venture into the thin air of the shore, we would carry our biology with us.

Cole wrote:

"Taking man as representative of multicelled life, we can say that man is the mean proportional between Macro-Life and the cell. Macro-Life is a new life form of gigantic size which has for its cells individual human beings, plants, animals, and machines .... Society can be said to be pregnant with a mutant creature which will be at the same time an extraterrestrial colony of human beings and a new large-scale life form." Cole defined his habitats as a life form because they would think with their component minds, human and artificial, move, respond to stimuli, and reproduce. Residing in space's immensities offered a unique extension of the human community, an innovation as fundamental as the development of urban civilization in the enlightened Green city-state. Yet living in the rest of the space around our sun re-created some desirable aspects of rural life, since habitats would have to be self-contained and ecologically sophisticated, with the attentiveness to environment that comes from knowing that problems cannot be passed on to future generations. Perhaps this nostalgia was crucial in the American imagination, with its rural past so quickly vanishing.

The arguments presented for such a long-term undertaking are economic, social, and cultural. Few would deny that the solar system offers an immense industrial base of energy and mass, enough to deal with all the material problems facing humanity.

We live under a sky ripe with fundamental wealth, but our technological nets are too small to catch what we need from the cornucopia above our heads.

Yet hard science had to come before high dreams.

While science fiction writers used the idea of space habitats for dramatic stories, engineers and scientists brought to it an increasingly revealing verisimilitude. Fundamentals of physics and economics came into play.

Space colonies have some advantages over our natural satellite, the Moon. A rocket needs to achieve a velocity change of 6 km/sec to go from low Earth orbit to the lunar surface. That same rocket can go to Mars with only about 4.5 km/sec investment, if it uses an aero-shell to brake in the upper Martian atmosphere. Also, any deep space operations could be much better managed from an orbit out beyond the particle fluxes of our magnetic Van Allen Belt, a fraction of the way to the Moon.

I've had a steady conversation with Buzz Aldrin for the last decade about his personal dream of returning to the moon. It's about hard realities.

Lunar resources are principally rocks that have about half their mass in oxygen. But the Moon has nothing we can unite with that oxygen to burn, such as hydrogen or methane. Since oxygen is a big fraction of chemical fuel mass, usually about three-quarters, the Moon's oxygen would be valuable if it did not cost so much to lift into orbit.

We would also need very high temperature techniques to bake the oxygen out of hard rock. As I put it to Buzz, suppose we found ordinary sidewalk concrete on the moon. It would be, relative to the local rocks, a bonanza: we would mine it for water. That's how dry Luna is.

Early on, many noted that in energy expended, once one has lifted a mass from Earth to the orbit of the Moon, one is halfway to the Asteroid Belt -- indeed, to most of the rest of the solar system. This is because the planets have considerable gravity wells, but the difference in gravitational energy between the orbit of the Earth and, say, an orbit as far away as Mars is not great. A typical asteroid, gliding in its ellipse between Mars and Jupiter, moves at about 9.4 km/sec. Earth moves about the Sun at about 30 km/sec. That difference of 6 km/sec (the delta-V, in NASA-speak) is what a spacecraft must provide to move between those two regions.

Velocities are easy to think about, even if they're in the ball park of miles per minute. But what rockets provide is energy, which is proportional to the square of velocity. This means the difference in rocket fuel between 24 km/sec and 30 km/sec is six times larger than the simple difference in velocities would make you believe. So saving velocity changes is big business.

There are other factors, too. Many asteroids do not orbit the Sun in precisely the same plane as Earth (the plane of the ecliptic); changing that inclination costs about a km/sec for each two degrees of alteration. To reach most interesting asteroids requires changes of about four degrees, so the total cost in "delta V" is 10 km/sec.

Going from Earth's surface to the Moon's orbit requires 11.4 km/ sec, about the same energy cost.

To someone contemplating a livable satellite in roughly Lunar orbit, then, getting raw materials from the asteroids is equivalent in energy expenditure to lifting resources from Earth. Even though the asteroids are, in total flight distance, a thousand times farther away, they have advantages.

Maneuvering in deep space is a matter of slow and steady, not flashy and dramatic. High-thrust takeoffs from Earth are expensive, and payloads have to be protected against the heat of rapid passage through the atmosphere.

A tugboat spaceship operating in the asteroid belt could load up long chains of barges and slowly boost them to the needed 10 km/sec, taking perhaps months. Powered by lightweight photovoltaic cells, the tugboat runs on sunlight, with perhaps backup from a small nuclear reactor. It would sling mass out the back at high speed, using an electromagnetic accelerator as a kind of electrodynamic rocket. The mass would come from the asteroids themselves, which are rich in iron.

Once the barges were set on their long, silent, sloping trajectory toward the inner solar system, the tug and crew would cast off. They would return to the asteroid mining community, to start hooking up to the next line of barges.

At the end of their eight-month flight to Earth, the barges would be pulled into rendezvous with a factory that would break down the metals they carry. The cheapest method of using these resources would be to manufacture finished goods in orbit, taking advantage of the ease of handling provided by low or zero gravity. Otherwise, the costly shipping of raw materials down to Earth's surface becomes necessary.

But such shipping assumes that Earth will forever be the final market. It would cost perhaps $10,000 per pound to move metals from the asteroids to near-lunar orbit, a cost far higher than that of supertanker transport on our oceans. And the manufactured product would still need to be moved to the market for it on Earth. Clearly a better way would be the construction of colonies and factories in orbit themselves.

The logical end of this argument is simply to move an asteroid into near-Earth orbit. This demands the setting up of electromagnetic accelerators on a metallic asteroid and slinging mined packets of iron-rich mass aft to accelerate the whole body.

The tugboat becomes the cargo. Studies show that at the optimum exhaust velocity of the slung pellets, about a quarter of the asteroid's mass would have to be pitched away at about 50 km/sec to get the asteroid into near-Earth orbit. We can already do this with electromagnetic guns developed in the U.S.

In moving the asteroid, one shapes it, hollowing it out for the mass to sling overboard, and applying spin to produce centrifugal gravity on the inner surface. We know a good deal about what asteroids contain, from studying their reflected light. Even today, prospectors can know more about the composition of an asteroid a hundred million miles away than they can find out, without drilling, about what lies a mile below their feet.

Asteroids should be good sources of the metals hardest to find in Earth's crust. They should also have the structural integrity to sustain a moderate centrifugal gravity on the inside, once a cylindrical space has been bored into them. A simple equation demonstrates the relation between spin and radius:

$$A = R \times S^{2}/1000$$

Here A is the centrifugal acceleration in units of Earth's gravitational acceleration, so A=1 is Earth-normal. S is the spin of the cylindrical space in units of a revolution per minute. R is the radius of the hollowed-out cylinder in meters.

For example, consider a cylinder of 100 meters radius and spinning about three times per minute; then A is near Earth-normal. The importance of this equation is that one can select high R (for a big colony on the inner surface of the cylindrical space) and spin it slowly, or high spin (large S) and a small colony, low R. NASA experiments of the 1960s showed that people in small containers could take spins up to 6 revolutions per minute without disorienting effects.

Living constantly in such conditions demands heavy shielding, about two meters of dirt or rock. This sets a huge requirement for the built-from-scratch O'Neill colony which was to come in the 1970s. That design had to carry this mass in its outer rim and support its centrifugal "weight" with steel struts -- a huge fabrication and construction job, even using raw materials from the Moon. By comparison, a cored asteroid is much safer.

The asteroid's massive outer layer would easily protect against background radiation, especially cosmic rays. These "heavy primaries" flooding our solar system are nuclei of helium, carbon, iron, and higher elements. They smash through matter, leaving a train of ionized atoms that can kill a living cell.

The Apollo astronauts noticed these energetic events as bright flashes in their eyes every few minutes, even in total darkness. Venturing outside both the Earth's atmosphere and, more importantly, its magnetic field which serves as a shield against cosmic rays, the astronauts incurred some nerve and cell damage, though it was insignificant. James Gunn, in his novel Station in Space (1958), presented this as a disquieting detail, a prediction actually, calling our attention to human frailty outside its usual environment.

The hope behind ambitious plans was that opening the solar system to industrial development would provide two important resources sunlight and metals -- right from the start. Early visions considered dropping metal-rich rocks directly onto the Earth, making iron mountains to mine. Imagine having to write the environmental impact report for that today! -- and having to calculate risks, get insurance, and so on.

The second development stage would come atop the first: direct manufacture in space, using the advantages of zero gravity and vacuum.

Chemicals and nutrients mix much more thoroughly in zero gravity, since they do not settle out by weight. Making "foamsteels" with tiny bubbles evenly distributed throughout seems possible, greatly reducing mass while losing little strength. Growing enormous carbon filaments for superstrong fibers seems straightforward. Similar methods, as spelled out in the late G. Harry Stine's The Third Industrial Revolution, sparked the optimism of the 1970s.

Generally, the more scientists learned of space as a real environment, the more hemmed in the writers became. But while the "hard" science fiction authors used these stubborn facts to fashion clever and insightful stories, the visionary intuitions behind the central idea remained plausible, and technical scrutiny supported the high dreams.

Stanley Kubrick's 2001 showed us a classic Bonestell-style space station, complete with interior views. The banality of the character's conversations was a deliberate commentary on the contrast between our closed-in selves and the wonders of our works.

Shortly afterward in the 1970s, Gerard O'Neill, a prominent particle physicist at Princeton University, conducted an advanced engineering feasibility study on space settlements (for undergraduates!), and reexamined these same ideas. O'Neill's group optimistically concluded that the technology already existed. The Moon could be mined as a source of raw materials, and once the first worldlets were built, they would quickly reproduce. The colonies would build solar collectors and beam microwave power back to Earth, plus exporting to Earth manufactured goods.

O'Neill asked whether such a space settlement would be viable. There was the problem of the two meters of necessary background radiation shielding.

Plus, it had to run its ecology on solar energy. How?

A crucial difficulty governs using raw sunlight. Most schemes envision capturing strong sunlight, converting it into microwave energy, then transmitting it by large antennas to Earth, for transformation into electrical power. Later studies showed that unmanned satellites in lower orbits would provide power more cheaply, but these studies led to no projects. As we shall see, the social dimension has loomed large in the plans of even the most detailed technical scenarios.

Direct sunlight is fine and good as a source of electrical power, but growing crops for people in the O'Neill-style colonies is another matter. Plants require considerable power themselves; a square kilometer of prime cropland absorbs a gigawatt of sunlight at high noon--the power output of the largest electrical powerhouses, capable of supporting a city of a million souls.

Sure, under less illumination plants still grow, but evolution has finely engineered them; at a tenth of the solar flux, they stagnate. This means that no artificial environment can afford the costs of growing plants beneath electrical lights.

However, the raw sunlight of space is harsh. Earth-adapted plants would wither under the sting of its ultraviolet rays. There is more solar power available in space, but it is at the high end of the spectrum, which on Earth is filtered out by our ozone layer and atmosphere.

Certainly ultraviolet absorbing canopies can be deployed, but the weather between the worlds has harsher stuff in store. Thin greenhouse shells on O'Neill colonies would not protect against solar flares of such ferocity as occur every few months. Defending people and plants against these fluxes of high-energy particles demands at least five-inch-thick glass, a massive measure.

Indeed, O'Neill colonies have much of their design dedicated to protecting people against solar storms by providing interior shelters. But people can be moved to shelter for a few hours; crops cannot.

In the early 1980s O'Neill spoke throughout the United States to drum up support for his ideas and for the National Space Society, which he founded. Already the O'Neill-colony idea (a term he modestly never used, preferring "L-5," the abbreviation for the orbital Lagrangian point which some thought would make the most stable orbit for a colony) was beginning to fade from the public mind. The 1975-85 spike in oil prices was momentary; fossil fuel would within five years plunge to the same cost level (in inflation-adjusted dollars) as 1950.

O'Neill's basic assumption, that electrical energy would be hard to generate on the Earth's surface without high costs both economically and environmentally, may yet come true, within a few decades. But market forces and improved technology have taken a lot of steam out of the argument.

Still, O'Neill's salesmanship put the entire agenda forward as no other cultural force had. Economics was central to the movement, blended with social ideas. The cover of the paperback edition of his The High Frontier proclaimed: "They're coming! Space colonies -- hope for your future." And the back cover sold space colonies as future suburban paradises, with Earth as the city to flee.

Historical parallels abound. The immigrants of the Mayflower and the Mormons who moved to Utah came with about two tons per person of investment goods. Freeman Dyson in Disturbing the Universe argued that these are better societal models for space colonization than the O'Neill notion of totally planned homes.

O'Neill's detailed "Island One" project would cost about $96 billion in 1979 dollars, and perhaps twice that today. Clearly, such a project would be so massive that only governments could run it. As Dyson remarked, "[Government] can afford to waste money but it cannot afford to be responsible for a disaster." O'Neill argued that his colony could build solar collectors and beam microwave power back to Earth to pay its bills. At the energy prices of the late 1970s, he said, the $96 billion could be repaid within 9.4 years. But a colonist would take 1500 years to pay off the costs by his own labor, which means the colony would always be a government enterprise, subject to the vagaries of political will of those who lived far away -- not a prescription for long-term stability.

Thus Dyson favors asteroid colonization, precisely because it could be done for less and by large families, not large nations. He imagines settlers moving out from early orbital colonies, though not necessarily of the massive O'Neill type. He invokes even scavenging, noting that "There are already today several hundred derelict spacecraft in orbit around the Earth, besides a number on the Moon, waiting for our asteroid pioneers to collect and refurbish them." The satellite business would dearly love to see such debris erased from the equatorial orbital belt, since collisions with them loom now as a significant threat to orbital safety.

O'Neill revisited ideas that had been around for most of a century, both in serious speculation and in visionary fiction, but he gave them the plausibility of the latest styles and engineering methods in space exploration. As Gary Westfahl's pioneering study, Islands in the Sky (1996) reminded us, the extensive science fictional history of this idea had been forgotten.

Westfahl writes that "there are four times during the development of the genre when space stations emerged as important factors--and four times when they faded from view." These were in the late nineteenth century, the 1930s, the 1950s, and the 1970s. Since science fiction has often predicted developments in space travel, this repeated decline of interest in space habitats shows that science fiction is not immune to the waxing and waning interest in ideas as they emerge in serious speculation and in popular culture. The reasons for the decline in project planning may have been human fears, lack of political will, and economic cold feet, with science fiction following suit, often with critical or disappointed treatments of the idea -- except in the cases of innovative authors, who in more disillusioned periods might seem out of touch to readers and critics.

Our construction of the U.S. Space Station Freedom in the late 1990s portends a fresh burgeoning of an idea that in science fiction has become a staple used for both utopian and dystopian visions.

In both fictional worlds and in the possibilities waiting in the real world, to
confront space habitats seriously means a complete change in our outlook toward
the solar system. Many have argued persuasively that the grand project of uplifting the bulk of humanity to the economic level of the advanced nations requires use of the solar system's resources, especially since manufacturing entails a level of pollution that the biosphere cannot abide. (This hard fact makes impossible the more cozy stories of expansive industrial futures.)

To use the resources of our sunspace demands treating it as a genuine "new frontier," not just as a place to go and come back from. But the fundamental changes needed to create a sunspace society are simply too radical for many people, who see such changes as either frightening or infinitely risky. Perhaps
it is right for social systems to leave innovation to the visionaries and pioneers; either they will succeed or fail, thus alerting the culture about which way to grow.

Unfortunately, our skeptical culture's critical resistance may also destroy valuable developments, leaving them to emerge at a later time or to die.

The style of discussion and pictorial presentation of skylife changed by the 1970s, but the substance was the same. Once again it dawned on researchers -- scientists and engineers as well as writers of science fiction -- that the planet of our origin may not necessarily be the best place to carry on the business of civilization; that this inadequacy, born of limits that threatened to choke off the possibilities made plain by our increasing knowledge and technology, might hold for all natural planets; and that sooner or later, we might have no choice but to build the city of man elsewhere.

Next time, I'll consider how it all might turn out.