Paths to Space Settlement

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"Earth is the cradle of humanity, but one cannot stay in the cradle forever," Konstantin Tsiolkovsky

I. Abstract

A number of firms are developing commercial sub-orbital launch vehicles to carry tourists into space. Let's assume they attract many customers and become profitable. The next, much more difficult, step is to develop orbital tourist vehicles and space hotels to go with them. These hotels will require maids, cooks, waiters, concierges and so forth, some of whom may decide to stay, becoming the first permanent residents in space. A luxury hotel plus good medical facilities could provide low-g living for wealthy disabled individuals where wheelchairs and walkers are unnecessary.

In the meantime, humanity could choose to solve, once and for all, our energy and global warming problems by developing space solar power. To supply a substantial fraction of civilization's 15 TW[a] energy consumption would require an extremely large number of launches, the ability to build extremely large structures in orbit, and eventually tapping the Moon and Near Earth Objects (NEOs) for materials to avoid the environmental cost of mining, manufacturing, and launch from Earth.

The first step towards NEO mining is to locate them. As a large fraction, roughly 30%, of these will eventually impact Earth, locating and characterizing the NEO population is essential for planetary defense. Furthermore, it would be prudent to deflect a representative set of non-dangerous NEOs to insure that we know how to do it should a NEO on an imminent collision course with Earth be found. A representative set would include at least one of each major type of NEO since these have different physical properties and thus may require different deflection techniques. This would give orbital space settlement designers a known source of materials and the means to move them if necessary.

If these paths are taken, each step of which is justified in its own right, humanity will have excellent launch, small orbital living facilities, the ability to build large objects in orbit, and access to extra-terrestrial materials – most of what is needed to realize Gerard O'Neill's orbital space settlement vision.[1,2] At that point, some extremely wealthy individuals may build themselves a small orbital habitat so they live only with like-minded individuals. The first, and most difficult, orbital space settlement will be built.

These are paths to space settlement.

II. Introduction

Although humanity has always lived on Earth, mankind is now space-faring. In the 1970s, Princeton physicist Gerard ONeill led two Stanford/NASA Ames Research Center summer studies that supported the feasibility of kilometer-scale orbital cities.[1,2] While the Stanford/Ames studies established the feasibility of orbital space settlement, they assumed a massive government funded project to build them paying for it with solar power satellites. It has been thirty years since those early studies. No massive government funded project has been initiated and there is no prospect that one will start anytime soon. We need another way.

Before describing that way, the paths, let's review some of the basics of space settlement.

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[a]TW = terawatt, a trillion watts.

A. Where

Orbital settlements are only one potential target for early space settlement. Indeed, Earth's Moon and Mars are usually considered better locations. While we are accustomed to living on the outside of a large planet and these bodies provide easy access to materials, there are substantial reasons why Earth orbiting settlements will come first. Specifically,

1. Rotation of orbital settlements can achieve 1g (pseudo-)gravity levels in the primary living areas. Rotation of lunar or martian habitats is impractical, so settlers will live at 1/3 (Mars) or 1/6g (Moon). Children raised in low-g will, at a minimum, almost certainly be too weak to visit Earth. There may be other serious problems as well. No children have ever been exposed to low-g and the consequences are unknown.

2. The first orbital settlements can be placed quite close to Earth, a few hours travel time away. By contrast the Moon is days away and trips to Mars require many months.

3. Continuous, ample, reliable solar energy is available in most orbits. The Moon experiences two week nights. Solar energy on Mars is half as dense than at Earth orbit. With a few exceptions near the lunar poles, any point on the Moon and Mars, of course, receives sunlight only half the time.

4. Radiation levels in orbit are twice that of the Moon and Mars [b], but even there radiation levels are high, too high for settlers to spend significant time outside. Since one will rarely go outside, habitats must be large to be livable. The weightless environment on orbit is much better adapted to building extremely large habitats, ideally kilometers across, than even the reduced gravity of the Moon and Mars.

5. The combined surface area of the Moon and Mars is roughly a third the surface area of Earth, about 40% greater than Earth's land area. The livable surface area inside orbital space settlements is limited by the total mass available for radiation shielding. Asteroidal resources are easily sufficient for orbital settlements with a total livable surface area from 100-1000 times the surface area of Earth[c].

6. Near-Earth orbital settlements can service our planet's tourist, exotic materials and energy markets more easily than the Moon; and Mars is too far away to easily trade with Earth. Both have significant gravity wells that makes transportation more difficult than for orbital settlements.

Orbital settlements have a major problem relative to the Moon or Mars: all the materials must be imported. A great deal of material is needed because all space settlements require shielding to protect inhabitants from the extreme radiation in space and the simplest shield is several tons of material per square meter of surface area. Thus, millions of tons of material is required per habitat. This problem can be overcome by co-orbiting settlements with asteroids. There are approximately 900 asteroids larger than 1 km in Earth approaching orbits, and about half cross Earth's orbit. Each with a mass of, very roughly, a billion tons or more. This is more than sufficient for a whole community of orbital space settlements. In addition, a 200-meter diameter NEO has enough materials for a good-sized space settlement, and there are probably 100,000 NEOs in this size range. Many of these smaller asteroids are energetically closer than the Moon, although travel times are typically much larger. It is even possible to use lunar gravity assists to bring small NEOs into Earth orbit to supply materials for settlement construction.[3] In any case, materials access is not a show stopper.

B. Why

It has been argued that any space settlement is a waste of time and that the massive resources necessary for success could be better used on Earth. The same argument could have been used by sea creatures before the colonization of land and suffers from the same deficiency. Namely, spreading out is a very effective

[b] Half of galactic comic rays are intercepted by the body.

[c] This assumes that most of the mass of a settlement is radiation shielding. The mass of Ceres, the largest asteroid, divided by the mass of shielding needed for each square meter of space settlement living space, produces the factor indicated. The spread is due to uncertainties in shielding mass needed and the mass of Ceres. The more accessible Near Earth Objects (NEOs) has a mass of about 10^{-5} of the asteroid belt and could give us a starting point of about one percent of the Earth's surface area.

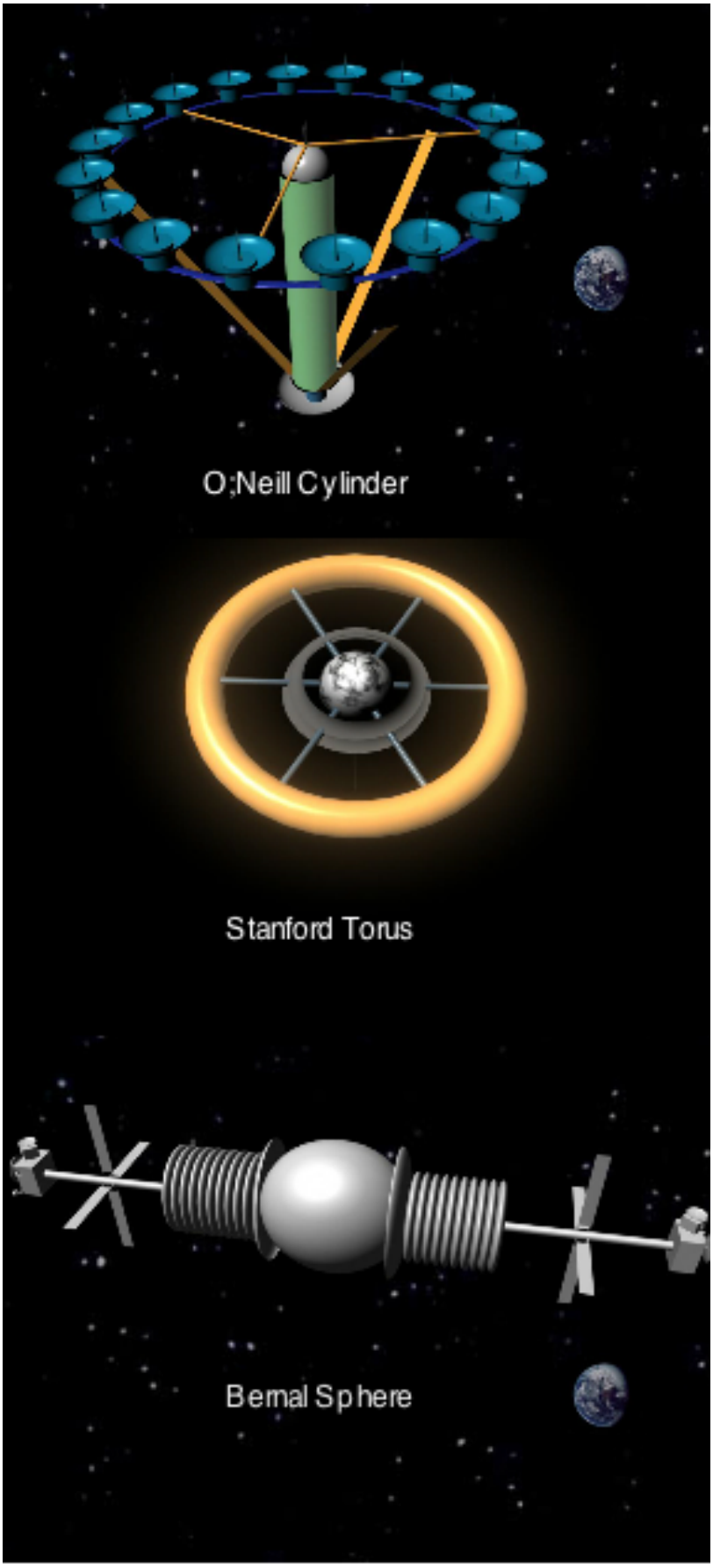

Figure 1. Settlement designs from the 1970s

survival strategy [d]. Species confined to a single, comfortable environment frequently find themselves on the endangered species list or extinct. Homo sapiens dominance is much shorter than that of the dinosaurs and there are numerous asteroids like the one that destroyed them. That asteroid, apparently, killed almost everything above ground. Humanity wouldn't survive such a strike any more than the dinosaurs did.

Similarly, civilizations that fail to grow, that look only inward, often find themselves under the thumb of more vigorous, expanding groups[e]. Growth leads to power and wealth, particularly in space. For example, the total energy available in this solar system is 2.2 billion times greater than that on Earth[f]. Or consider that one smallish Earth-crossing asteroid, 3554 Amun, contains $20 trillion worth of materials[4] and there are are thousands of such asteroids. Today it is very difficult for civilizations to grow on Earth; all the territory is taken and conquest doesn't work well in an era of massive arsenals of nuclear tipped missiles and deadly effective insurgencies. Space offers an arena to grow without military conflict, and that growth can be massive.

As we have alluded to, space settlement may eliminate certain kinds of wars; namely, wars generated by competition for resources. As the resources of space are so vast it is likely that exploiting them will be far easier and cheaper than fighting to take someone else's resources away. Competition for resources is a major cause of war: examples include the German desire for Lebensraum (living room) and the Japanese need for oil in World War II; and the seemingly endless series of wars around the Persian Gulf driven, at their core, by access to oil.

Of course, settling a new land is not attractive if it's not a nice place to live. The residents of space settlements will, of necessity, be technologically sophisticated. They are not likely to be driven off of Earth by hunger. Fortunately, there are a few features of orbital real estate worth mentioning:

1. Great Views. Many astronauts have returned singing the praises of their view of Earth from orbit. Low earth orbit settlements, and eventually settlements near Jupiter and Saturn, will have some of the most spectacular views in the solar system. Of course, all space settlements will have unmatched views of the stars, unhindered by clouds, air pollution, or (with some care) bright city lights.

2. Low-g recreation. Consider circular swimming pools around and near the axis of rotation. You should be able to dive up into the water! Sports and dance at low or zero-g will be fantastic. For dancers, note that in sufficiently low gravity, always available near the axis of rotation, anyone can jump ten times higher than Baryshnikov ever dreamed.

3. Environmental Independence. On Earth we all share a single biosphere. We breathe the same air, drink the same water, and the misdeeds of some are visited on the bodies of all. Each space settlement is completely sealed and does not share atmosphere or water with other settlements or with Earth. Thus if one settlement pollutes their air, no one else need breathe it.

4. The ultimate gated community. On Earth it is essential that diverse groups learn to live in close proximity. It's hard to live with six or seven billion homo sapiens, and some people do not do it gracefully. Space settlements offer an alternative to changing human nature or endless conflict – the ability to live in fairly homogeneous groups, as has been the norm throughout hundreds of thousands of years of human existence. Those who can not get along can be separated by millions of miles of hard vaccum, which in some cases seems necessary. All entry into a space settlement must be through an airlock, so controlling immigration is trivial.

[d] In the case of moving onto land, the immediate motivation may have been to escape predators, but the effect was to spread out.

[e] The classic example is China. Between 1400 and 1450 China's Ming dynasty sent a mighty fleet to explore Asia, the Mid-East, and Africa. Had China continued this expansive policy this piece might well have been written in Mandarin. However, the Chinese who favored continuing expansion lost an internal power struggle, and by about 1500 the fleet had been destroyed by court factions opposed to growth. Laws were passed prohibiting the construction of large ocean-going ships. The opponents of growth claimed that the fleet was too expensive and the resources were needed to solve China's problems at home. A few years after the Chinese fleet was destroyed, the Portuguese seized the Chinese island of Macao. Expansionistic European powers eventually divided China into spheres of influence and the Chinese spent the next few centuries under the thumb of foreigners. The people suffered horribly and China did not become truly independent until the 20th century.

[f] The vast majority of the energy available on the Earth comes directly from the Sun, which generates all of the food and keeps the whole planet at temperatures suitable for life. Only one part in 2.2 billion of the Sun's energy falls on Earth, the rest is radiated away into space.

5. Custom living. Since the entire environment is man-made, the residents can get what they want. Like lake front property? Make lots of lakes. Like sunsets? Program sunset simulations into the weather system every hour. Like to go barefoot? Make the entire environment foot-friendly.

Space settlement development is an enormous engineering task, far more difficult than any we have attempted to date; significantly more difficult than, for example, building New York City. While the first space settlements will undoubtedly be much smaller than the city that never sleeps, New York has breathable air, drinkable water, reasonable temperatures, and is surrounded by farmland. None of this is true for space settlements.

The first space settlement will be, of course, the most difficult to build. Once one has been built, we will know at least one solution to all of the major problems and a great deal of infrastructure will have been created that can be reused. To build the first settlement major problems that must be solved include:

1. Earth to Orbit transportation. While we have rockets that can lift people and supplies from Earth to orbit, existing vehicles are completely inadequate for space settlement. They are like the Viking galleys that first brought Europeans to North America, incapable of sustaining real settlements. We need the equivalent of the sailing ships that later brought tens of thousands to the "new world."

2. Large scale orbital construction. Space settlements need to be big, kilometer scale at least. Residents will rarely leave the settlement, so a can 20-30 meters across will be inadequate. I live in a California beach town about a kilometer and a half in each dimension. It would be a little cramped, but I can image living in town almost all the time. Indeed, our peasant ancestors rarely traveled more than a kilometer or two from the place of their birth.

3. Stay Alive in Orbit. Every day, every settler will need food, water, and air. On Earth food and air are produced by an enormous web of life and the water is cleansed and recycled by massive, solar-driven processes. None of this is available in orbit. The ISS and other human spacecraft depend on food brought from Earth, limited water recycling and electromechanical CO_2 to O_2 conversion. For viability, space settlements must reproduce, on a much smaller scale, the biological processes that produce our food, breathable air and clean water. Limited experiments have been conducted on Earth.[5]

4. Pay For It. Space settlements will never be built without massive funding to develop the technology, build the infrastructure, and ultimately create functioning orbital space settlements. Today's financial environment suggests that private enterprise cannot make money even if they could build a settlement today, and government is not likely to add a fiscal line item for space settlement anytime soon. We need another way.

III. Paths to Space Settlement

This paper proposes developing much of the technology and infrastructure needed to build practical orbital space settlements by piggy backing on relatively near term developments that can pay for themselves. Specifically,

1. Space tourism. Flying people into space for the same reason people go to Hawaii on vacation, they want to go and will pay for it.

2. Space solar power. Collecting energy in space, converting it to electro-magnetic radiation, and sending it to Earth to supply vast quantities of clean, reliable energy with a plethora of benefits.

3. Planetary defense. Preventing large asteroids and comets from striking Earth with devastating consequences.

IV. The Launch Problem

The first two of these paths address the most important problem to be solved: today's rockets cost many thousands of dollars to place a single kilogram of anything in orbit, and these same rockets fail completely roughly one percent of the time, killing everyone and destroying everything on board. Without greatly improved transportation, we will never settle the cosmos.

Satellites are usually more expensive than the rockets that launch them, so why not reduce the cost of satellites rather than that of rockets? Satellites are expensive, in large part, because of the limitations of rockets. As it costs thousands of dollars per kilogram to launch satellites into space, spacecraft must be as light as possible. Since bigger, heavier components are stronger, this means exotic, expensive materials must be used and lots of expensive testing and analysis is required to determine exactly how light components can be. It also means that the solar arrays that power most spacecraft must be as small as possible, so spacecraft must get by on as little power as possible. Again, a great deal of analysis and testing is required to determine exactly how much power is necessary and expensive special low-power components must be used.

Perhaps worse, the high cost of launch means no repairman and no spare parts can be brought from the factory or warehouse. Spacecraft must get by on what they are launched with. For reliability, spacecraft must be redundant, with multiple ways of accomplishing the same thing so the mission can continue even if some components fail. This increases cost directly, of course, and requires even more analysis and testing to make sure redundant pathways work together.

Not only are today's launch vehicles too expensive, but until recently things were not improving. Indeed, over the last 50 years a wide variety of launchers have been developed up to and including the U.S. Space Shuttle, the most capable space vehicle to date. The Saturn V used to send men to the Moon in the 1960s and 1970s was less expensive, measured in man-hours per kilogram to orbit, than most of today's launchers; and by a fairly large margin.[6] Furthermore, the Saturn never suffered a catastrophic failure, although there were many close calls. By contrast, shuttle costs ran approximately $1,200 million per flight[g] to deliver, at most, a few tens of tons of payload to the International Space Station, and the shuttle suffered two catastrophic failures in a bit over a hundred flights. Bucking the cost trend, SpaceX has recently developed and flown the Falcon 9 and announced development of the larger Falcon Heavy. These vehicles, particularly the Falcon Heavy, cost significantly less per kilogram to orbit and suggest that there is hope the transportation problem can be solved.

The core reason launch is so expensive, besides the inherent difficultly of reaching orbit, is very simple: low volume. There were only 55 launches in 2005.[7] In all of history there have only been a few thousand. By contrast there were hundreds of thousands, if not millions, of flights in the first 50 years of aviation and today there are over one half billion person-flights yearly just in the United States. To get good at something as difficult as getting to orbit will require a great deal of practice, perhaps tens of thousands of launches per year. None of the traditional uses of space: communications, Earth observation, military, humans-in-space at government expense, or science requires anything resembling this launch rate, but space tourism and space solar power do.

V. Space Tourism

At the right price, space tourism would require thousands of flights per year. In 1994, Patrick Colins, et al.[8] found that the Japanese market could provide about one million customers per year for space flight at about $10,000 per passenger. In 1996, Sven Abitzsch[9] found that approximately 20% of the U.S., Canadian and German populations and nearly 40% of the Japanese population would be willing to pay six months salary for a trip into space. This represents nearly a hundred million people. In 1999, Oily Barrett[10] found that 12% of United Kingdom residents, representing 3.5 million people, said they were willing to pay over $10,000 for a trip to space. In 2001, Crouch[11] surveyed the literature and found that the global space tourism market is a strong function of price. Table 1 shows Crouch's demand vs. price per ticket. If these projections are optimistic by no more than a factor of ten, and the price per ticket can be brought down to about $10,000, there is good reason to believe space tourism can support tens of thousands of launches per year, a rate comparable to the early decades of aviation [h].

Considering space tourism from the easiest to the hardest, the following progression seems to make sense:

1. Sub-orbital flights. These flights go more-or-less straight up then straight down again. The whole flight may be less than an hour and tourists are in space for a few, extremely exciting, minutes.

[g] This is calculated by dividing the yearly cost of the shuttle program by the number of flights. There were 10 flights from 2006-2008 while the shuttle budget was around $4 billion/year

[h] It seems obvious to many that airline-style operations are required to make space access affordable: fully reusable vehicles, operations costs a small multiple of fuel costs.

price/ticket (1994 $)	passengers/year
$1,000	20 million
$10,000	5 million
$100,000	400 thousand
$250,000	1,000
$500,000	170

Table 1. Projected demand for orbital tourism as a function of price[11]

2. Orbital flights. The vehicle enters orbit and circles Earth for some time before returning. Such flights might last many hours.

3. Orbital hotels. The vehicle docks with a hotel in orbit then returns for more passengers. Visits might be anywhere from a few days to a few months. Interestingly, we already have a space hotel. The International Space Station (ISS), built at fantastic government expense, has hosted a number of tourists.

4. Zero/Low-G retirement homes. Weightlessness could be of great benefit to those confined to wheelchairs on Earth. Adding a first-rate medical facility to an orbital hotel makes a very desirable home for the disabled – you don't need walkers or wheelchairs.

5. "Special group" habitats. Some of these groups are quite wealthy and may want to build themselves a place in space where they can live in a very homogenous community.

6. Space settlements. Solving the basic problems and lowering the price through the previous steps may, at long last, bring space settlement within the economic grasp of the upper middle class.

A. Sub-Orbital Tourism

Spurred by the $10 million Ansari X-Prize Scaled Composites, LLC built and flew the human piloted SpaceShipOne into space twice in as many weeks in 2004. While Scaled reportedly spent considerably more than the purse to win, other commercial deals involving advertising and technology sales netted a small profit.[12] As a direct result, Scaled is now flight testing SpaceShipTwo for Virgin Galactic.[i] Virgin Galactic is building a space port in New Mexico and intends to fly tourists into space for $200,000 per seat. They are taking reservations and as of 2009 had booked the first 290 customers, collecting $40 million in deposits.[13] Significantly, Virgin has a competitor in RocketShip Tours using an XCOR Aerospace vehicle. RocketShip Tours is asking $95,000 per passenger for flights in the not-too-distant future.

Time will tell if the sub-orbital tourism business is profitable; we will know in a few years. The industry must avoid early accidents that kill some tourists and scare off the rest. If this industry is successful it will conduct many hundreds if not thousands of launches a year, developing the experience base to take on the much more difficult problem of reliable, inexpensive orbital tourist flight.

B. Orbital Tourism

Orbital flight is far more difficult due to much higher velocities required, longer exposure to the space environment, and high-speed atmospheric reentry. To be in orbit a spacecraft must travel fast enough horizontally so that as the spacecraft falls towards the surface it travels far enough to curve around Earth rather than crash into the surface at about 25,000 km/hour. Using current technology this involves very large forces, high temperatures and other major challenges. Not surprisingly, launch failure is common, particularly during the first few launches of a new vehicle. Only 5 of the first 9 Pegasus launches succeeded, 9 of 20 for Atlas, 3 of 5 for Ariane, 9 of 18 for Proton, and 9 of 21 for Soyuz.

In "Contest-Driven Development of Orbital Tourist Vehicles,"[14] this author proposed using prizes to develop orbital vehicles for the tourism industry. The idea is to provide a series of prizes for successive

[i] Virgin Galactic is part of the Virgin Group run by Richard Branson. The Virgin Group is a large commercial enterprise including airlines, hotels, telecommunications, and much else.

Figure 2. Scaled Composites' SpaceShipOne on its way to winning the Ansari X-Prize by reaching space. Image credit Scaled Composites, LLC.

Figure 3. Virgin Galactic SpaceShipTwo in flight test. It is expected to carry paying customers soon. Image credit Virgin Galactic.

launch of people into orbit. The dollars-per-passenger ratio decreases as more and more passengers are flown; starting at something near current costs ($30 million) and ending at the desired price point of $10,000. A simple computer program was developed to explore the implications of this model. Using development cost and operations data from commercial firms circa 2006 it appears that one to eight billion dollars in prize money might be sufficient to get the orbital tourism market going. For reference, space shuttle flights cost over one billion each! The usual experts may say such a prize could not work, but they were wrong about the Ansari-X prize. Of course, prizes may fail to stimulate the desired development, but in that case no prize money need be spent.

In a dramatic pro-free enterprise and pro-space settlement move, president Obama recently proposed a $6 billion program (subsequently reduced but not eliminated by Congress) to develop private, commercial human space launch. Successful candidates will get contracts to fly astronauts to the ISS. Several companies, both new and old, are positioning themselves to win these fixed-price contracts. If this is successful, the winning companies would develop launchers suitable to fly orbital tourists and provide customer transportation to private space stations, which brings us to the next step.

C. Orbital Hotels

Space Adventures, Ltd. and the Russian space program have flown several tourists to the ISS, reputedly for about $20-30 million apiece. Space tourism may be the legacy of the ISS, and it could be a very good one indeed.

The Russians appear to have made a profit flying tourists, but this profit is enabled by massive government expenditure to build the ISS (roughly $100 billion). Furthermore, the tourists fly in a spare seat on a launch paid for because the Soyuz capsule is the ISS lifeboat and must be replaced every six months. The Soyuz has three seats but only requires two crew members to operate. Without these government subsidies the price of a tourist launch to the ISS would be much larger.

However, the private sector is coming to the rescue. Bigelow Aerospace[j] has flown two sub-sized, pressurized space stations, Genesis I and Genesis II. They are planning to launch Sundancer, suitable for a crew of three, whenever a private launcher is available to deliver customers. Both Genesis and Sundancer are based on soft-skin pressurized modules using technology originally developed but abandoned by NASA. Bigelow has brought the technology to in-space operational status and demonstrated a number of advantages over traditional, aluminum-skin space station designs.

Although Mr. Bigelow made his money in the Las Vegas real estate business, including hotels, Bigelow Aerospace does not consider tourism to be their primary market. Instead, their target market is low-cost national human space programs. While the U.S., Russia, and China have spent hundreds of billions of dollars to develop human space flight programs,[k] a human space mission using Sundancer might cost as little as a few hundred million for transportation and housing, meaning that many countries could afford an indigenous human space program of their own.

If orbital hotels come to be, they will require staff: maids, cooks, maitre'ds, managers, etc. Eventually, some of these people may decide to stay permanently and find a way to do it, becoming the first people to make a home in space.

D. Zero/Low-G Retirement Homes

If orbital hotels develop into a profitable business, it is reasonable to expect that, eventually, quite a few will be built, each larger and more luxurious than the last – until someone starts building budget versions for the cost conscious. Severely handicapped individuals might at some point note that living in a zero-g environment means you don't need a wheelchair or a walker; and you will never fall and break your hip. They may not want to return from their week-long vacation. To serve as a retirement home for those who have a hard time with the demands of Earth's gravity, there is only one essential element missing from an orbital hotel: health care.[l]

For more-or-less healthy people visiting for a week, some sort of minimal health care for emergencies is needed. For older, handicapped, and generally somewhat sick individuals, much more capable facilities are

[j] See http://www.bigelowaerospace.com/

[k] Perhaps a bit less in China's case, but data are unavailable

[l] Actually, there is a second – the grand kids must want to visit. To get to this point the launch problem will have to have been solved, and play in zero-g should provide the motivation.

required. While this will take some work, it is a relatively small step beyond orbital hotels. Old, handicapped, wealthy retirees may be the second class of permanent residents in space, after hotel staff.

There is a major fly in this ointment. Most rockets are a pretty rough ride accelerating from a stand still to orbital velocity in a few minutes, not recommended for the old and infirm. There is another possibility. Instead of depending on high temperatures and tremendous forces, it might just be possible to float into orbit over many days rather than in a few exciting minutes.

The book *Floating to Space* by experimentalist John Powell of JP Aerospace lays out a conceptual solution that could conceivably work. The basic idea is to use three types of lighter-than-air ships. The first travels from Earth to about 120,000 feet. Research balloons do this all the time. The second lives permanently at about 120,000 feet. Research balloons have stayed this high for long periods of time, but permanence requires on-site maintenance. JP Aerospace has demonstrated some of the key capabilities in ground test. The last vehicle is a km-scale, inflatable, hypersonic flying wing that uses hybrid chemical-electric thrusters to achieve orbital velocity over a period of days. This may not be feasible.

It's not clear if this third vehicle can work, but if it can the key is that the atmosphere doesn't end, it extends indefinitely becoming more and more diffuse as one gets further from Earth. The third vehicle concept takes advantage of this to float to about 180,000 feet. This is possible because it is assembled at the 120,000 base and need not be strong enough to survive in the denser lower atmosphere. This means a thinner skin and hydrogen rather than helium to fill the balloons as there isn't enough oxygen at these altitudes to support combustion. The vehicle's enormous size allows aerodynamic forces generated by the upper atmosphere to provide lift. This lift allows very slow acceleration into orbit. Slow acceleration allows use of extremely efficient propulsion. However, current engines do not provide enough thrust to overcome the drag of even the extremely diffuse upper atmosphere. JP Aerospace expects to test a new chemical-electric hybrid engine in the near future that should come closer to the required performance. Deorbit is relatively easy - pitch the vehicle up to expose its enormous cross section to atmospheric forces. This will decelerate the vehicle enough in a diffuse atmosphere that reentry heating is minor. The orbital vehicle then docks with the station at about 120,000 ft. Unlike today's rockets, there are no high temperatures, no enormous forces, and time is measured in hours not milliseconds.

If this doesn't work, which is quite likely, then it will be necessary to develop more conventional rockets with a smoother ride. Difficult but hardly impossible.

E. Tourism Concluded

Tourism can supply the launch rate needed to develop low-cost human access to space. Orbital hotels and retirement homes will be much more economical if they can recycle their air and water, grow most of their own food, and recycle waste – all essential for space settlement. As we can expect many hotels and retirement homes to be built, there will be ample opportunities to develop techniques and a strong profit motive to do so.

However, at least at first, there is little incentive to develop lunar or asteroidal resources to support space hotels and retirement homes. Launch prices must be reasonably low in any case, just to get the people back and forth, so the expense of developing lunar or asteroidal resources needed to build massive space settlements may not be worth it. In addition, the tourism business may, for a variety of reasons, fail. Fortunately, space solar power (SSP) also needs robust launch and SSP and planetary defense can both help develop extra-terrestrial resources.

VI. Space Solar Power (SSP)

The basic idea behind SSP is to build huge satellites (PowerSats) in Earth orbit to gather sunlight, convert it to electricity, and transmit it to Earth wirelessly. This is technically feasible. Most satellites are powered by solar energy today and wireless energy transfer has been demonstrated with very high efficiency. Economic viability is more problematic. SSP should be considered a high risk, huge payoff investment.

If we succeed the payoff is fabulous: just 320 solar power satellites, 2 km radius each, could supply a terawatt (one trillion watts)[m] of energy continuously and extremely predictably. Less than five thousand such satellites could deliver the equivalent of all the energy produced today (roughly 15 TW). At a 10 km radius, fewer than 200 satellites are necessary.

[m] Assuming 20% end-to-end efficiency.

Figure 4. Bigelow Aerospace's Genesis I sub-sized space station in orbit. Image credit Bigelow Aerospace, LLC.

All this energy can be produced with no operational emissions of any kind and, eventually, the mining, construction, and disposal of the satellites can be conducted entirely outside of the Earth's biosphere. SSP is potentially one of, if not the, most environmentally sound large scale energy systems. If PowerSats are built from lunar materials, SSP has only two major terrestrial environmental impacts: the antenna and the power beam. The antennas must be built on Earth and take up a fair amount of land, although most sunlight passes through microwave antennas so the land below can be used or let go wild. For greatest efficiency and profit the beam's frequency must be chosen to minimize loss into the atmosphere, which is exactly what is needed for minimal environmental impact. Thus, profit and the environment are perfectly aligned. If PowerSats are built from materials launched from Earth, the environmental cost of the launch, mining and manufacture must be borne by the biosphere. This will almost certainly be necessary at first to minimize the already difficult task of getting SSP started, but eventually PowerSats built from lunar materials can eliminate these environmental costs. In either case, however, SSP environmental impact compares very favorably with coal, oil, nuclear, hydro and even ground solar and wind for one simple, fundamental reason: for all other energy sources all of the work is on Earth, with the attendant environmental damage. With SSP, most of the work is done thousands of kilometers away.

Producing one terawatt of power with SSP would require roughly 4,000 trips by the largest launcher ever designed, the Sea Dragon, capable of lifting 500 tons per flight.[n] To lift the equivalent using the shuttle would require over 66,000 launches.[o] Thus, if SSP can become profitable it creates an enormous market for launch vehicles.

If SSP's worst critics are to be believed, we must accomplish something close to the following:[p]

1. Bring the cost of space solar energy collection down to near $1,000/kw, from roughly $750,000/kw today. This will be difficult but perhaps not impossible. Today's satellite power systems are made in very small quantities, a few hundreds of kw per year. For PowerSats, the demand will be thousands of times greater allowing huge economies of scale.[q] Not only have similar cost reductions been accomplished by economies of scale in the past,[r] but the demand for PowerSats is large enough to enable new concepts, such as in-space manufacture of simple mirrors, that may radically reduce cost.

2. Bring the mass of PowerSats to 5 kg/kw. Solar-dynamic systems developed and ground-tested at NASA Glenn Research Center are estimated to achieve this.[s] Solar dynamic refers to concentrating sunlight with mirrors to heat a fluid that drives turbines to produce electricity. Somewhat more long term, PowerSats using thin film solar cells and fiber lasers for infra-red power beaming may achieve around 4 kg/kw at 2% end-to-end efficiency or, following some research and development, 0.72 kg/kw at 11% efficiency.[15]

3. Keep maintenance costs to not much greater than those for ground solar systems of similar size. This may be the most difficult, and is extremely difficult to predict. Robots controlled by operators on the ground may be able to achieve this. Unlike most of the others, this area is not being developed today.

4. Develop the antennas to transmit power from space to Earth with reasonable efficiency and minimal atmospheric impact. Ground tests indicate that very high efficiencies can be achieved and efficiency correlates with minimal environmental impact. The theory and engineering of electro-magnetic antennas is very well understood, so there is good reason to believe this can be accomplished.

5. Bring the cost of launch down to $350/kg. This figure can be larger if the 5 kg/kw target can be beaten. If $0.72/kg can be achieved, launch costs of of $2,430/kg are acceptable, about the projected cost of a Falcon Heavy. In April 2001 SpaceX announced their Falcon Heavy, which is expected to take 53,000 kg to orbit for $125 million, or about $2,400/kg to LEO. Unfortunately, PowerSats need to

[n] Assuming 2 kg of PowerSat per kw of solar energy delivered. This is subject to a great deal of variation.

[o] Assuming 30 metric tons per launch.

[p] Most of these items were identified by Steve Fetter in an paper critical of SSP. Fetter's paper can be found at www.publicpolicy.umd.edu/Fetter/2004-P&S-SSP.pdf. This author's rebuttal to Fetter can be found at space.alglobus.net/papers/FetterResponse.html.

[q] In this context, economies of scale refers to mass production of very large numbers of identical items, which can be much cheaper than the hand-crafted space systems of today.

[r] Consider the computer keyboards used by air traffic controllers. These are custom, not used anywhere else, and are produced in low volume. They cost approximately $2,500. In 2009 one could buy a standard, mass-produced computer keyboard at Office Depot for as little as $13. The price difference is roughly a factor of 192, not too far off of 750.

[s] See "An Isoinertial Solar Dynamic Sunsat" by Philip Chapman at http://space.alglobus.net/papers/PhilChapmanSSP.pdf.

be in a much higher orbit than LEO and that reduces the payload of any vehicle; so we are not quite there, but we're close.

A less developed, but perhaps better, option is the Sea Dragon design from the 1960s. This 150m tall, 23m diameter ocean launch and recovery design uses simple pressure fed engines: LOX-RP1 for the first stage and LOX-H for the second. LOX and H are manufactured on-site by a nuclear aircraft carrier until SSP is available. The design calls for 8mm steel tankage so the Sea Dragon could be built in shipyards, not expensive aerospace facilities. The payload target was 500 tons – enough for 250 MW of ground power from a single launch at 2 kg/kw. Development costs were expected to be $27 billion in 2007 dollars. Estimated launch costs, including amortized development costs, for 240 flights in 10 years was $242/kg in 2007 dollars according to design documents available on the web[t]. This would supply 24 GW of power, and increasing the number of flights would further reduce costs.

There is also a launch system proposal specifically designed for SSP: Keith Henson suggests that launch costs can be reduced to about $100/kg by combining a pop-up sub-orbital launch vehicle with a large laser system to accelerate the payload to orbital velocity.[u] Payloads are placed inside of a simple vehicle with a large block of ice in the back. This is delivered above the atmosphere by a fairly small sub-orbital rocket. Once above the atmosphere, the ground-based laser system is fired to evaporate the ice at very high temperatures to produce high velocity thrust. To make the geometry work, the laser beam is bounced off mirrors in geosynchronous orbit. While there are plenty of interesting problems that must be solved to make this system work, it has the fundamental advantage that only reaction mass, not fuel, is used for most of the necessary acceleration and the exhaust velocity of the laser-excited ice is approximately the same as the necessary orbital velocity, substantially reducing the reaction mass required.

Clearly, either tourism or space solar power, if profitable, could provide the launch rate needed to drive the price of transportation from Earth to Orbit down significantly. Space tourism could develop the systems to make life in orbit wonderful, and SSP could develop our ability to build very large systems in orbit and, of course, to supply ample electrical power to large space settlements.

Furthermore, SSP will provide an incentive to develop lunar mines to supply the materials for PowerSats from outside of Earth's biosphere. Metals and silicon are expected to be major components of PowerSats and we know from the Apollo program, which returned lunar materials for analysis, that the Moon contains large quantities of both. However, the Moon has very little of other materials, such as carbon and nitrogen, needed for large scale space settlement. Fortunately, there is another source of materials and a pressing need to understand and manipulate them.

VII. Planetary Defense

There are thousands of large asteroids and comets that cross Earth's orbit and hundreds of thousands of smaller ones. Collectively, they are called Near Earth Objects (NEOs). Unlike the Moon, which is mostly silicon, oxygen, and metals; NEOs contain a wide variety of materials including metals, carbon compounds, water, and almost everything else needed for space settlements. The reason is simple: there are many different kinds of NEOs and each type has a different composition. We know what's inside NEOs because we have characterized the surfaces using spectroscopic techniques and NEOs that have already hit the Earth, meteorites, have been collected and examined so we know their composition exactly. For a good survey of NEOs and their utility, see *Mining the Sky,* by John S. Lewis.

Not only do these NEOs exist, but our survival depends on knowing exactly where they are and finding a way to move them around. Contrary to popular belief, if we do nothing, about one third of all NEOs will hit Earth. These collisions have happened many times in the past with devastating consequences, far greater than any war or natural disaster humans have experienced. We do not know when the next massive NEO strike will occur. It might be a million years – or in five minutes. If it's not for at least a few years or decades, which is very likely, we have the means, at a cost governments can easily afford, to detect and deflect dangerous NEOs thereby making this the one natural disaster that humanity can avert entirely. In the process, we will pave the way to provide all the materials needed for orbital space settlement. To get an idea of how dangerous NEOs are, consider:

On March 18, 2004 an asteroid came so close to Earth it passed below our communication satellites in

[t] http://neverworld.net/truax
[u] http://htyp.org/Hundred_dollars_a_kg

Figure 5. Meteor Crater in Arizona.

geosynchronous orbit. It was detected only two days in advance, not nearly enough time for deflection. On 23 March 1989 NEO 1989FC with the potential impact energy of over 1000 megatons (roughly the equivalent a thousand of the most powerful nuclear bombs) missed Earth by about six hours.[16] 1989FC was detected eight days after closest approach. If it had come in six hours later it could have killed millions.

In October of 1990 a very small asteroid struck the Pacific Ocean with a blast about the size of the first atomic bomb; the one that destroyed Hiroshima, Japan. If this asteroid had arrived ten hours later it would have struck in the middle of more than a million U.S. and Iraqi soldiers preparing for war. It could have struck near U.S. forces. The U.S. might well have thought Iraq attacked with a nuclear weapon and used its immense nuclear arsenal to turn Iraq into a radioactive wasteland. These small asteroid strikes occur roughly once a month.[17]

In 1908 a small asteroid (perhaps 50 meters across) hit Tunguska, Siberia and flattened 60 million trees. That asteroid never hit the ground, just exploded in mid-air. If it had arrived four hours and fifty-two minutes later it could have obliterated St. Petersburg,[17] the capital of Russia. As it was, dust from the blast lit up the skies of Europe for days. Asteroid strikes this size probably happen about once every hundred years, on average. There was another Tunguska-class strike in the Brazilian rain forest on 13 August 1930.[17]

In 1178 the Moon was hit by an NEO creating a 120,000 megaton explosion (about six times the force of Earth's entire atomic arsenal). The collision dug a 20 km crater. This strike was recorded by a monk in Canterbury, England. In July 1994 the comet Shoemaker-Levy 9 hit Jupiter. The comet broke up into roughly 20 large pieces before contact, but when the pieces hit they left a string of enormous explosions clearly visible to Earth telescopes. Each impact was the equivalent of about 10 million megatons of TNT.

Sixty-five million years ago a huge asteroid several kilometers across hit the Yucatan Peninsula in Mexico. The explosion was the equivalent of about 200 million megatons of TNT, about the same as all 20 pieces of Shoemaker-Levy. There is evidence that the blast turned the air around it into plasma. Enormous quantities of red-hot material were thrown into space, most of which rained down worldwide probably burning the entire planet. Anything not underground or underwater was killed. Surprisingly, only about 75% of the plant and animal species on Earth were exterminated. This scenario has been repeated over and over, perhaps once every 100 million years or so.

The first bit of good news is that this is one natural disaster that can be averted. We do not know

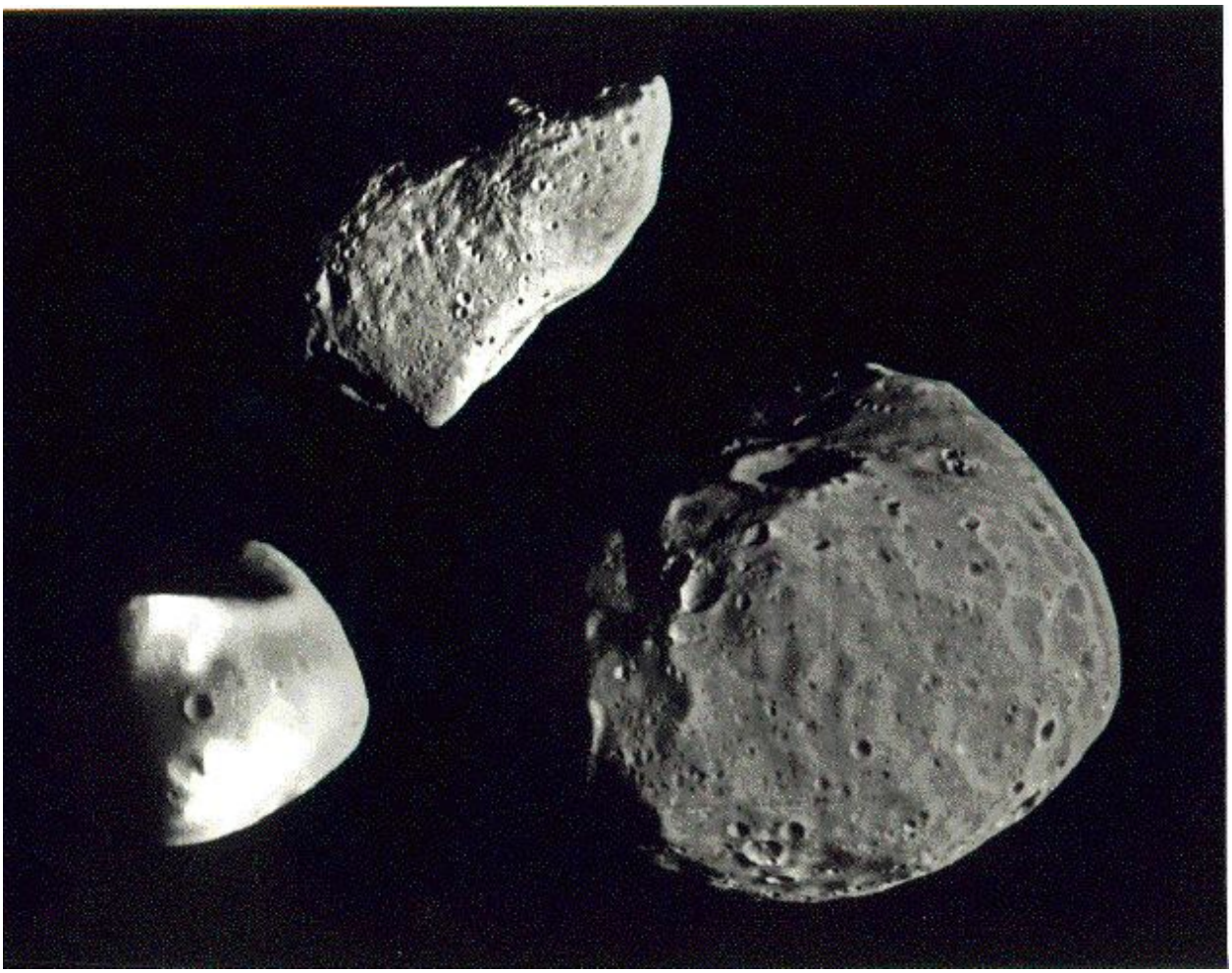

Figure 6. Collage of asteroids. Image credit NASA.

how to predict or prevent earthquakes, and we can't divert hurricanes, but we can detect and divert NEOs. Astronomers have already found over 90% of the large NEOs, those bigger than 1 km, and many, many smaller bodies that could cause regional disasters. Congress has asked NASA to find 90% of the NEOs that could cause regional devastation, those 120 meters in diameter or greater. NASA found that this could be done in a decade or two with quite modest funding, far less than currently spent on space science, human space flight or even aeronautics. Furthermore, scientists and engineers have proposed a number of techniques to divert dangerous NEOs just enough to miss Earth. Given sufficient warning time one need only delay or speed up the asteroid a small amount.

The other good news is that NEOs aren't just a threat, they are an opportunity. NEOs contain billions of tons of materials, including all the elements needed for space settlements. Some of them, those that come closest to striking the Earth, are relatively easy to get to, in some cases requiring less spacecraft fuel than going to the Moon. Other NEOs come close enough to Earth that a small velocity change is enough to use Earth and Lunar gravity assists to bring the NEO in high Earth orbit. A sensible, robust planetary defense program to find NEOs and determine if their orbits will bring them into a collision with Earth is exactly the first step necessary to develop NEO materials for space settlement [v]. Thus, we can protect ourselves and our planet while at the same time paving the way for space settlement.

VIII. Our Future

We know, more-or-less, how to build space settlements, although a dizzying array of engineering problems must be solved. However, to an engineer, that is the fun part. More important, there are paths to space settlement that either promise relatively near-term profitability – space tourism and space solar power – or are essential for the protection of civilization – planetary defense against NEOs. These paths could develop most of the technology and infrastructure necessary for the construction of the first space settlement. If the first space settlement is successful, the second will be far easier, the third easier still, and soon our solar system will swarm with thousands, if not millions, of orbital communities living off abundant sunshine and the vast material wealth of our solar system. Once part of humanity has lived for twenty generations in orbital space settlements, would it be so terrible to take a few decades to fly a group of settlements to the nearest star? Perhaps a group with a hundred thousand inhabitants or more? These people would live almost exactly as if they were in orbit around our sun, the main difference being a tighter energy budget and fewer other settlements to visit. Once that first star-to-star migration happens, the whole galaxy, over 200 billion stars, will be open to Life.

The settlement of the solar system could be the next great adventure for humanity, an adventure dwarfing anything done before. There is nothing but rock and radiation in space, no living things, no people. The solar system is waiting to be brought to life by humanity's touch.

IX. Acknowledgements

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