

Colonization of Venus

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Abstract. Although the surface of Venus is an extremely hostile environment, at about 50 kilometers above the surface the atmosphere of Venus is the most earthlike environment (other than Earth itself) in the solar system. It is proposed here that in the near term, human exploration of Venus could take place from aerostat vehicles in the atmosphere, and that in the long term, permanent settlements could be made in the form of cities designed to float at about fifty kilometer altitude in the atmosphere of Venus.

INTRODUCTION

Since Gerard K. O'Neill (1974, 1976) first did a detailed analysis of the concept of a self-sufficient space colony, the concept of a human colony that is not located on the surface of a planet has been a major topic of discussion in the space community. There are many possible economic justifications for such a space colony, including use as living quarters for a factory producing industrial products (such as solar power satellites) in space, and as a staging point for asteroid mining (Lewis 1997). However, while the concept has focussed on the idea of colonies in free space, there are several disadvantages in colonizing empty space. Space is short on most of the raw materials needed to sustain human life, and most particularly in the elements oxygen, hydrogen, carbon, and nitrogen. Oxygen could be imported from a rocky source, such as the lunar surface, but the volatile materials hydrogen, carbon, and nitrogen form primarily volatile materials that are not present in abundance on the lunar surface. Furthermore, for optimum performance, human beings require gravity-- it requires major engineering structures to simulate (via rotation) the presence of gravity in a free-space colony.

Even for colonizing the asteroids, it is not clear that a free space base is the optimum location: any given asteroid is, on the average, rather distant from all the other ones, both in actual distance and in terms of the propulsion delta-V required to get there.

An alternate possibility is to locate a colony on the surface of another planet. Most recently, the case for colonizing the surface of Mars has been argued by Zubrin (1996). However, at least compared to the benign environment of Earth, the surface of Mars has several disadvantages. It has a low atmospheric pressure, low temperatures, and high exposure to cosmic radiation, and, while it is not a zero-gravity environment, it is not yet known whether the roughly one-third Earth-normal gravity of Mars is sufficient to avoid the bone decalcification and muscle tone loss experienced by astronauts in microgravity.

So let's colonize Venus.

VENUS EXPLORATION

In many ways Venus is the hell planet. Results of spacecraft investigation of the surface and atmosphere of Venus are summarized by Fimmel, Colin, and Burgess (1983) and by Bougher, Hunten, and Phillips (1997):

- Surface temperature 735K: lead, tin, and zinc melt at surface, with hot spots in excess of 975 K
- Atmospheric pressure 96 Bar (1300 PSI); similar to pressure at a depth of a kilometer under the ocean
- The surface is cloud covered; with little or no solar energy
- Poisonous atmosphere of primarily carbon dioxide, with nitrogen and clouds of sulfuric acid droplets.

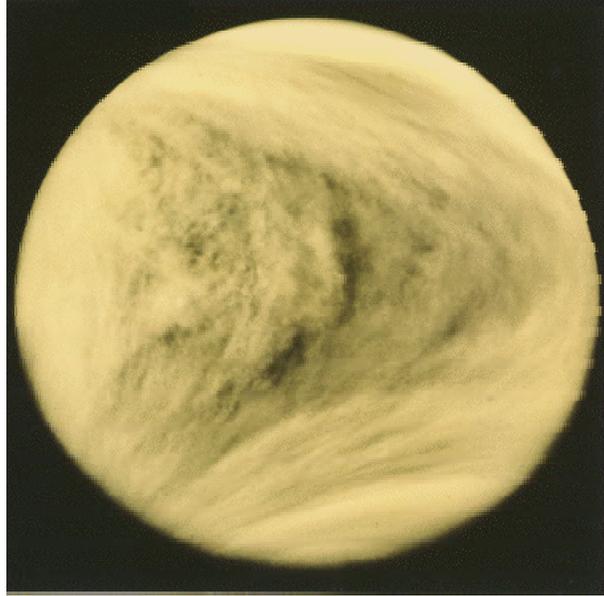


FIGURE 1. Venus, viewed in the ultraviolet by the Pioneer Venus mission (Fimmel, Colin, and Burgess 1983).

However, viewed in a different way, the problem with Venus is merely that the ground level is too far below the one atmosphere level. At cloud-top level, Venus is the paradise planet. As shown in figure 2, at an altitude slightly above fifty km above the surface, the atmospheric pressure is equal to the Earth surface atmospheric pressure of 1 Bar. At this level, the environment of Venus is benign.

- above the clouds, there is abundant solar energy
- temperature is in the habitable "liquid water" range of 0-50C
- atmosphere contains the primary volatile elements required for life (Carbon, Hydrogen, Oxygen, Nitrogen, and Sulfur)
- Gravity is 90% of the gravity at the surface of Earth.

While the atmosphere contains droplets of sulfuric acid, technology to avoid acid corrosion are well known, and have been used by chemists for centuries.

In short, the atmosphere of Venus is most earthlike environment in the solar system. Although humans cannot breathe the atmosphere, pressure vessels are not required to maintain one atmosphere of habitat pressure, and pressure suits are not required for humans outside the habitat.

It is proposed here that in the near term, human exploration of Venus could take place from aerostat vehicles in the atmosphere, and that in the long term, permanent settlements could be made in the form of cities designed to float at about fifty kilometer altitude in the atmosphere of Venus.

Is Floating Difficult?

On Venus, breathable air (*i.e.*, oxygen/nitrogen mixture at roughly 21:78 mixture ratio) is a lifting gas. The lifting power of breathable air in the carbon dioxide atmosphere of Venus is about half kg per cubic meter. Since air is a lifting gas on Venus: the entire lifting envelope of an aerostat can be breathable gas, allowing the full volume of the

aerostat to be habitable volume. For comparison, on Earth, helium lifts about one kg per cubic meter, so a given volume of air on Venus will lift about half as much as the same volume of helium will lift on Earth.).

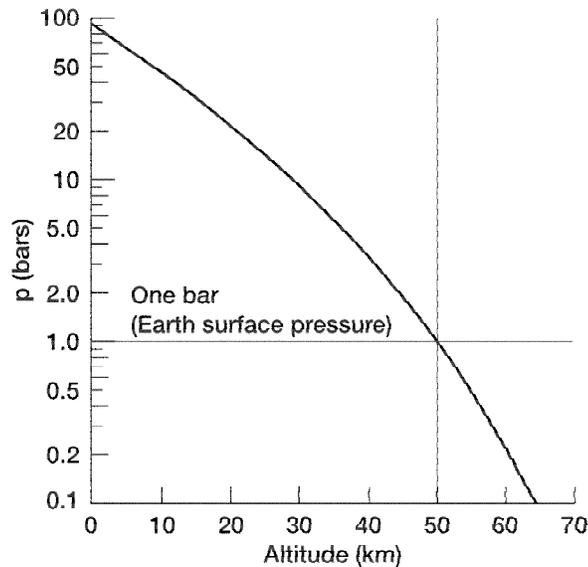


FIGURE 2. Pressure as a function of altitude in the atmosphere of Venus.

Science on Venus

Venus, the "greenhouse planet", is a scientifically fascinating place (Landis 2001, Landis *et al.* 2002). In many ways it can be considered "Earth's evil twin." A huge number of important scientific questions need to be answered:

- Before the runaway greenhouse effect, was early Venus temperate?
- Did Venus once have an ocean? If so, did it ever have life?
- What causes the geological resurfacing of the planet?
- What is the nature of the atmospheric superrotation?
- What are the aerosol particles in the atmosphere?
- What is the "snow" on Venus mountaintops?
- Can we learn about Earth's climate from Venus?
- What is the nature of the disequilibrium chemistry in the Venusian atmosphere? Could it indicate atmospheric life?

At a temperature of 450 Celsius, and with 90 atmospheres of pressure of carbon-dioxide atmosphere, the surface of Venus is far too hostile to land humans upon, but we can put humans in the atmosphere to explore the surface via rugged telerobot.

Venus Telescience Technologies

In the telerobotic exploration scenario (Landis 2003), the humans remain in a habitat, and use teleoperation to rove across the surface of Venus and explore. This requires a high-fidelity, high-bandwidth connection to give the humans a fully-detailed virtual presence in the robotic body.

Humans participate in the exploration both by direct operation of the telerobots across a high-fidelity virtual-presence link, and also by analyzing samples collected by the teleoperated robots in a fully-equipped on-site laboratory. Because of the high wind velocity in the middle atmosphere of Venus, an atmospheric aerostat habitat would not stay over the same surface location, but would constantly move. Although this would have some disadvantages, such as requiring a relay station if long exploration of a single spot is required, it would also have some advantages in constantly moving over new ground.

A robot to explore the surface of Venus will require new technologies; specifically, it will require electronics, scientific instruments, power supplies, and mechanical linkages designed to operate at a temperature above 450 C—hot enough to melt the solder on a standard electronic circuit board. This will require devices made from advanced semiconductor materials, such as silicon carbide, or even new approaches, such as micro-vacuum tube electronics. Such materials are now being developed in the laboratory. In addition, for a fully immersive virtual-reality, high-bandwidth virtual-presence technologies will have to be developed, as well as highly capable exploratory robotics.

While the human explorers could live in a habitat/laboratory in orbit around Venus, a better location for exploration is an aerostat habitat. Teleoperation from the atmosphere allows near “real time” operation with minimum time delay, giving a virtual presence on the surface. An atmospheric habitat has an advantage over an orbital habitat of advantages of gravity (90% of Earth surface gravity) and atmospheric protection against cosmic radiation (same equivalent mass as Earth's atmosphere), and the presence of useful atmospheric gasses, including carbon dioxide and nitrogen. Breathing oxygen for life support can be easily provided by separation of oxygen from atmospheric carbon dioxide, either by zirconia electrolysis or by Sabatier processes.

So it should be possible to explore the surface of Venus remotely from an aerostat habitat. An atmospheric location for the habitat has the addition advantage that it will be easy to bring samples up from the surface to be analyzed in the habitat. The atmospheric pressure is high enough that both airplanes (Landis 2001) or balloons could lift samples (assuming, of course, that the vehicles are adapted for high-temperature and pressure operation).

SETTLING VENUS

In the long term, permanent settlements could be made in the form of cities designed to float at about fifty kilometer altitude in the atmosphere of Venus.

The thick atmosphere provides about one kilogram per square centimeter of mass shielding from galactic cosmic radiation and from solar particle event radiation, eliminating a key difficulty in many other proposed space settlement locations. The gravity, slightly under one Earth gravity, is likely to be sufficient to prevent the adverse affects of microgravity. At roughly one atmosphere of pressure, a habitat in the atmosphere will not require a high-strength pressure vessel.

Humans would still require provision of oxygen, which is mostly absent from the Venusian atmosphere, but in other respects the environment is perfect for humans (although on the habitat exterior humans would still require sufficient clothing to avoid direct skin exposure to aerosol droplets).

Since breathable air is a lifting gas, the entire lifting envelope of an aerostat can be breathable gas, allowing the full volume of the aerostat to be habitable volume. For objects the size of cities, this represents an enormous amount of lifting power. A one-kilometer diameter spherical envelope will lift 700,000 tons (two Empire state buildings). A two-kilometer diameter envelope would lift 6 million tons. So, if the settlement is contained in an envelope containing oxygen and nitrogen the size of a modest city, the amount of mass which can be lifted will be, in fact,

large enough that it could also hold the mass of a modest city. The result would be an environment as spacious as a typical city.

The lifting envelope does not need to hold a significant pressure differential. Since at the altitudes of interest the external pressure is nearly one bar, atmospheric pressure inside the envelope would be the same as the pressure outside. The envelope material itself would be a rip-stop material, with high-strength tension elements to carry the load. With zero pressure differential between interior and exterior, even a rather large tear in the envelope would take thousands of hours to leak significant amounts of gas, allowing ample time for repair. (For safety, the envelope would also consist of several individual units).

Solar power is abundant in the atmosphere of Venus, and, in fact, solar arrays can produce nearly as much power pointing downward (toward the reflective clouds) as they produce pointing toward the sun. The Venus solar day, 116.8 terrestrial days, is extremely long; however, the atmospheric winds circle the planet much more rapidly, rotating around the planet in four days. Thus, on the habitat, the effective solar "night" would be roughly fifty hours, and the solar "day" the same. This is longer than an Earth day, but is still comfortable compared to, for example, the six-month night experienced in terrestrial near-polar locations. If the habitat is located at high latitudes, the day and night duration could be shortened toward a 24-hour cycle.

A permanent settlement will need access to the resources required for human life and for greenhouses to provide food and oxygen, and the atmosphere of Venus has these in abundance. Atmospheric carbon dioxide and nitrogen are a plentiful resource. Along with hydrogen reaped from condensing atmospheric sulfuric acid droplets, the basic elements needed for human survival can be found in the atmosphere.

A settlement will require structural and industrial materials as well. These materials, such as silicon, iron, aluminum, magnesium, calcium, potassium, sodium *etc.* can be mined from the surface material, which is apparently primarily a basaltic silicate. Access to the surface is relatively simple from an aerostat, since the thick atmosphere allows flight by airplanes (Landis 2001) or balloons (already demonstrated on Venus during the Russian VEGA mission (Bougher, Hunten and Phillips 1997)). In an alternative scenario, a cable in the form of a high-temperature fullerene tether could be used to directly lift ore from the surface to the habitat. Since the habitat will be stationary with respect to the middle-atmosphere wind, the lifting will be done with the habitat in motion with respect to the surface. It may simplify the process if the habitat temporarily lowers its altitude to take it out of the high altitude wind levels; while this will move it toward the higher temperature region of the atmosphere, a habitat of the size considered would have an enormous heat capacity, and would likely have little difficulty with a temporary dwell at higher temperature levels.

Finally, with surface area 3.1 times the land area of Earth, Venus has plenty of room. A billion habitats, each one with a population of hundreds of thousands of humans, could be placed float in the Venus atmosphere.

Accessibility of Asteroids from Venus

One possible economic objective for space colonization is to serve as habitats from which humans can prospect and mine asteroidal resources. It would be intuitive to think that a base to mine asteroids should be close to the asteroid belt, and hence further from the sun than the Earth, but detailed consideration of astrodynamics brings this conclusion into some question. In terms of flight time, Venus is closer to the asteroid belt than either the Earth or Mars. This is shown in figure 3. For example, the minimum-energy trajectory to the largest main-belt asteroid, Ceres, takes 0.95 yeears from Venus, and 1.05 years from Earth. In terms of flight time, the closer you are to the sun, the more accessible the asteroids are.

The asteroids are not actually close to each other, and hence if a habitat is to support prospecting and mining more than one asteroid, the asteroid belt is in some ways the worst location for it. An asteroid is as likely as not to be on the opposite side of the sun, and although the Earth is further from the sun, that does not put it closer, on the average, to any given asteroid. The higher orbital velocity of Venus actually makes transfer orbits somewhat faster, as well as increasing the number of transfer opportunities (that is, decreasing the synodic period).

CONCLUSION

In the long term, permanent settlements could be made in the form of cities designed to float at about fifty kilometer altitude in the atmosphere of Venus. The advantages of the Venus atmosphere over other proposed space settlement locations includes an abundance of atmospheric volatiles, sufficient for life support, benign temperature and pressure, shielding from cosmic and solar-flare radiation, plentiful solar energy, and nearby access to the rocky (silicate) surface materials.

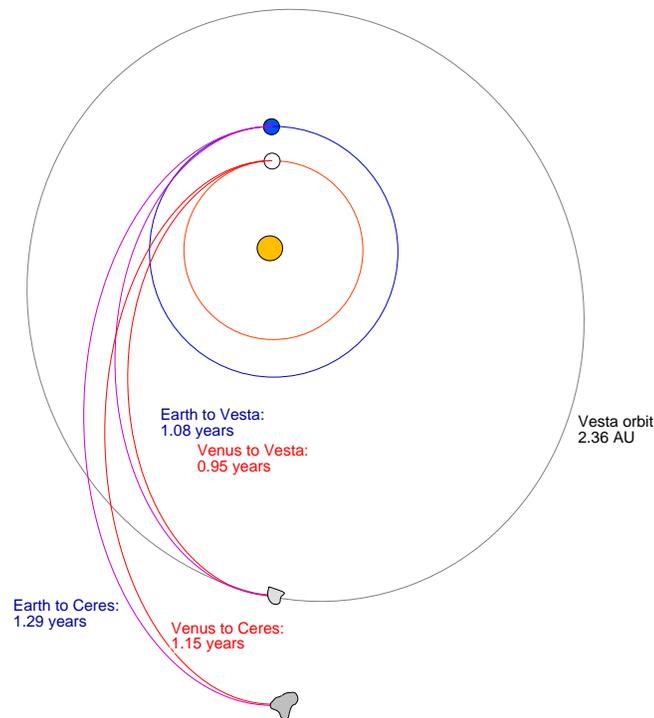


FIGURE 3. In terms of flight time, Venus is closer to the asteroid belt than either the Earth or Mars. Minimum-energy trajectories to the two largest main-belt asteroids, Ceres and Vesta, are shown.

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