Mercury, Venus and Titan

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Chapter 14
Mercury, Venus and Titan

Sushruth Kamath, Jullian Rivera, Michael Garcia and Haym Benaroya

14.1 Introduction

The exploration of space has been at the forefront of scientific thought and discovery for the last half century. Beginning with the first Sputnik satellite in 1957 to the Curiosity landing and the other numerous ongoing missions of today, mankind is setting its sights away from Earth.

As more information is gathered and the realm of understanding reaches farther into the cosmos, the important question of “where can humans land next?” inevitably arises. After conquering the Moon and exploring Mars, there is much debate on the future travel destinations. Therefore, it becomes imperative to fully catalog every possible option and ensure that all necessary data has been taken into account in defining the environment for which engineers must design habitats.

Speculation on futuristic and visionary possibilities for the exploration and settlement of the Solar System is a worthy intellectual exercise – it is fun, but it also helps us map current technological abilities into the near future. It is likely that when humanity decides to return in full force to space exploration and settlement it will be with a return to the Moon and then to Mars. This paper summarizes some key data that are needed by engineers on the environment of three bodies in the Solar System in order to place robots or humans on those bodies. The bodies considered here are Mercury, with the orbit that is closest to the Sun, Venus, the planet that is closest in size to Earth, and Titan, Saturn’s largest moon.

These three bodies in our Solar System are very different from each other as well as from Earth, its Moon and Mars, bodies with which we are most familiar. Mercury, Venus and Titan are three extremes in our Solar System. They offer challenges that we are not ready to currently undertake. Studying their environments and considering challenges that have to be overcome is necessary to explore them

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with robots and people. In essence, we are thinking out of the box with the hope that new ideas may be generated in efforts to explore and settle the Moon and Mars, and eventually the three bodies that are our focus here – Mercury, Venus and Titan.

14.2 Mercury

14.2.1 Introduction

One such, perhaps surprising, possibility is the planet Mercury. The small, first planet in the Solar System has largely been ignored by the countless missions and satellites from Earth. Yet collecting and analyzing existing and new data paints a picture of a planet that may be able to harbor a colonial base for future endeavors. As of now, it is incredibly difficult and dangerous to reach Mercury, but the plethora of resources and knowledge that can be gained from traveling to the small planet warrants its study and consideration for a manned mission.

The first step is to fully characterize Mercury's environment in order to understand its essence and nuances so that we can determine whether a settlement can be designed for and placed on the planet.

14.2.2 Missions to Mercury

Mercury has long been analyzed from Earth through various telescopes and ground based observation platforms. Being the smallest and fastest orbiting planet makes Mercury very difficult to study. Another challenge arises in the position of the planet's orbit compared to that of the Earth. Mercury's proximity to the Sun and distance from the Earth generally hampers man-made satellites and missions to orbit the planet and to observe it from close range.

So far, only two spacecraft have visited Mercury. The first was the limited Mariner 10. Launched on 3 November 1973, Mariner was designed to visit both the inner planets of Venus and Mercury. The vessel carried a basic array of instruments including TV and photographic cameras, airglow and occultation ultraviolet spectrometers, a charged particle telescope, an infrared radiometer, and magnetometers. Although the craft ran into technical difficulties reaching and passing Venus, Mariner 10 reached Mercury on March 29, 1974 for the first of three passes (*Mariner 10,* space.com). Mariner 10 and its orbital path are shown in Fig. 14.1.

Mariner 10 provided first images of Mercury and the on board equipment gave scientists much-needed data to begin to understand the planet. Mariner 10 carried very simple instruments and soon it ran out of fuel. On March 24, 1975, the craft turned off its transmitters and has not been heard from since. The data from the vessel was the only information on Mercury for more than three decades, until the planet was visited again in 2008.

On 3 August 2004, NASA launched the MErcury Surface, Space ENvironment, GEochemistry, and Ranging spacecraft. MESSENGER was a state-of-the-art vessel carrying an impressive payload of scientific equipment. The instruments included dual imaging systems, gamma-ray and neutron imaging systems, a laser altimeter, an atmospheric and surface composition spectrometer, and an energetic particle and plasma spectrometer. After using Venus as a gravitational slingshot, MESSENGER arrived at Mercury on 14 January 2008. The spacecraft and its orbital path are shown in Fig. 14.2.

Within days of arriving, MESSENGER had mapped 99 % of the planet's surface and had eclipsed the data total from Mariner 10. MESSENGER was inserted into Mercurian orbit on 18 March 2011 and continues to beam back torrents of data. The majority of what we know about Mercury today comes from the work MESSENGER has done (Bedini et al. 2012).

14.2.3 Interior Planet Structure

The European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) are currently in the process of planning and building the third mission to Mercury. Named BepiColombo and set for launch in mid-2016, this craft will add significantly to our understanding of the innermost planet of the Solar System (*BepiColombo,* European Space Agency). Next, we review all the newly MESSENGER-discovered facts and examine whether or not a landing on Mercury is feasible.

In order to characterize the first planet fully, a suitable starting point is Mercury's interior and core. Using basic readings from MESSENGER and from ground based observations of rotational time and speed, the average density of Mercury has been found to be 5.427 g/cm^3. This means that Mercury is the second densest planet, second to Earth whose density is 5.51 g/cm^3.

The reason for the high density of the smallest planet perplexed scientists who were modeling its interior (Cameron et al. 1988). However, after analyzing MESSENGER's gamma-ray spectrometers, magnetometers and x-rays, it was determined with a high certainty that Mercury is composed of a large molten iron core that is nearly 3/4 the diameter of the planet. The rest of the interior is composed of a 600 km thick silicate and basalt mantle and a 200 km thick crust made of the same composition (Rivoldini and Van Hoolst 2013). In addition, there appears to be a layer of solid iron sulfide lying between the core and the mantle (*Lunar and Planetary Science Institute*, NASA).

The composition and structure of the inside of Mercury has a significant impact on the way the planet behaves and also dictates the planning and preparations of any future landing missions. Figure 14.3 shows the structure of Mercury's interior along with a comparison to the cross section of the Earth.

Another important aspect of Mercury's core that must be understood is its proclivity to be affected by outside factors. The first such factor is temperature. The

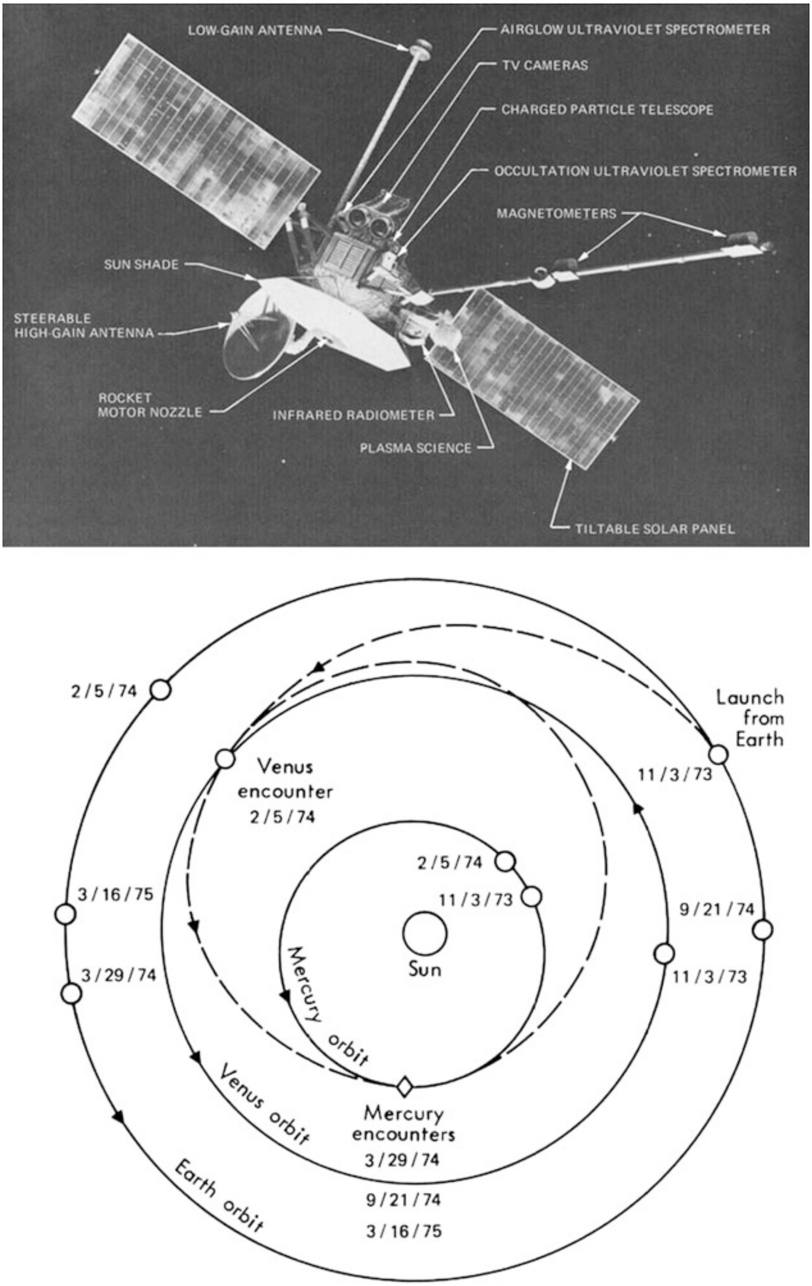

Figure 4 Mariner 10 trajectory.

Fig. 14.1 Mariner 10 and its trajectory. NASA images

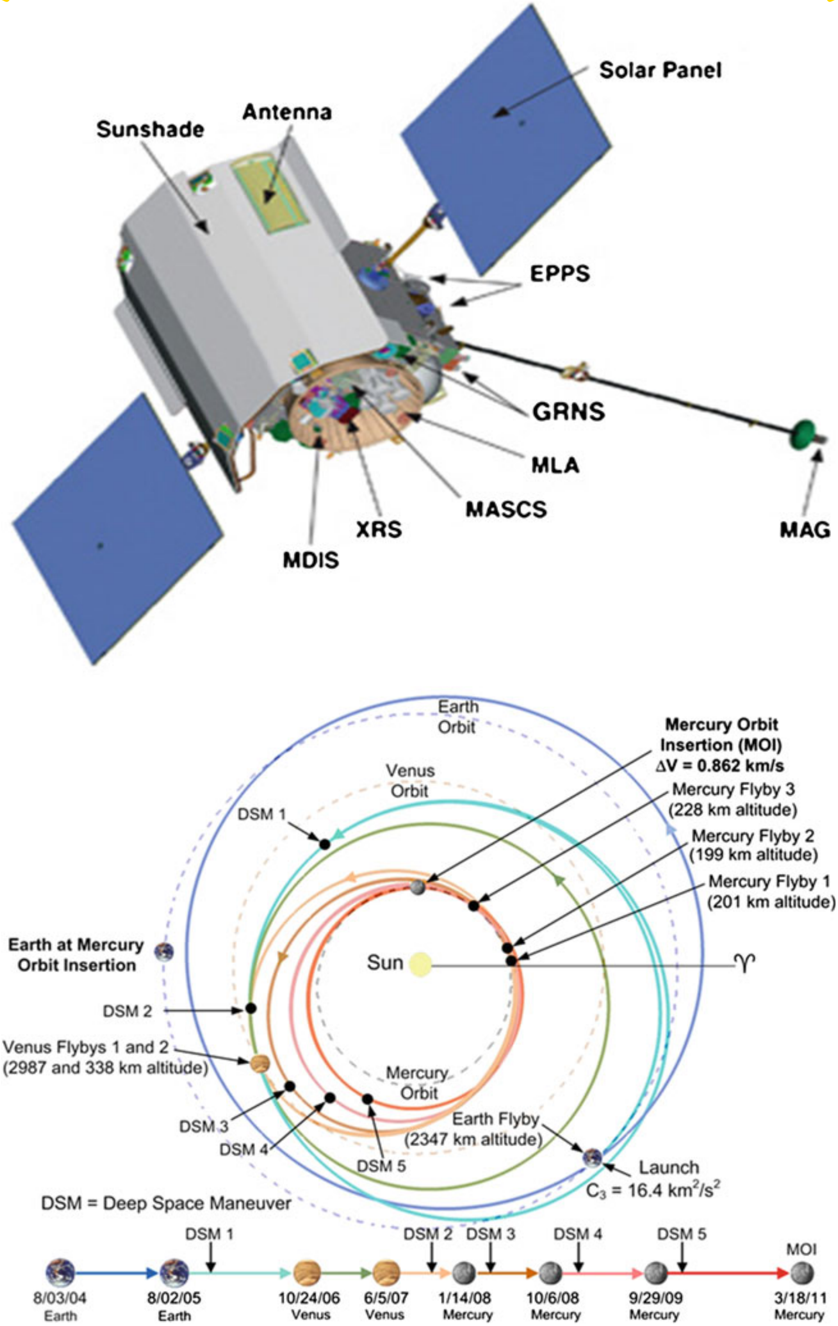

Fig. 14.2 MESSENGER and its trajectory. NASA images

proximity to the Sun causes very large temperature differences around the plane This in turn causes heat currents and heightened movements in the large liquid core that not only affect surface conditions but also result in magnetic field fluctuations (Solomon 2003). Increased internal motion also causes changes in planet libration dynamics, which, if studied further, could help explain magnetic field strength and rotational properties (Koning and Dumberry 2013).

Another influence on Mercury's interior is the force of gravity (Smith et al. 2010). The gravitational pull on the surface of the planet has been determined to be around 0.38 g. The reason the planet's gravitational field strength is more than double that of the Moon's 0.16 g, and roughly the same as Mars' 0.38 g, is that, despite its small size, Mercury's high density iron core is inherently massive (*Solar System Exploration,* NASA). How this relatively high gravity affects the liquid core of a rocky inner planet is not entirely known. Scientists expect that the data sent daily by MESSENGER (Genova et al. 2013) will address this question.

Due to its close proximity to the Sun, less than 0.47 AU, Mercury experiences some of the strongest tidal forces in the Solar System (Solomon 2003). As opposed to oceanic bulges caused by the Moon on Earth, the core and surface of Mercury show significant protuberance due to solar gravity. It was long thought that Mercury was tidally locked with the Sun; however, careful ground based observations and calculations led to the discovery and confirmation of the planet's stable 3:2 spin-orbit resonance and tidal bulge properties (Solomon 2003).

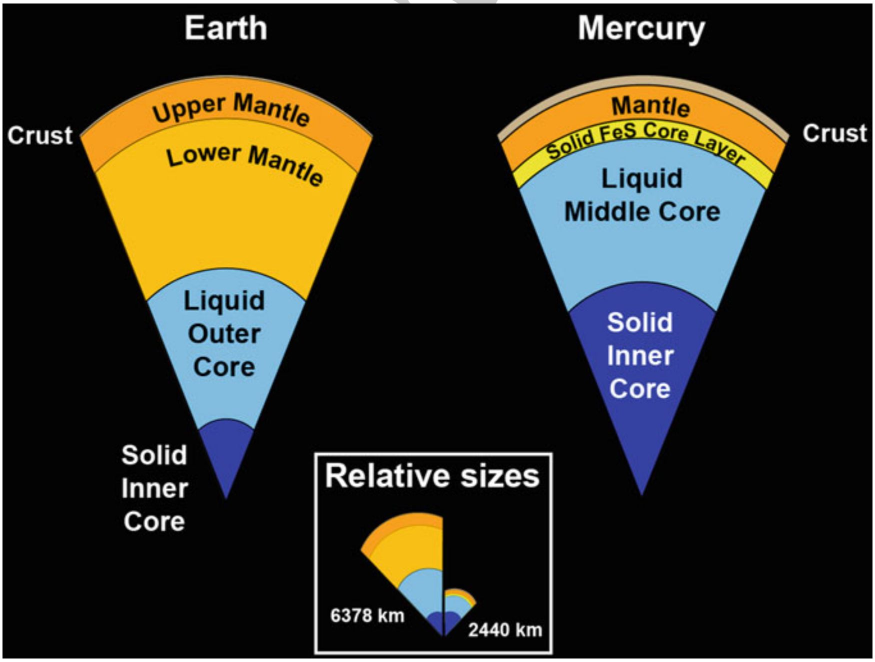

Fig. 14.3 Comparison of Earth and Mercury interiors. NASA image

Another external factor that may have had serious effects on the planet's core is debris impact. It has been speculated that medium to large asteroid impacts on the inner planets could potentially cripple core dynamos (Arkani-Hamed and Ghods 2011). A dynamo is a mechanism by which a celestial body such as Earth or a star generates a magnetic field. The asteroid impact theory applies particularly to Mercury since the planet has a small crust/mantle and a reasonably large liquid core. Analyzing the antipodal region of the large Caloris Basin on Mercury illustrates that severe impacts may affect both the core and the rest of the planet's surface. MESSENGER's images of the Caloris Basin (left) and the region known as the Weird Terrain (right), antipodal to the basin, are shown in Fig. 14.4.

An advanced mission to land on Mercury may be able to tap the core of the planet for resources, but also exposure to hazards. The character of the interior of Mercury plays a large role in how we might plan a landing on the planet. One could speculate that in a not-near future the core could be mined for metals provided the crust is thin enough for our drilling technologies. The vast iron and sulfur sources could be a valuable asset to settlement and exploration. In addition, the core's intrinsic heat currents could provide geothermal power for a base on the surface. The motion of the liquid core ensures a magnetic field around the planet, which provides minimal safety from the extreme radiation delivered via the solar wind.

However, as discussed earlier, the core may not be stable since it is possible that tidal forces and repeated impacts may disrupt the core significantly enough to have destructive consequences.

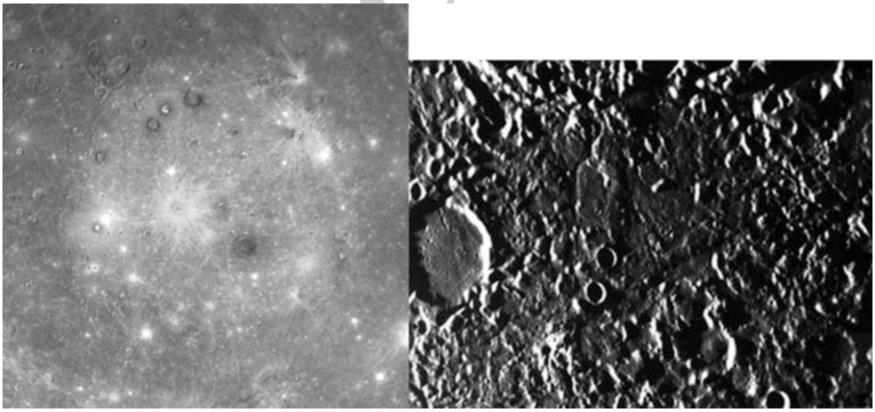

Fig. 14.4 (L) Caloris basin and (R) weird terrain. NASA images

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14.2.4 *Planetary Surface Structure*

In order to have a successful touchdown on Mercury, a thorough and exhaustive analysis of the planet's surface must be done. Before Mariner 10, countless ground based systems had predicted that the surface of Mercury would be very similar to that of the Moon. In 1974, this notion was proven right. Early images from Mariner 10 showed similar characteristics between the Mercurian landscape and that of the Moon (*Mariner 10,* space.com).

Following the more advanced and careful screening done by MESSENGER, the composition and structures of Mercury were identified and explained (*MESSENGER,* NASA/JHUAPL). The surface of the first planet is composed of silicates and basalts similar to those found on other terrestrial planets (Carli and Sgavetti 2011). However, the notable difference arises in the formation and maturity of this sand-like substance.

Through MESSENGER's spectrometers, the color of Mercury's surface seems to be more uniform and not as dark as the surface on Mars or the Moon. This indicates an absence of iron and titanium rich silicates, as these materials would have created much darker surface planes and crevices (Blewett et al. 2009). The data received also indicates low quantities of iron oxides, which presents the theory that Mercury was formed in conditions without oxygen, or conditions in which oxygen was stripped away (Elser et al. 2012).

The surprising conclusion is that Mercury's surface contains very little iron-based material when the planet has a large iron core (Izenberg et al. 2014). This may be due to the fact that the Mercurian surface is more "mature" than those found elsewhere (Wasson 1988). Since the crust of the planet is exposed to multiple harsh influences, including continual extreme radiation, superheating, and supercooling, the composition is considered to have numerous unknown and unique characteristics, hence the term "mature" (Rhodes et al. 2011). MESSENGER's multi-spectral images of planet Mercury's surface were used to indicate possible compositions as shown in Fig. 14.5.

After understanding the current data on the composition of the innermost planet's surface, the next step is to examine the geologic structures present. Much of the knowledge about the formations on Mercury comes from carefully analyzing the images taken not only from Mariner 10 and MESSENGER, but also from Earth-based instruments (Ksanfomality 2008). The most obvious features on the planet's exterior are the lunar mare-like planes and impact craters. Photographic evidence also shows volcanic activity and vents on the surface of the planet.

The mares were likely formed by cooling volcanic eruptions (Rothery et al. 2014). The craters serve as an historic record of numerous debris impacts. As there are very limited atmospheric effects on Mercury, asteroids do not get destroyed prior to impact, as on Earth, and craters are not erased by fluid dynamics. Thus, if volcanic ejecta cools on the surface and is not subsequently hit, the only means of affecting its composition is through solar heat, radiation and gravity (Xiao et al. 2014). In addition, the vent-like structures give rise to questions about potential gas

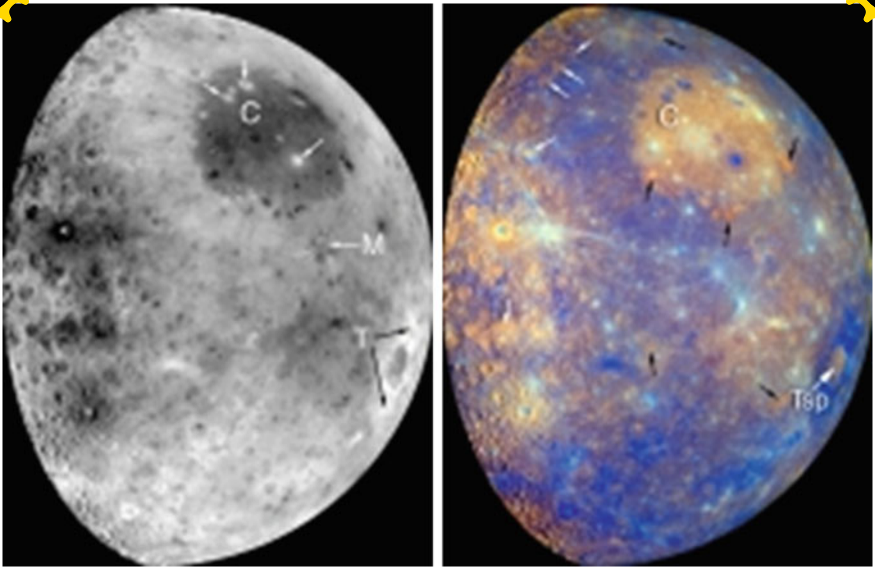


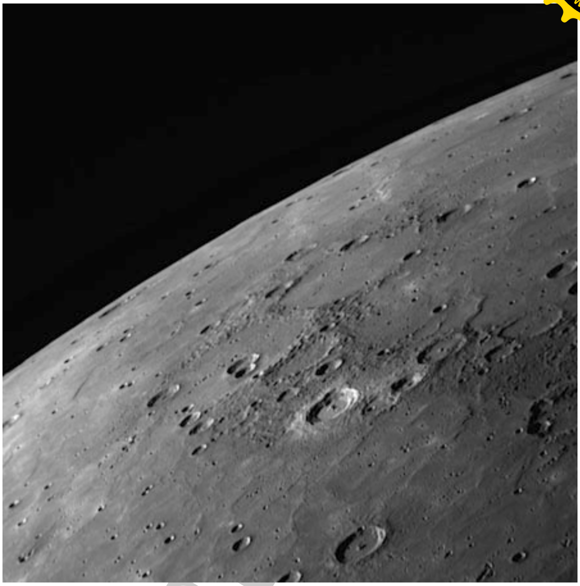
Fig. 14.5 MESSENGER's multi-spectral images. NASA/JHUAPL images

deposits and the existence of a significant pseudo-atmosphere (Xiao and Komatsu 2013).

MESSENGER's images of the planes and craters on Mercury are shown in Fig. 14.6, and of possible gaseous vents on the surface in Fig. 14.7.

The most surprising surface structures found on Mercury were several lobate (curved scalloped edges) scarps (significant vertical landform), or rupes. These winding cracks in the facade of the planet strongly indicate the presence of fault lines, and consequently, tectonic activity and movement (Watters et al. 2009). Therefore, the possibilities of an unstable crust and earthquake-like phenomena are heightened. In addition, the scarps indicate areas of high fault pressure where surface structures are destroyed or fused depending on motion. Many rupes were only recently discovered in images from MESSENGER and, as more information is gathered, will better understood (Ruiz et al. 2012). The image shown in Fig. 14.8 is of a lobate scarp on the surface of Mercury.

The final and most important characteristic of the planet's exterior is the extreme temperature differences. Mercury was wrongly assumed to be tidally locked with the Sun for a long time, leading to the belief that only one side of the planet endured the intense solar heat, while the other 'dark' side would only be exposed to the bitter cold of space. The Sun's close proximity to Mercury and the planet's 3:2 spin-orbit resonance means that the side facing away from the Sun can experience temperatures as low as 80 K (−316 °F or −193 °C). Then, as the planet rotates, that side faces the Sun and is subjected to temperatures as high as 700 K (800 °F or 427 °C) (*Solar System Exploration*, NASA). Thus, surface materials face conditions



ig. 14.6 Mercury planes. NASA image

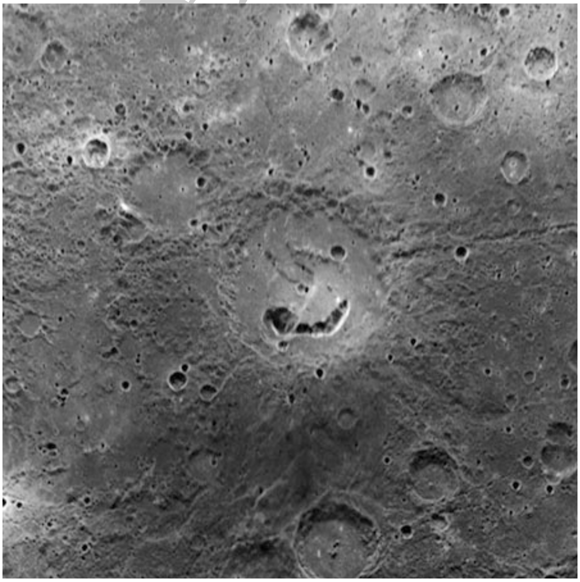


Fig. 14.7 Mercury vents. NASA image

cold enough to almost freeze nitrogen and hot enough to melt lead in just a few rotations of the planet (Helbert et al. 2013).

The poles, however, experience a far less dramatic temperature differential due to their positions relative to the Sun. Thus, areas of relatively stable conditions exist around each pole. The temperatures in these zones are near the surface temperatures

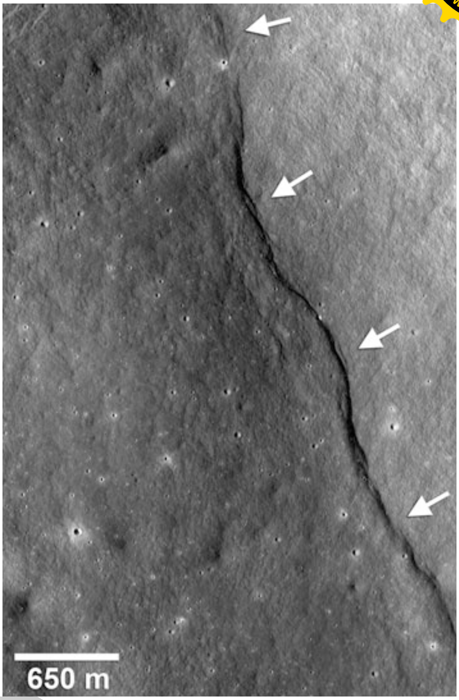


Fig. 14.8 Lobate scarp on Mercury. NASA image

found on Earth, albeit much less stable. Figure 14.9 shows the biannual maximum temperature (left) and average temperature (right) around the North Pole.

When planning travel to first planet, we should consider that the surface of Mercury can provide many natural resources as well as several potent dangers. One of the most significant finds on the planet's exterior is a substantial deposit of ice located just under the North Pole (Prockter 2005). Analyzing MESSENGER's x-ray and spectrometer data along with Earth-based radar readings and outputs revealed that large quantities of ice were present in Mercury's polar regions.

Evaluating surface maps showed how large, deep craters had provided the necessary protection from the heat of the Sun to harbor pockets of ice (*Lunar and Planetary Science*, NASA). Figure 14.10 shows the surface map of the North Pole with the red overlay indicating areas of lowest illumination, that is, most shadowed, and the yellow overlay indicating detected pockets of ice.

Although the surveying of the pole is far from complete, if the ice there is deemed usable and harvestable, it would be an enormously crucial asset for manned missions to Mercury (Vasavada et al. 1999). In addition, the regolith can be used as building blocks for construction or as protection from destructive radiation and from meteorites.

The heat and light from the Sun can provide unlimited solar and thermal power for the entire planet, assuming the solar panels can be prevented from vaporizing almost instantaneously. On the other hand, the surface poses its own set of dangers,

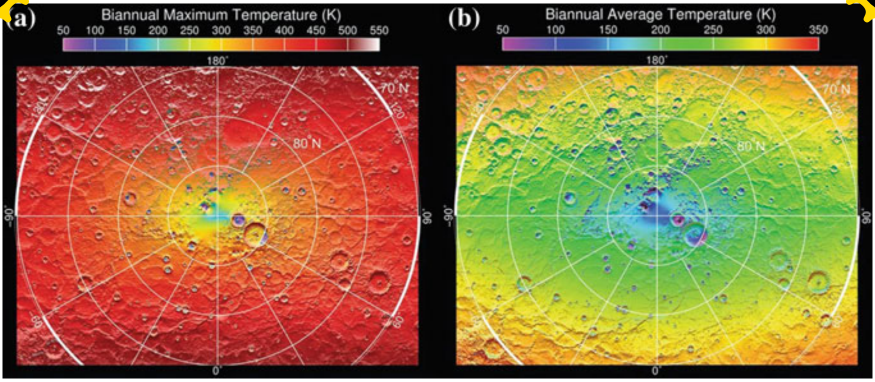


Fig. 14.9 Biannual Mercurian pole temperature. NASA/JHUAPL images

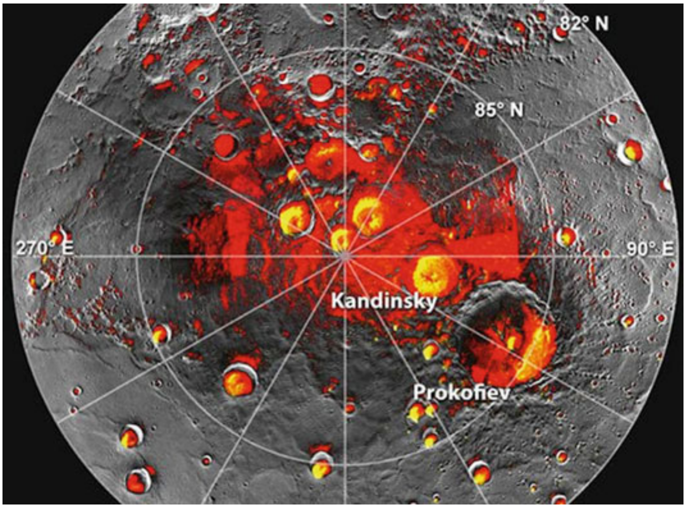


Fig. 14.10 Mercury polar ice overlay. NASA image

as well. The vast temperature differences that are either too hot or too cold for habitation must be quarantined from humans or robots. Secondly, asteroid impacts pose a major threat to colonies or any structures on the planet.

14.2.5 Planetary Atmospheric Conditions

Mercury hosts a thin atmosphere and a unique magnetic field, and understanding both is critical to any mission to visit the planet. The proportionally large molten iron core is strong enough to generate a magnetic field around the planet (Grosser et al. 2004). Measured to peak at approximately 300 nT, Mercury's field is only approximately 1.1 % the strength of that of the Earth (*Lunar and Planetary Science Institute*, NASA). However, Mercury's innermost position in the Solar System means that in order to protect the planet's surface from the harsh solar wind, it would need a magnetic field immensely more powerful.

Mercury's magnetic field has been carefully documented by MESSENGER's sensors (McNutt et al. 2010). After passing through the bow shock, particles hit Mercury's magneto sheath. Particles not deflected away are then met with the planet's magnetopause, which is structured much like that of the Earth's, with polar cusps, lobes, and an intermediate plasma sheet (Hiremath 2012). Since the solar wind is very strong in the orbit of Mercury, most of the Sun's radiation passes through the magnetosphere and bombards the surface, possibly changing surface composition characteristics.

There is much to be learned from Mercury's electromagnetic dynamics (Anderson et al. 2011). Mercury is the only inner planet, other than Earth, to have a substantial inherent magnetosphere. In addition, it is imperative to uncover how the instability of the core and the intense heat currents affect the production and strength of the magnetic field. The plasma environment near the planet may provide valuable insights on the effects of solar wind (Raines et al. 2011).

Figure 14.11 shows a concise diagram of Mercury's magnetic field components. Figure 14.12 shows the measured strength of the magnetosphere of Mercury from the proximity of the northern half of the planet.

Within Mercury's magnetic field is a tenuous and little studied atmosphere (Baker et al. 2011). Mercury might have an exceptionally high density, but this does not make up for its small volumetric size. As such, Mercury is simply not massive enough to harbor a large, developed atmosphere. In addition, the high temperatures on the planet expel gasses and prevent the planet from retaining an atmosphere (Wasson, *Building Stones*).

It was long thought that Mercury had no gaseous upper layer at all; however, data from Mariner 10 and also from MESSENGER proved the existence of both a weak, unstable atmosphere and metal rich "tails" (McNutt et al. 2014).

The planet's atmosphere, barely more than a flimsy sheet around the surface, is composed of 42 % molecular oxygen, 29 % sodium, 22 % hydrogen, 6 % Helium, and 0.5 % potassium. The other 0.5 % is comprised of trace amounts of argon, nitrogen, and various other elements as well as carbon dioxide and water vapor (*Lunar and Planetary Science*, NASA). This gaseous layer is not considered to be stable. In other words, the various molecules in the atmosphere are continually lost and replaced via various processes.

For example, hydrogen and helium are thought to be remnants of solar wind impacts on the magnetosphere. The atoms are trapped for a short while by the magnetic field before escaping and being substituted by newer arrivals. Sodium, potassium, and other metals are most likely emitted from the surface through the effects of radiation on the planetary regolith, through the ejecta of unending asteroid

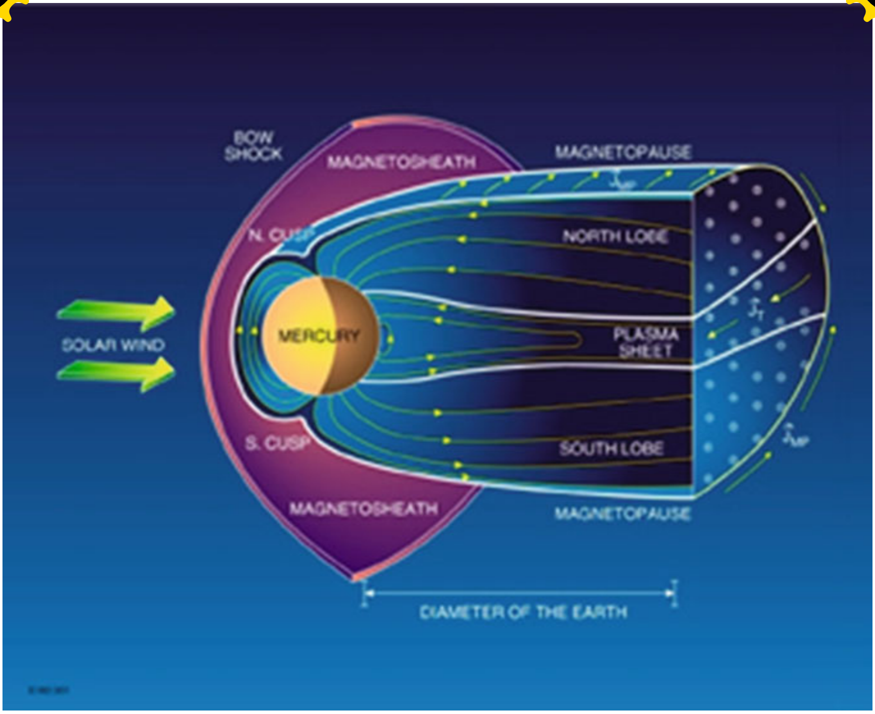


Fig. 14.11 Magnetic field structure. NASA/JHUAPL images

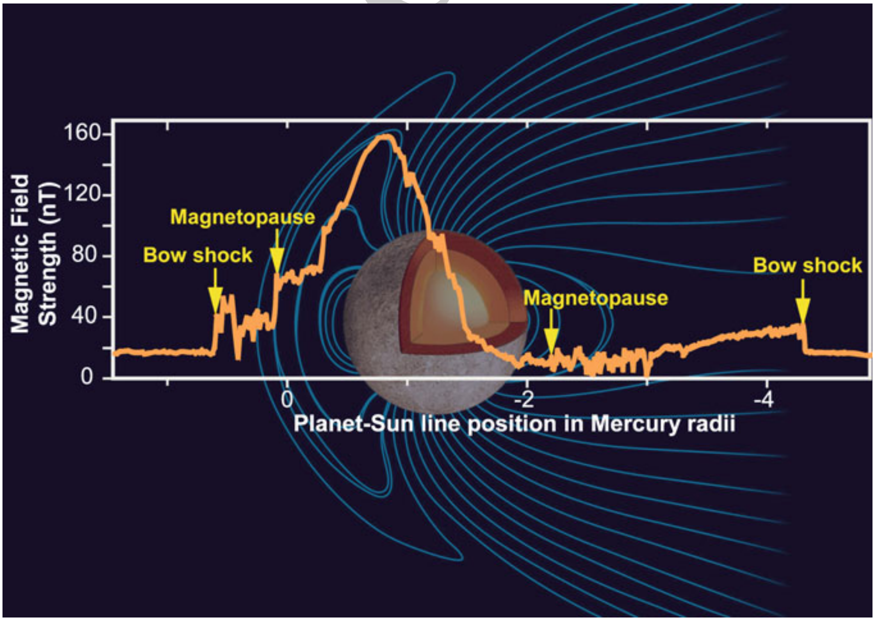


Fig. 14.12 Magnetic field strength. NASA/JHUAPL images

impacts, or through the photographed vents on the surface (Wasson, *Building Stones*).

Thus, as opposed to the stable and contained atmosphere on Earth, Mercury does not have a strong enough gravitational force to retain gasses. Instead, it is always replenishing its dwindling gaseous layer. In other words, Mercury possesses an exosphere rather than an atmosphere (*Solar System Exploration*, NASA).

MESSENGER and ground based systems also discovered “tails” behind the planet. As solar wind passes any planet, it picks up elements of the surface, atmosphere, and other loose components; these can be detected and analyzed to better understand planetary characteristics. The most important and valuable tails are those of the element sodium (Leblanc and Johnson 2003). Thus, the detected sodium tail, along with the notable magnesium tail and calcium tail, from MESSENGER’s on board spectrometers are shown below in Fig. 14.13.

While some of Mercury’s resources lie in the magnetosphere and the atmosphere/exosphere, these areas are also the most hazardous. The magnetic field of the planet provides a layer of security for the surface by deflecting some harmful radiation away. In addition, the atmosphere provides the natural gas resources of sodium, oxygen, and hydrogen.

More research must be done in order to determine whether all the detected elements are from the solar wind or from the surface via asteroids and vents. Also, more data and information is needed on possible ways of harvesting these transient gasses (Schmidt et al. 2009).

Unfortunately, Mercury’s magnetic field is extremely leaky. The sheer amount of solar emission affecting the planet causes much radiation to penetrate the field and directly impact the surface. In many cases, vortices of radioactivity, almost like tornadoes of radiation, have been detected ravaging Mercury’s surface. Further investigation into the full effects of the continual solar wind battering is necessary to better understand this phenomenon.

As for the atmosphere, while it does provide gaseous elemental resources and allows for much of the planet’s heat to dissipate without being trapped by greenhouse effects, it is highly unstable and does little to protect the surface from asteroid impacts. On Earth, much of the debris heading for the planet is burned up in the upper atmosphere. The thin gaseous layer in Mercury does not provide any protection from incoming asteroids. Hence, strikes on the surface of Mercury are a very common and dangerous occurrence.

In summary, although Mercury is one of the few reachable entities with its own magnetic field and tenuous, but existent, atmosphere, landing on the planet does entail serious hazards from the dearth of intrinsic planetary surface protection.

14.2.6 Discussion and Conclusions - Mercury

Mercury is an extraordinary planet. As the innermost solid body orbiting the Sun, Mercury experiences the harshest conditions. From extreme cold to incredible heat

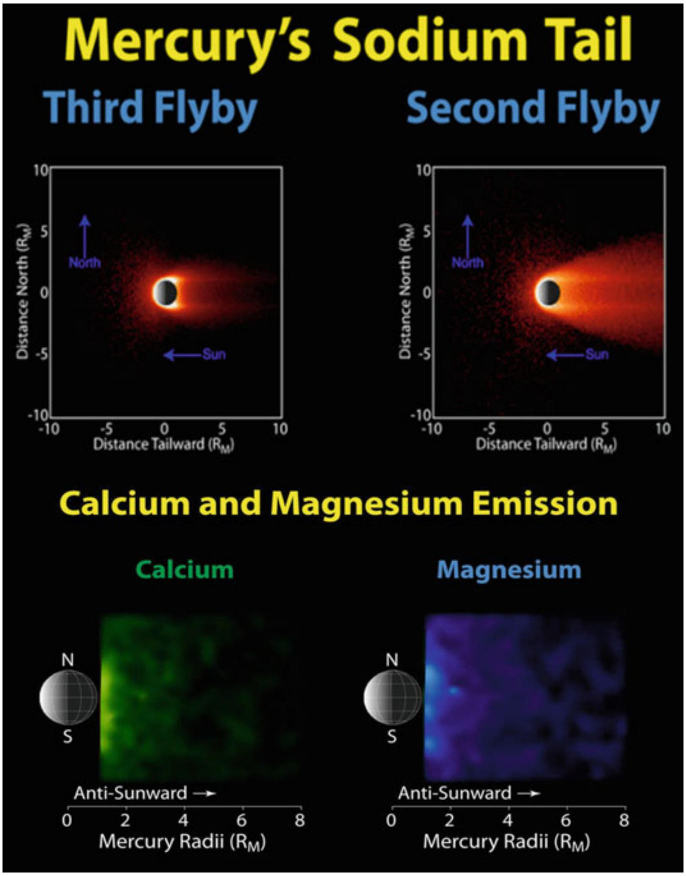


Fig. 14.13 Mercury tails and emissions. NASA images

(80–700 K), a consistent and severe solar radiation and unending asteroid impacts, the small planet weathers it all.

From a scientific standpoint, Mercury presents the perfect example of an accessible planet from which we can learn much about the creation of our Solar System.

It is clear that more research is needed to better understand the numerous hazards of travelling so near to the Sun and to such a barren land. The upcoming ESA and JAXA joint mission of BepiColombo likely will shed more light on these mysteries. BepiColombo, set for arrival at Mercury in early 2024, will consist of two spacecraft: the Mercury Planet Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO). The MPO will scrutinize the surface and crust of the planet in order to better define its properties (Rothery et al. 2010). The MMO will study the magnetic fields and atmosphere of Mercury in order to analyze the properties of such a field and its interactions with solar wind. With the completion of BepiColombo's one-year mission, Mercury will be much better understood, and one day this knowledge will allow us to plan robotic and human travel to it, possibly with even a manned landing.

There would be many unique advantages of creating a base on Mercury. Proximity to the Sun is the most significant advantage. The technology to reach the planet exists and has been implemented. As advances in low thrust propulsion methods are made, novel orbits of the planet and missions carrying more loads and heavier cargo can be designed for landings on the planet (Anderson et al. 2014).

Once on the planet's surface, the regolith could be used to build shelters and protective shells for permanent structures. Another option is to construct underground laboratories. These would use the natural defenses of the regolith and also potentially enable access to not only the aforementioned ice, but also to metals and various resources of the core. In addition, a successful base on Mercury would allow departing vessels to use the enormous solar gravity well as a slingshot to further destinations. Clearly, vast arrays of incredible assets are untapped.

As with any planetary body, Mercury presents serious hazards. The instability of the core and crust due to asteroid impacts, tidal bulging, and even heat currents must be fully understood and prepared for. The surface temperature variations pose many challenges to survival. Furthermore, the possible tectonic activity must be studied and then mapped, and the mountains and vents thoroughly explored to ensure no volatile ejections.

Most importantly, the leaky magnetic field that allows violent radioactive storms on the planet's surface must be mitigated, as any landing would need sufficient protection from the Sun's deadly rays. If a manned mission is to be made, essentials for life must be accounted for. Food and water must be transported and stored on the planet. Oxygen for respiration must be harvested or brought in. Pressurized capsules must be brought in for the initial habitats.

Taking all of these issues into consideration, it seems that the most plausible next step after BepiColombo would be to send a landing craft or rover onto the surface of Mercury. Originally, the BepiColombo craft was to have carried a lander element. It was proposed that this "self-inserting 'mole' device" would execute an airbag-assisted soft landing before entering the Hermian regolith and being hammered down to a depth of 2–5 m (Spohn et al. 2001). The lander craft was eventually cut from the mission due to budget constraints; however, the ideas can still be utilized in the future.

A full topographical map of the surface must be constructed in order to visualize and comprehend the intricacies of a possible landing site (Oberst et al. 2011). Lastly, and most importantly, Mercury's crust may be unstable due to the effects of tidal bulging and the unknowns regarding the lobate scarps. Luckily, these mysteries might be solved with the ongoing and future research, eventually enabling access to the surface of the innermost planet.

Similar to the Mars Curiosity rover, a Mercurian unmanned exploration craft could be well protected from the harsh environment, could land using an airbag deployment method and could help us better understand and characterize surface conditions, paving the way for other landing missions and even human settlements.

It may be quite a few decades before a human sets foot on another planet, but th building blocks are being created upon the knowledge that MESSENGER is providing. With research and continued exploration, the next giant leap for mankind might be one small step onto the first planet, Mercury.

14.3 Venus

14.3.1 *Introduction*

Venus can be considered to be Earth's twin in the Solar System. However, the divergent evolution of the Venus environment has made it a scorched, lifeless rock with a toxic atmosphere. These harsh conditions pose many challenges for the planet's exploration, including temperatures (740 K) that melt electronic systems on the surface, the crushing pressures of 100 times those on Earth, and clouds of corrosive and poisonous sulfuric acid (Gao et al. 2014; Landis 2003; Williams 2014).

Here, we seek to characterize the Venus environment and outline the challenges that faced past missions to the planet and threaten the success of future endeavors. We also speculate on technological breakthroughs that could make the in-depth exploration of the planet more feasible. Lastly, we identify a region in the Venus environment that may be sufficiently Earth-like, to facilitate the construction and survival of a human settlement.

Before the beginning of the space exploration era, mankind observed the planets through ground-based telescopes, using analysis techniques to draw conclusions where raw data was unobtainable. From these observations, scientists discovered a world that outwardly looked very much like our own: Venus. Closest to Earth in orbital distance from the Sun, in radial size, in bulk mass, in bulk composition, and in gravitational pull, many considered this yellow planet covered in a thick carbon dioxide atmosphere to be Earth's twin sister. See Table 14.1. Naturally, there were those who wondered if the conditions were similar enough to also harbor life, but a cloud layer that covered the entire surface from view prevented Earth observers from finding an answer.

Table 14.1 Side by side comparison of bulk characteristics of the inner planets

	Earth	Venus	Moon	Mars
Mean distance from Sun	149,598,261 km	108,208,000 km	Same as Earth	227,939,100 km
Mean radial size	6371.0 km	6051.8 km	1737.1 km	3389.5 km
Gravity in Earth g's	1 g	9/10 g	1/6 g	1/3 g

14.3.2 *Missions to Venus and Their Discoveries*

To confirm the presence of other life in the Solar System, in situ missions to Venus are required. As the Space Race picked up speed and mankind forged its way into space, the Soviet Union selected Venus to be the site of humanity's first expedition to another planet.

Starting in 1961, the Soviet Space Program launched two attempts at flybys of Venus with the unmanned Sputnik 7 and Venera 1 spacecraft. Both missions failed, with the Venera 1 coming closest to Venus but losing communications with the Earth along the way (Williams 2014).

The second attempt by NASA in 1962 made its way successfully to Venus, communications intact. The unmanned Mariner 2 accomplished this feat, performing a flyby of the planet within 35,000 km (Williams 2014). While passing Venus on the way to Mars, Mariner 2 took several measurements of the conditions on Venus, confirming a carbon dioxide atmosphere, a thick cloud layer, and also a surface temperature reading of over 400 °C (Williams 2014). This last discovery of temperatures high enough to vaporize water and to melt lead killed hopes for life on Venus. Figure 14.14 shows some of the spacecraft that made it to Venus.

Exploration of the planet continued and new questions arose. Chief among these questions was how Venus evolved so differently from Earth over its lifetime and if knowledge of its past could give insights to the Earth's own future and planetary mechanisms (Squyres et al. 2011).

Soviets conducted most of the early exploration, sending dozens of flyby probes, orbiters, and landers to Venus over a 20-year period. It became increasingly apparent that Venus not only was lifeless but also bore extremely hostile conditions.

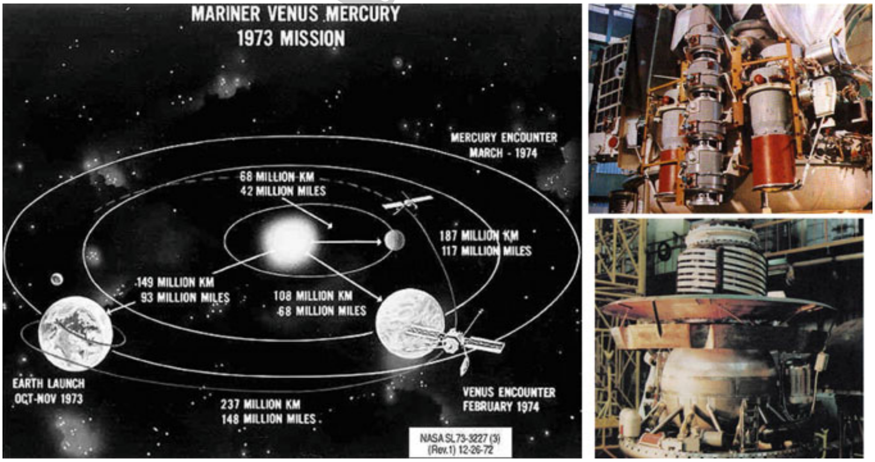


Fig. 14.14 (Left) 1973 Mariner mission to Venus, (Top Right) Soviet Vega probe, (Bottom Right) Soviet Vega lander. NASA images

Hard lessons were learned by surface probes that were destroyed, while descending through the atmosphere, due to the rising temperatures and pressures.

Even when probes survived the descent through the atmosphere, via engineering solutions such as the cooling of their interiors to sub-zero temperatures and their containment in pressurized vessels, each probe barely lasted an hour or two before all systems failed and communication was lost.

The Soviets eventually ended their Venera and Vega mission programs. Their last probes, and the last probe to touch the soil of Venus, were the Vega 1 and 2 in 1984 (Williams 2014). Venus has long been placed on the backburner of space exploration priorities. Only a few key missions have been planned for the next 30 years. These include the Magellan orbiter, the Pioneer Venus orbiter, the MESSENGER flyby from NASA, and the Venus Express orbiter from the European Space Agency. The Japanese space program JAXA will attempt an orbit of its AKATSUKI probe around Venus in 2015 (Williams 2014).

While those missions have returned most of the data we have today about Venus, they are limited by the lack of direct physical measurement of the environment. In order to fully understand the planet, a series of new in situ missions are needed.

Here, we summarize some of the information collected over the last 50 years of the direct exploration of Venus and from observations using Earth-based telescopes, to provide a characterization of the Venus environment for purposes of engineering a habitat.

We focus on defining the harsh conditions of the planet, as illustrated in Fig. 14.15, and the threats these pose to future missions. Ultimately, we speculate on future technology that might make overcoming the environment possible as well as a location in the Venusian atmosphere that might be suitable for human habitation.

Fig. 14.15 Artist's representation of the Venus environment. NASA image

14.3.3 *The Surface of Venus*

The surface of Venus has been described as a "hellish land" riddled with volcanoes and gigantic plains of lava rock. It experiences vaporizing temperatures of around 740 K (around 470 °C or 870 °F), much higher than Earth's hottest regions (Williams 2014). These temperatures vary little over time due to the oven-like effect created by Venus' cloud layer above, remaining intense regardless of night or day or season, depending more on elevation and surface composition than other factors (Cañon-Tapia 2014). Likewise, pressures of nearly 90 atm have been recorded (Williams 2014).

Past missions to the surface of Venus focused heavily on analyzing its composition and its geological history (Squyres et al. 2011). Primary issues that limited the amount of data that could be gathered included a lack of well-defined target locations, deployment and landing difficulties damaging sensors and drilling equipment, poor communications with the landers, and the limited time of operation associated with an environment blocked from the Sun and experiencing extreme temperatures/pressures (Williams et al. 2014). Measurements from different regions of the planet were recovered by the Russian Venera and Vega probes (Williams 2014).

The surface of Venus is composed primarily of mafic, or basaltic, rock, a result of millions of years of gradual lava flow (Basilevski et al. 2012). Volcanic plains of up to 400–500 m thickness produced by enormous, shield-like volcanoes that dwarf those on Earth cover about 70 % of the planet. The plains and volcanoes are categorized extensively based on formation, structure, and level of deformation by tectonics (Ivanov and Head 2013). However, though vast and diverse, these structures offer very little information about the underlying composition of Venus and its history, merely representing the years of covering up and erasing the planet experienced (Basilevski et al. 2012).

The remaining 30 % of the surface consists of either heavily tectonized volcanic plains or, more promisingly, areas of complex rock and lava flows that may hold a key to understanding the structure and evolution of Venus below the plains (Ivanov and Head 2013). Infrared and ultraviolet emissivity readings were used to identify these regions, which differ from those indicative of mafic plains. It was discovered that Venus possesses another type of volcanic structure other than shield-like domes. Steep slopes were found instead of gentle domes. This suggests slower, more viscous or foamy lava flows that could be attributed to more enriched lava containing large amounts of dissolved water or other chemical/mineral components.

Plateau-like formations called Tessera terrain were also found in these regions, believed to be composed of a material more geochemically differentiated from the mafic rocks, perhaps feldspathic silicates, intermediate rocks, or anorthosites (Basilevski et al. 2012). Some suggest though, that tesserae may just be more tectonically deformed rock made up of older materials possibly of volcanic origin (Ivanov and Head 2013).

Figure 14.16 is a map based on data from the Pioneer Venus Orbiter.

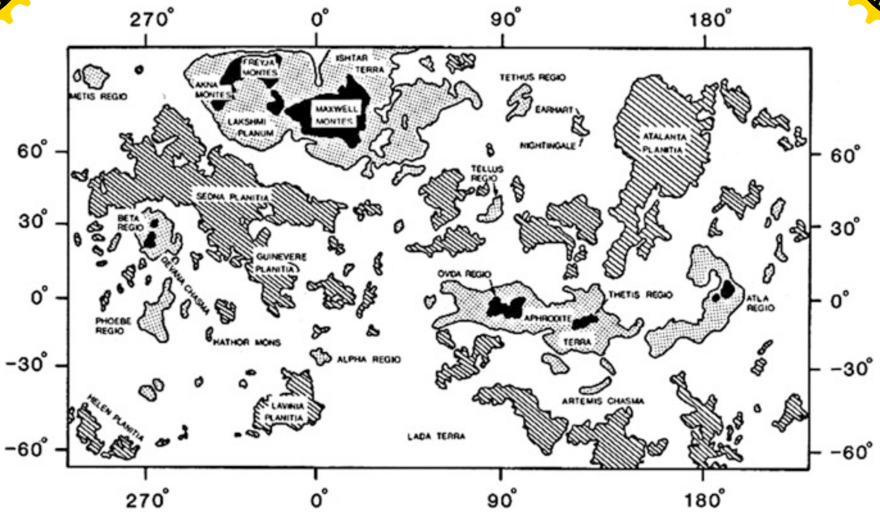


Fig. 14.16 Notable mountains, plateaus and other land formations as mapped by the Pioneer Venus orbiter. NASA image

In the early years of Venus exploration, it was speculated that Venus was a planet of extreme volcanic and tectonic activity due to the vastness of the volcanic plains. As more data was assembled and further studies were conducted, many clues were brought to light that allowed scientists to begin to piece together the geological and evolutionary history of Venus, clues that include relatively recent but minimal volcanic activity and a low number of impact craters visible on the surface (Romeo 2013).

Two theories for the geological history of the planet have been proposed based on the above information and that a large percentage of the surface is covered in lava formations. The first suggested that Venus underwent extensive volcanic activity over the years that both covered the surface and erased a large number of impact craters that otherwise would be visible. Moving forward in time, this activity gradually decreased to the minimal activity we see today.

The second theory proposes a more dynamic history that involved a "catastrophic resurfacing" of Venus several million years ago when a violent volcanic event covered the planet in lava flows (Romeo 2013). Following that event a sharp decline in volcanic activity ensued, a calming period that we experience still today. All of the geological landmarks and impact craters of the past were erased by the resurfacing and what we see today are only the most recent of markings (Romeo 2013). Many models were generated to simulate these two theories in an attempt to reproduce a scenario and surface similar to the one we see today of Venus. The present consensus based on all this information, supports the resurfacing theory.

Interestingly, it has been observed that the majority of active volcanoes are heavily concentrated on one hemisphere of the planet, suggesting that there may

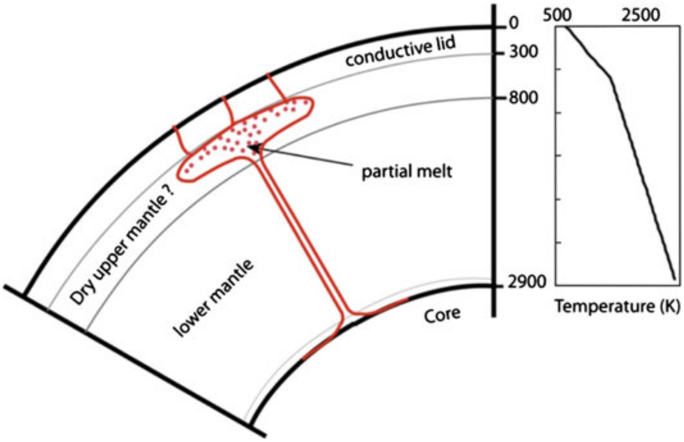


Fig. 14.17 Representation of Magma plume theory and inner structure of planet. NASA image

exist within the inner structure of Venus a plume-like magma process on this side of the planet that has found its way to the surface through a thinner layer of the lithosphere (Cañon-Tapia 2014). Figure 14.17 is a schematic of this possibility.

Besides volcanic activity, Venus also possesses signs of tectonic activity that shapes its surface. The processes by which this occurs remain largely unknown. There is no evidence of the plate mechanics that occur on Earth and it is believed that subterranean Venus is far less dynamic than subterranean Earth. The weak magnetic field of Venus is considered to be supporting this theory by comparison with Earth's strong magnetic field that generated by the polarization of its moving liquid mantle and core.

It is theorized that Venus once existed in an era dominated by tectonic activity much like that of Earth. This then subsided and the dynamics of the planetary insides slowed, giving way to a volcanism-dominated era (Ivanov and Head 2013). Mantle degassing and the disappearance of a magnetic field contribute to the "runaway" greenhouse conditions that exist today. Sulfur and carbon were spewed into the atmosphere, water was consumed by lava flows or evaporated away, the surface was covered, radiation bombarded the planet, hydrogen and oxygen were lost to the atmosphere, temperatures and pressures rose, and the clouds formed (Driscoll and Bercovici 2013). At the end of this era of great change, the final catastrophic resurfacing event occurred and reshaped the planet permanently, leaving behind a new, volcanic plain-covered, crater-free surface. This was the beginning of the era that continues today, of continuous but diminished volcanic and tectonic activity with a scorched surface and a highly toxic atmosphere (Ivanov and Head 2013).

14.3.4 *The Lower Atmosphere of Venus (0–45 km Altitude)*

The lower atmosphere has been poorly characterized and might be one of the biggest mysteries of Venus. Other than its general transition from surface to cloud level temperatures and pressures, we know very little of its composition and dynamics due to being masked from view by the thickness of the sulfur clouds above and the intensity of conditions at the surface (Squyres et al. 2011). Balloon probes have entered the clouds and landers have reached the surface. Orbiters and ground-based telescopes have observed the upper atmosphere and cloud tops. None have delved into the tiny region tucked between all those areas. Thus, the lower atmosphere of Venus is a high priority target for future in situ missions to Venus (Squyres et al. 2011).

What is known is that the lower atmosphere of Venus transitions quickly from temperatures of up to 750 K at the surface to about 400 K at the cloud bottoms at an altitude of 50 km. There is also a dip in pressure from under 100 atm at the surface to 1–2 atm at 50 km. The lower atmosphere is presumed to be windy, though it does not possess the super-rotational wind flows of the upper atmosphere, as will be discussed later. On the other hand, powerful bursts of wind are generated by the convection currents as air flows between regions differing in temperature by up to 350 K. These upwelling and down-welling gusts are largely responsible for volcanic outgassing components rising into the atmosphere and into the clouds (Imamura et al. 2014).

Compositionally, we know that over 95 % of the atmosphere is CO_2 and there is evidence of high CO concentrations (Cotton et al. 2012) and of a sulfur particle haze below the clouds at altitudes of around 45 km (Gao et al. 2014). Water vapor traces have been observed in the atmosphere, concentrations of about 30 ppm at 30 km altitude (Chamberlain et al. 2013; Cottini et al. 2012). Though most water has been lost to space over time, water is still a key source of hydrogen necessary for the formation of acids, especially the sulfuric acid in Venus' clouds, suggesting that Venus is presently more hydrated than oxidized and that hydrogen may be dissolved and outgassed by volcanoes or deposited in the past by comets (Cottini et al. 2012).

14.3.5 *The Sulfur Clouds of Venus (45–70 km Altitude)*

The most iconic features of Earth's "evil twin" are no doubt her enormous super-rotating clouds. These clouds generally hover at heights of about 45–70 km (Khatuntsev et al. 2013; Stoddard and Jurdy 2012). The clouds consist mainly of sulfuric acid, which was spewed into the atmosphere over time from volcanic out-gassing and upwelling convection currents at the surface (Driscoll and Bercovici 2013). Figure 14.18 is an artist's rendering of these clouds.

ig. 14.18 Artist's representation of the Venus clouds and the presence of lightning. NASA image

Once inside the atmosphere, the sulfuric acid coagulates and condenses in the middle region of the cloud layer, initially forming tiny micrometers particles (Gao et al. 2014). Gradually, these particles combine and form even larger, heavier particles that then descend and form a lower haze at the bottom of the clouds while displacing smaller particles upwards. Strong updrafts from the much hotter Venus surface blow small midlevel particles higher where they can nucleate with meteoric dust in the upper atmosphere and form an upper haze of sulfur (Gao et al. 2014). Average particle size in the clouds increases from mid latitudes toward the poles and toward the equator. Thus, thicker clouds are found around those regions than in latitudes between 30^0 and 60^0 in both hemispheres (Haus et al. 2014).

It has been speculated that another key chemical component other than sulfuric acid exists in the clouds. From ground-based observations using emission spectrum analysis of Venus' atmosphere, it has been noted that the clouds are absorbing a higher amount of UV radiation than sulfuric acid typically would on its own (Markiewicz et al. 2014). Studies of an optical phenomenon known as "Glory" suggest that the unknown component may be $FeCl_3$ or elemental sulfur either in the core of particles or as a coating (Markiewicz et al. 2014). Similar to traces of water vapor found in the lower atmosphere, notable concentrations of water vapor have been observed at the cloud top layer as well (Cottini et al. 2012).

Khatuntsev et al. (2013) describes clouds moving at high speeds under high winds, orbiting the planet in approximately three days at the mid-latitudes to the poles, and in about five days at the equator. Due to having constant periods of rotation of around three days in such a large continuous region, it has been theorized that the clouds near the poles behave as a quasi-solid body with a much denser consistency than the more fluid flowing clouds at low latitudes. Mean velocities in the upper clouds peak at 80–110 m/s with daily oscillations due to up-welling and down-welling currents from the lower atmosphere.

This super-rotational flow is directed retrograde with a polar flow component of around 10 m/s. In the mid-latitude regions, there is a strong variability in wind speeds over short periods of time of up to 35 m/s. This “mid-latitude jet” indicates that this region vacillates between the jet-like behavior of the low latitudes and the quasi-solid body behavior of the high latitudes. The lower layer winds from the middle cloud deck downward peak at 70–80 m/s.

In normal Earth conditions, the day typically produces stronger winds than during the night due to sunlight heating up the surface air. Convection currents are created as hot air rises and cools in the upper atmosphere. The opposite cycle occurs on Venus (Imamura et al. 2014). The high temperatures on the surface of Venus remain relatively constant while the sulfur clouds block and absorb most of the solar heat that reaches the planet, resulting in calmer convection currents in the lower atmosphere that become even calmer during the day as the clouds heat up in the Sun resulting in more uniform atmospheric temperatures (Imamura et al. 2014).

The average temperatures for the cloud region range from a cold 240 K in the top layers to as high as 380 K in the bottom layers (around −30 to 110 °C). Cloud temperatures can vary 10 K in a daily cycle but the general thermal structure of the planet does not vary with time. Over 23 years of observations, the average temperatures of the planet have not changed significantly (Haus et al. 2014).

14.3.6 The Upper Atmosphere of Venus (70+ Km Altitude)

As first surmised by Landis (2003), despite the harshness of the surface and lower atmospheres of Venus, the upper atmosphere of Earth’s twin has relatively tame Earth-like conditions of temperature, pressure, and chemical composition. This is at altitudes of 65–120 km, above the toxic sulfur cloud layer and under the radiation protection of a magnetized ionosphere.

As discussed in the previous sections, the sulfur clouds are a dense area of high pressure and high temperature. At higher altitudes, sulfuric acid particulates fail to form and atmospheric pressures plummet from peaks of 90 atm at the surface to 5 atm in the clouds, to less than 0.1 atm at an altitude of 65 km (Migliorini et al. 2012). At greater altitudes, the atmosphere becomes extremely thin and pressures drop further, in part due to the loss of atoms and molecules stripped away in the outward flux of particles into space (Lundin et al. 2011). Figure 14.19, based on the data of Lundin, shows these variations of pressure with altitude.

Temperatures also decrease significantly at higher altitudes. The sulfur clouds absorb and entrap solar radiation and heat. Thus, while the lower atmosphere and cloud layer remain at superheated temperatures of several hundred Kelvin, at altitudes just above the clouds of 55–65 km, temperatures mellow out to Earth-like, livable conditions of −243 K to 303 K (−30 to 30 °C). At altitudes of 100 km and greater temperatures begin to drop to less than 150 K (−123 °C) (Haus et al. 2014). Figure 14.20, based on the data of Haus, shows these variations in temperature with altitude.

Like the rest of Venus, the upper atmosphere is a CO_2 based greenhouse (Driscoll and Bercovici 2013). However, it does contain traces of N, O_2 and CO,

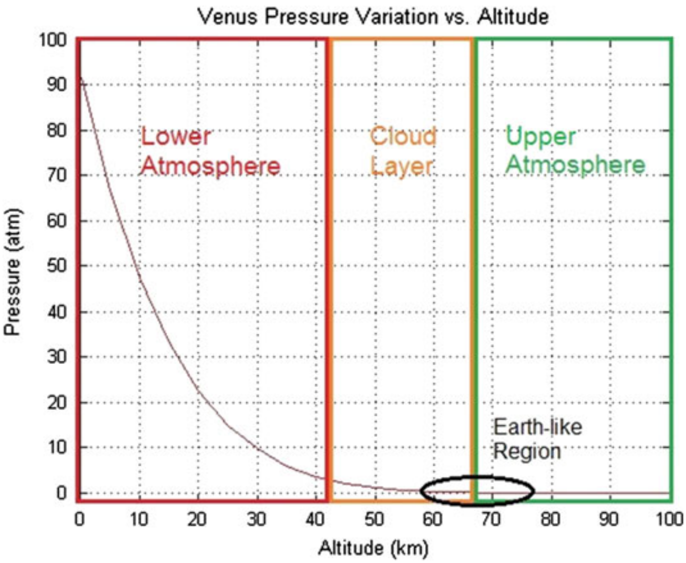


Fig. 14.19 Venus average pressure vs. altitude

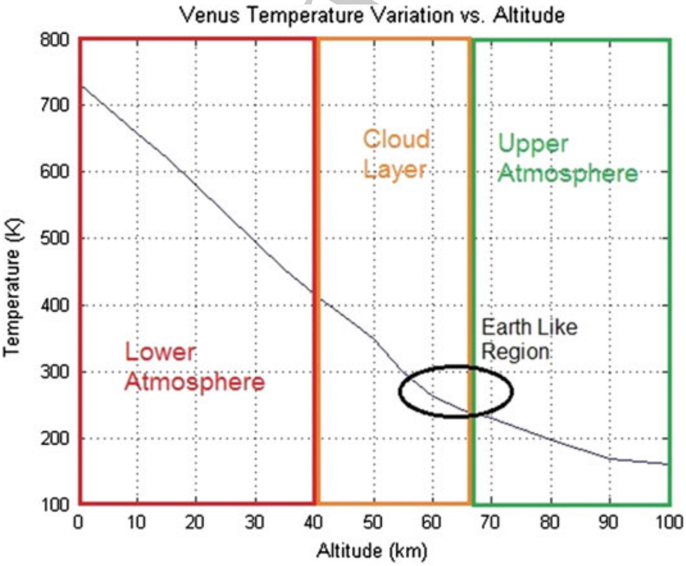


Fig. 14.20 Venus temperature vs. altitude

which are the primary constituents of our atmosphere on Earth (Landis 2003). There is evidence indicating that water vapor can be found in low concentrations at the cloud tops in certain locations around the planet (Lundin et al. 2011). Concentrations of CO are quite high above the clouds, though the values can vary greatly over periods of 20 or more days (Cotton et al. 2012). Figure 14.21 compares such concentrations.

While this benign region of Venus at altitudes of 65–90 km has potential for human and robotic use, high winds in the range 80–110 m/s are present. At higher elevations, around 90–120 km, wind characteristics are poorly defined but have strong variability in wind velocity. Beyond 120 km, winds are generated by the mix of solar generated heat and the cold air, resulting in peak speeds of 130 m/s (Sornig et al. 2013).

Many studies have attempted to create accurate models of the wind flows at different altitudes, latitudes, and times, but they still fail to encompass the complexity of the dynamics observed in all regions and altitudes (Sornig et al. 2013). Overall, there is a higher average velocity at the equator and lower average near the poles with temporal variations resulting in peak gradients of ±50 m/s in certain areas over several days (Sornig et al. 2013). Long-term data shows that average wind speeds consistently are increasing over time (Khatuntsev et al. 2013). Figure 14.22 shows this trend.

14.3.7 The Ionosphere of Venus

Unlike Earth, Venus generates a very weak magnetic field. This in turn allows much of the Sun’s more intense electromagnetic radiation to penetrate the planet instead

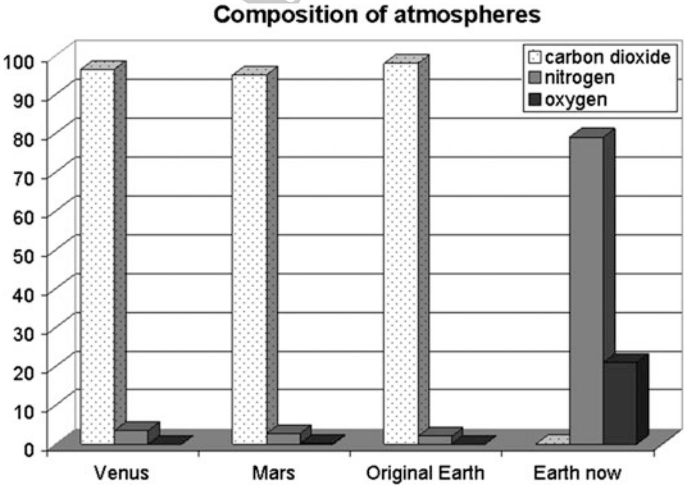


Fig. 14.21 Atmospheric composition of Venus (Evans et al. 2012)

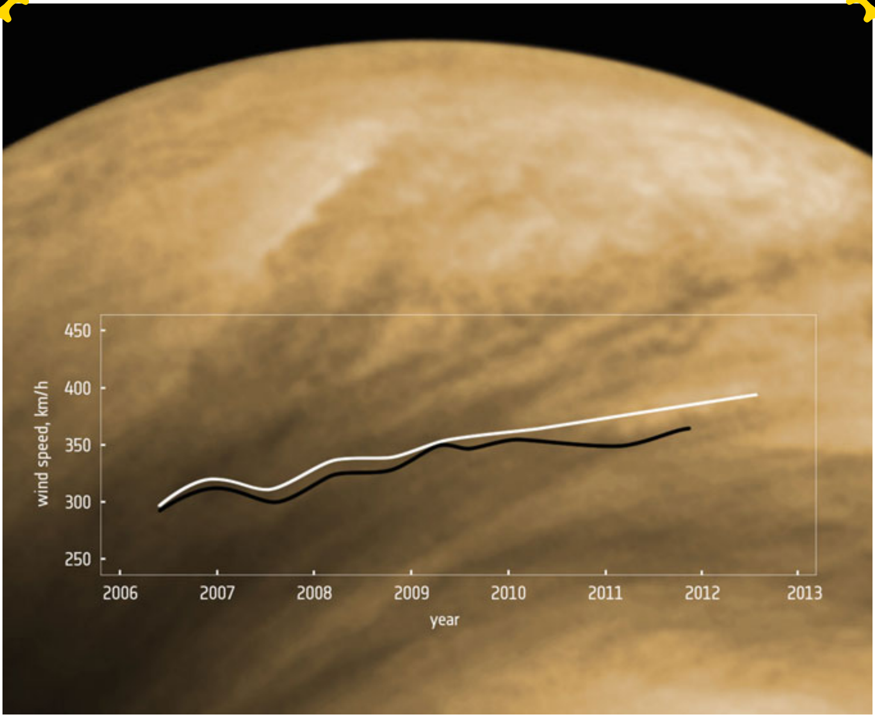


Fig. 14.22 Venus cloud level wind speed trends over recent years. NASA image

of being deflected or neutralized (Driscoll and Bercovici 2013). As a result of this high solar insolation, the particles at the very edge of the atmosphere become highly energized to the point of ionization, creating what is known as Venus' upper ionosphere, which becomes magnetized and deflects (Zhang et al. 2006). This barrier consists of mainly O^+ and H^+ ions (Lundin et al. 2011).

Due to continuous solar wind bombardment, Venus' upper atmosphere ions and particles are stripped away under the drag and momentum exchange between the wind and the ionosphere (Lundin et al. 2011). This loss is theorized to have contributed to the depletion of hydrogen, ozone, oxygen, and other chemical substances in the atmosphere, leading to the runaway greenhouse evolution of the planet (Ruess et al. 2006). Studies suggest that the flux loss occurs at a rate of 10^{25} ions or 250 g per second (Ruess et al. 2006). Comparatively, this is far less than the 3 ktons per second lost by Haley's Comet and the 1 ton per second lost by Io, but it has been noted that the acceleration and loss of these ionized and plasma particles forms a tail effect around Venus similar to that of a comet (Ruess et al. 2006). Another subsequent result of the drag interaction between the ionosphere and solar wind is the addition of neutral particle winds in the upper atmosphere (Lundin et al. 2011).

14.3.8 Venus: The Remaining Questions

We see that a reasonable knowledge base has been created about Venus. Key questions are left unaddressed, however, and the answers to these questions can yield significant insights to the evolution of Venus and its intertwining fate with Earth. These questions include:

- What is the composition of the lower atmosphere with respect to volatile and neutral chemical components, which cannot be studied from orbiters or ground-based telescopes beneath the cloud layer?
- What is the underlying composition of the surface below the thick regional plains of volcanic rock, with Tessera terrain being chief target areas?
- What are the mechanisms behind the volcanic and tectonic activity within the planet?
- What is the inner structure of the planet?

14.3.9 Venus: Summary of Engineering Challenges

In summary, each region of the Venusian environment poses different extremes and challenges to our understanding, but also to our ability to place instrumented rovers on, or in orbit around the planet.

14.3.9.1 Surface and Lower Atmosphere

- Constant high temperatures of 740 K (Cañon-Tapia 2014)
- High pressures in the range 90–100 bar (Williams 2014)
- Volcanic and tectonic activity, active lava flows (Ivanov and Head 2013)
- Sulfuric acid out-gassing and upwelling into clouds (Driscoll and Bercovici 2013)
- Sulfuric acid haze and possible acid rains (Gao et al. 2014)
- Limited sunlight, like very cloudy Earth days (Williams 2014)
- Poor signal reception, high interference from cloud layer and ionosphere

14.3.9.2 Cloud Layer and Upper Atmosphere

- High global wind speeds upwards of 80 m/s, retrograde super-rotational flow (Khatuntsev et al. 2013; Sornig et al. 2013)
- Dense clusters of sulfuric acid particles and haze (Gao et al. 2014)

- Ionized upper atmosphere due to direct exposure to solar radiation, may cause communications interference and with probe materials (Zhang et al. 2006)
- "Cold" temperatures (Haus et al. 2014)
- Nightside and dayside cycles of about 117 Earth days (Landis 2003)

With respect to landing probes on the surface, measures should be taken to make sure that the probes would endure the very high temperatures that exist. Unlike the Moon and Mars, which fluctuate between lesser extremes of cold and heat, the surface of Venus remains over 700 K at all times due to the oven-like conditions the cloud layer creates over the lower atmosphere and the planet's surface. These temperatures are hot enough to melt the lead solder and circuit boards of the current electronic systems on Mars probes (Landis 2003; Williams 2014). High Temperature Electronics or HTEs are a possible solution. While current technology falls short of operating at Venus conditions, HTEs developed for Earth-application in oil well drills, avionics, and automobiles have been proven to operate at up to 200 °C (Watson and Castro 2012).

If an extended presence is demanded of a surface probe similar to the operating lifetimes of Mars probes, methods for renewable energy will be needed as little sunlight penetrates the dense cloud layer above and Venus' nights are many Earth days long. Possible solutions are harnessing wind or thermal energy instead or deriving fuel in situ from Venus' surface. Protecting wind turbines and airfoils from dust and corrosion will be difficult challenges, however.

With sulfuric acid and other particulates outgassed into the atmosphere through volcanic events, anti-corrosion materials and systems should be considered for longer missions on the surface. There are materials with high sulfuric acid exposure tolerance, but they have never been used in planetary probes and at Venus temperatures.

For probes that intend to operate in and study the atmosphere of Venus, depending on the specific altitude, they will need several specialized systems as well. In the final surface and atmospheric missions to Venus by the Soviet Vega 1 and 2 craft, balloon probes were launched into the atmosphere along with the landing probes that were sent to the surface (Williams 2014). These balloons were made of lightweight material protected from sulfuric acid corrosion by a special coating. While this method protected the balloons over their two-day long flights, it is questionable whether such light coating is enough to protect a probe for an extended period of time (Williams 2014). Because Venus' atmosphere is so dense, the buoyancies of helium and even breathable air is higher (Landis 2003). Therefore, atmospheric probes can be made of heavier materials if they can provide sufficient protection from corrosion while also making them more structurally sound against high winds.

If these balloon probes are designed for the lower atmosphere or within the cloud layer, similar energy supply considerations should be taken as with the surface location. With limited exposure to sunlight, harnessing wind energy is an option, though this adds much more complexity to the probes. Likewise, while temperatures and pressures do decrease at higher altitudes on Venus, temperatures and pressures in the lower atmosphere and clouds are still at values much higher tha conditions on Earth, Mars, or the Moon. While high outer pressure means that the threat of leaking lifting gas from balloons is reduced, high temperatures means that HTEs will need to be applied to the atmospheric probes as well.

Landis (2003) makes useful suggestions in order to mitigate potential communications problems between landing probes and lower atmospheric probes with Earth. Serious additional challenges exist if samples are to be taken from the atmosphere and soil of Venus and brought back to Earth for extensive analysis; problems arise with the reclamation of probes since they will need to be designed not only for survival but also for powered flight out of the Venus gravity well.

14.3.9.3 Establishing a Settlement on Venus for Future Missions

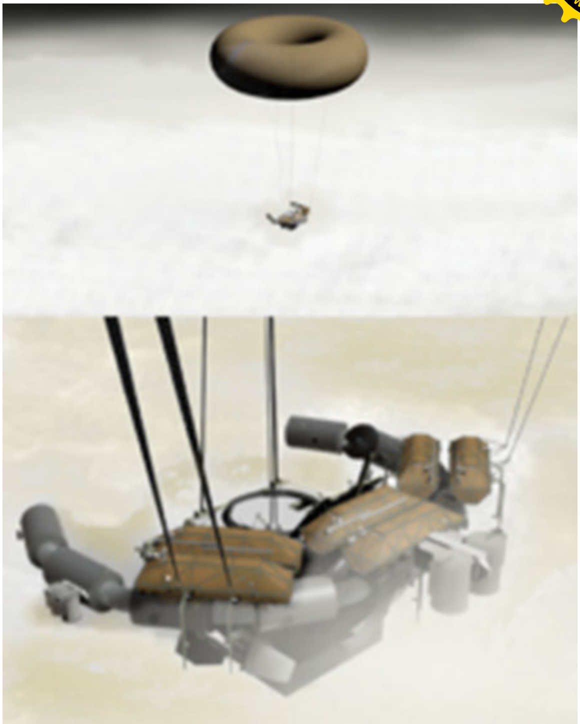
While there are many difficulties facing stand-alone probes operating in the Venus environment for extended periods of time, Landis suggested that there was a region on the planet that has almost Earth-like conditions. By creating a base of operations in this region with the focus on possible human habitation, probes can be constructed and deployed on smaller scale missions with more feasible prospects for data retrieval, sample reclamation, and extensive study by scientists, in situ. This region is within the upper atmosphere of Venus just above the cloud tops and between 65–70 km altitudes and is characterized by:

- Mild temperatures varying from 240–300 K (Haus et al. 2014)
- Low pressures from 0.2–1 bar (Williams 2014)
- High winds ranging from 80 to 100 m/s (Sornig et al. 2013)
- Ample sunlight access with super-rotational days of 50 h (Landis 2003)
- Low radiation exposure due to protection by the ionosphere and upper atmosphere (Landis 2003)
- Lower dangers of sulfuric acid corrosion above the cloud tops (Gao et al. 2014)
- Thick carbon dioxide atmosphere with traces of oxygen, nitrogen, hydrogen, and water vapor
- 90 % Earth’s gravity (Landis 2003)

Although the time when mankind can realistically consider constructing a settlement on Venus or on any other body in the Solar System remains far in the future due to limits on technology, infrastructure, costs, and economic and other incentives, an analysis of a settlement in a future scenario where it is of consideration can still be made.

The conditions mentioned above, at that “sweet-spot” within Venus’ atmosphere, offer a unique opportunity for human habitation unlike any concepts considered for settlements on the Moon, Mars, or any other planet, that is, a floating base in the atmosphere, an “aerostat base” (Landis 2003). Figure 14.23 shows such a hypothetical base.

Because of benign pressures at the aerostat elevation, Landis considers risks associated with gas losses as manageable. Landis further points out that an aerostat



ig. 14.23 “Venus Balloon Outpost” – hypothetical aerostat habitation on Venus with torus shaped balloon. Wikimedia image

habitation that is free to drift in the atmosphere will experience pseudo-days of only 50 h. Furthermore, Venus’ thick atmosphere and magnetized ionosphere will block much of the radiation reaching the base (Landis 2003).

Of course, not only must this settlement survive in the environment, but it must also be able to generate the vital resources necessary for self-sufficiency. It has been reported that the atmosphere at the top cloud layer is predominantly carbon dioxide but contains traces of other elements like oxygen, nitrogen, and hydrogen. While these trace elements can be harvested in small quantities, more oxygen and hydrogen can be obtained through chemical processing of the carbon dioxide and sulfuric acid readily available in large quantities (Landis 2003). These can then be combined into water through known processes.

One of the great unknowns and dangers regarding manned space activities is the disparity in local gravitational fields as compared to that of Earth. Venus, with 90 % Earth gravity, removes one troublesome problem that exists for manned operations on the Moon and Mars.

As with the manned settlement of any body in the Solar System, settling Venus will require a significant transport of mass from Earth (or the Moon more likely at the time when we consider settling Venus) for the initial infrastructure. It will take time to create an in situ resource utilization infrastructure.

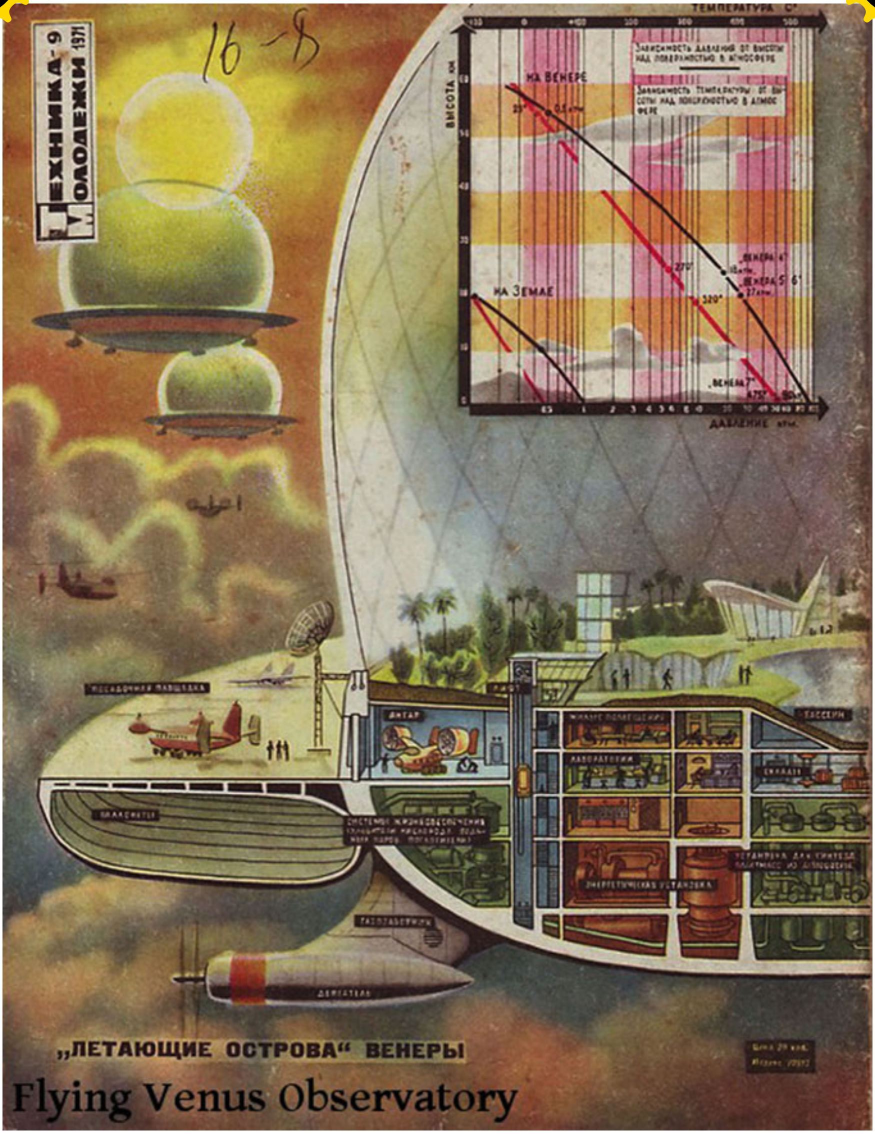


Fig. 14.24 Russian concept for a floating settlement on Venus. OrbitalSwap 2013

Regardless, should these challenges be surmounted, eventually more bases can be deployed to Venus while older settlements can grow in size, and become more self-sufficient. Permanent settlements can be created on Venus. Figure 14.24 shows an artist's rendering of a significantly evolved base floating and orbiting in the Venusian atmosphere.

14.3.9.4 Discussions and Conclusions – Venus

Venus is a unique planet in the Solar System, outwardly very similar to Earth but having diverged in evolution to the point of being hostile to all life on its surface and in its lower atmosphere. These harsh conditions make exploring the Venus environment very difficult and leave scientists with many unanswered questions about the underlying structure of the planet and how it came to be. To answer these questions, future missions are needed, but manned missions to the surface and atmosphere are out of the question at this time for life-threatening reasons. Similarly, unmanned probes face challenges unlike those faced on other bodies, like the Moon and Mars, which prevent them from operating for extended periods of time. While orbiters collect large amounts of data and can operate for many years around Venus, they are limited due to interference and lack of visibility through the planet's thick atmosphere.

In order to fully explore Venus, technological breakthroughs must be made that allow probes to cope and function in the Venusian environment for more than the few hours they survived previously. Additionally, at a certain altitude in the upper atmosphere of Venus, there may be conditions suitable for the construction of a floating human habitation that will give mankind a permanent foothold on (in low orbit over) the planet. There, human explorers can live and conduct more feasible exploration of the planet. These settlements can eventually grow and become more self-sufficient, a human colony independent of outside resources for its survival.

This poses many advantages for the evolution and expansion of mankind beyond Earth as well as economic advantages of a better location with which to reach and mine asteroids.

14.4 Titan

14.4.1 Introduction

We are interested in Titan because it has drawn the interest of the scientific and engineering communities as more data has been gathered about its composition and environment. Understanding particular planetary bodies can provide a framework for understanding all the planetary bodies, including Earth. From the perspective of engineers who will be called upon to design and construct facilities and habitats on our future homes in the Solar System, it is clear that the technologies will have overlapping capabilities, even though all these bodies have dissimilar environments. It is in this spirit that we include Titan in this paper on Mercury and Venus.

Here we focus on Titan's environmental characteristics that would affect a structure on its surface. Important factors for structural integrity include temperature, atmospheric pressure, troposphere density, Titan's regolith composition, wind velocity, seismic activity, and the surface liquid density. These factors will have to taken into consideration when designing a surface structure and constructing i, either using available surface materials or using materials brought to the surface from Earth (or more likely, from the Moon). We will also mention a likely location for such a settlement.

Titan's environment is unique in our Solar System in the sense that it is very similar to Earth. The atmospheric composition on Titan is mostly nitrogen, like on Earth, and the atmospheric pressure is only 0.467 atm (Harria et al. 2006). The atmospheric density in the troposphere is roughly 4 times greater than Earth's surface air density (Lorenza et al. 2012). The oceans on Titan, near the equator, have a density of 614 kg/m^3, which is relatively close to Earth's 1025 kg/m^3 oceans (Tan et al. 2013). These characteristics, along with a few other examples, are why Titan will eventually be a suitable candidate for building a surface habitat.

14.4.2 Atmospheric Composition

Titan's atmosphere has components that are similar to our own on Earth. Titan is one of the only places in our Solar System where there is a surface pressure similar to Earth's atmospheric pressure at sea level. Titan's atmospheric pressure is 146.7 kPa (+/−0.1 kPa) while Earth's sea level pressure is 101 kPa (Harria et al. 2006). The gases present in the atmosphere are 98.5–98.6 % N_2 and 1.4–1.5 % CH_4 (Tokano 2014). Earth's atmosphere is 78.09 % N_2 and 20.95 % O_2. N_2 can be used for plant fertilizer, allowing plants to be grown inside a surface structure. N_2 is a macronutrient that is a key component in chlorophyll. The atmospheric density was found using the nominal Yelle model (Yelle et al.). The troposphere density was reported to be 5.24 kg/m^3 at the surface using the Yelle model. Saturn induces a magnetic field on Titan, although it does occasionally leave this magnetic field (Simon and Motschmann 2009).

14.4.3 Temperature Profile

The temperature profile of Titan is one of the major features of this moon that is very unlike our own planet. The surface temperature has been recorded by the Cassini spacecraft to be 92.5 K +/−2.5 K close to the equator. Tropospheric temperatures become cooler as we go from the equator to the poles by approximately 15 K in contrast to the equator (Schinder et al. 2012). Seasons on Titan last about 30 times longer than seasons on Earth. During northern winter the South Pole is always illuminated, which causes a temperature difference that allows a Hadley cell (a tropical atmospheric circulation) to form in the troposphere (Rodriguez et al. 2011). Data concerning the temperature profile was gathered in order to understand how fluctuations and temperature gradients could affect a structure on Titan.

14.4.4 Orbit

Titan has an orbital period of 15.95 Earth days. The length of a Titan “day” is the same as its orbital period. The surface gravity is 1.354 m/s^2 and Titan has a mean radius of 2,574.7 km.

14.4.5 Wind

The most probable wind speeds have been estimated to be 0.3 m/s at 10 m from the surface. The surface wind can go as high as 0.9 m/s. Greater wind speeds are seen as we begin to ascend in altitude – roughly 10–60 m/s from 30–50 km above the surface (Lorenza et al. 2012). It may be possible for energy to be harvested at higher altitudes on Titan using airborne turbines.

14.4.6 Surface Liquids

Surface liquids vary slightly from the equator to the poles in density and composition because of temperature differences. Surface liquid density at the equator is 614 kg/m^3 with a composition of C_2H_6 (53 %), CH_4 (32 %), C_3H_8 (7 %), and N_2 (7 %) with the given mole percent. Toward the poles the density is 551 kg/m^3 with compositions of 68 % CH_4, 22 % N_2, and 8 % C_2H_6 (Tan et al. 2013).

14.4.7 Titan Regolith

The ESA-build spacecraft, the Huygens probe, landed on Titan in 2005. It was the first spacecraft to land on Titan. The regolith near the probe-landing site, the Xanadu region, was determined to have a muddy consistency. It was determined that the regolith may consist of a damp and cohesive material with interstitial liquid contained between its grains (Atkinson et al. 2010). The liquid could possibly be methane or another surface liquid that is present. On the surface there are certain areas that have concentrations of water ice. There are also deposits of what could be CO_2 ice or HC_3N (Soderblom et al. 2009). The density of the liquid in between the grains is important to consider because its density changes as we approach the poles.

14.4.8 Seismic Activity

Titan may have cryovolcanoes on its surface. The surface could be experiencing a few types of cryovolcanism, such as mud volcanism, which involves acetylene. Another type of volcanism that could be occurring is methane-clathrate-hydrate volcanism. Finally a type of cryovolcanism involving ammonia could be occurring on Titan. The magnitude of these eruptions is not known but it is believed that one of these processes is currently happening and is depositing material on the surface (Soderblom et al. 2009).

14.4.9 Discussion and Conclusions – Titan

Titan has some Earth-like traits although there are some very important exceptions. Titan lacks numerous materials needed for long-term settlements, such as metals and certain macronutrients for plants. Materials needed for structures and crops may have to be brought from Earth or even mined from nearby moons. Saturn's rings are thought to have concentrations of Fe_2O_3 that could be mined for the iron and oxygen content (Filacchione et al. 2012). This may be a cost effective way to obtain iron and oxygen.

A suitable location for a structure could be along the equator and away from the Hotei region, which is a volcanically active area of Titan. The equator experiences less temperature fluctuations and has a greater average temperature. The temperature affects the density of the liquid in some areas with muddy regolith, which would affect a surface structure.

Deposits of water ice on the surface will also be an added benefit to future settlers. Using electrolysis water could be separated into oxygen and hydrogen. The hydrogen then could be used alongside nitrogen in the atmosphere in a Haber process to produce ammonia for crops and oxygen for breathing. Ammonia may be present in some volcanically active areas of Titan. Mining it may be an alternative.

Few possible methods exist for powering such a structure. Solar panels would not work efficiently because of the distance from the Sun and also due the smog present in Titan's atmosphere. Nuclear reactors or some type of reaction involving radioactive material would also be a plausible way to generate power. Another method involving airborne wind turbines could be a possibility. Titan has a very thick atmosphere and low gravitational pull. In the stratosphere there are large wind speeds that could be taken advantage of in order to harvest energy.

14.5 Robotic Outpost and Human Habitation – The Lunar Experience

We appear to have a good bit of information, at least enough to be able to perform preliminary analyses and designs for structures that will safeguard robots and humans who are sent to Mercury, Venus, and Titan to explore and, in the case of humans, life for a time. We will call these structures, whether for machine or man, habitats. In this section, we will summarize the key considerations for habitat structural analysis in extraterrestrial environments.

It is fair to assume that the first habitats on Titan and Mercury will be placed on the surface in whole. Without any infrastructure, the habitats cannot be erected locally. On Venus, given its unique atmosphere, it has been suggested that an orbital/floating habitat is not only feasible, but also optimal. It certainly will be a greater challenge to place a habitat in orbit rather than on a planetary surface, but perhaps not.

Some of the discussion below is based on Ruess et al. (2006) and Benaroya and Bernold (2008).

14.5.1 Lessons from Our Studies of Lunar Habitats

Any structure outside the safe Earth environment will need to be designed for and built with the following prime considerations:

Safety and Reliability. Human safety and the minimization of risk to “acceptable” levels are always at the top of the list of considerations for any engineering project. Extraterrestrial sites offer new challenges to the engineering designer, some of which are still problematic to resolution today. Minimization of risk implies in particular structural redundancy, and when all else fails, easy escape for the inhabitants. The key word is “acceptable.” It is a subjective consideration, deeply rooted in economics. What is an acceptable level of safety and reliability for an extraterrestrial site, one that must be considered highly hazardous? Such questions go beyond engineering considerations and must include policy considerations: Can we afford to fail?

Other than one-g gravity. For example, on the Moon traditional structures will have, in gross terms, six times the weight bearing capacity as it does on the Earth. (Cable structures, such as cableways, will benefit even further from the reduced gravity.) Or, to support a certain loading condition, one-sixth the load bearing strength is required on the Moon as on the Earth. In order to maximize the utility of concepts developed for extraterrestrial structural design, mass-based rather than weight-based criteria should be the approach of extraterrestrial structural engineers. All of NASA’s calculations have been done in *kg-force* rather than *Newtons*. Calculations are always without the gravity component; use kg_f/cm^2 as pressure, for example.

In the area of foundation design, most classical analytical approaches are based on the limit state condition. That means that the design is based on the limit of loading on a wall or footing at the point when a total collapse occurs, that is, the plastic limit. Since extraterrestrial structures require accurate pointing capabilities for astronomy and communications, for example, a settlement based design method would be more useful.

A note against assuming that less gravity means a footing can support more load: if soil can be assumed to be linearly elastic material, then the elastic modulus is not affected by gravity. However, the load bearing capacity of a real soil depends on the confining stress around it. If the soil surrounding the point of interest is heavier because of a larger gravity, the confining stress would be higher and the soil at the point of interest can support a higher load without collapsing. On the Moon, the lunar regolith has very little cohesion, and the undisturbed regolith is very dense. These facts will affect how the regolith is used and controlled in a construction setting.

Internal Air Pressurization. The extraterrestrial structure will be a life-supporting closed environment. It will be a pressurized enclosed volume with an internal pressure of 6.9×10^4 to 10.3×10^4 Pa. The enclosure structure must contain this pressure, and must be designed to be “fail-safe” against catastrophic and other decompression caused by accidental and natural impacts.

Shielding. A prime design consideration is that the structure be able to shield against the types of hazards found extra-terrestrially: continuous solar/cosmic radiation, meteorite impacts, and extreme variations in temperature and radiation. On the Moon, a layer of regolith (lunar soil) is placed atop the structure is stipulated to be adequate for shielding, where the added weight would only partially (in the range of 10–20 %) balance the forces on the structure due to internal pressurization mentioned above. In addition to general shielding, special radiation shelters will be needed for periods of increased solar activity. Extreme care would have to be taken not to disturb the regolith due to its damaging and carcinogenic nature.

Shielding against micrometeorite impacts is accomplished in one way by covering the outpost with dense and heavy materials, in this case compacted regolith, to absorb the kinetic energy. Some suggest that for shielding purposes alone, it is better to design and place human rated structures underground. This may be so, but it is then necessary to factor in the added costs and difficulties of subsurface work.

Long-term sustained low-level radiation effects, such as those that would be encountered on the Moon, lead to an annual dose-equivalent on humans on the exposed lunar surface of about 0.3 Sv and the dose-equivalent over an 11-year solar cycle is about 10 Sv, with most of the particles arriving in one or two gigantic flares lasting one to two days. It is estimated that at least 2.5 m of regolith cover would be required to keep the annual dose of radiation at 0.05 Sv, which is the allowable level for radiation workers (0.005 Sv for the general public). A shallower cover may be inadequate to protect against the primary radiation and a thicker cover may cause the secondary radiation, which consists of electrons and other radiation as a result of the primary radiation hitting atoms along its path.

In recent years, there is a move away from silicon- and germanium-based electronic components towards the use of gallium arsenide. Lower current and voltage demand, and miniaturization of electronic components and machines would make devices more radiation hardened.

Vacuum. A hard vacuum surrounds the Moon. This will preclude the use of certain materials that may not be chemically or molecularly stable under such conditions. This issue warrants further research.

Construction in a vacuum has several problems. One would be the possibility of out-gassing of oil, vapors, and lubricants from pneumatic systems. Hydraulic systems are not used in space for this reason. The out-gassing is detrimental to astronomical mirrors, solar panels, and any other moving machine parts because they tend to cause dust particles to forms pods. Another problem is that surface-to-surface contact becomes much more abrasive in the absence of an air layer. The increase in dynamic friction can cause fusion at the interfaces, such as a drill bit fusing with rock. This is of course aggravated by the fact that the vacuum is a bad conductor of heat. The increase in abrasiveness at interfaces also increases wear-and-tear on all moving parts, for example, railways and wheels.

Blasting in a vacuum is another interesting problem to consider. When the explosive in a blast hole is fired, it is transformed into a gas, the pressure of which may sometimes exceed 100,000 terrestrial atmospheres. How this would affect the area around the blast and the impact of ejecta resulting from the blast is difficult to predict. Keeping in mind that a particle set in motion from the firing of a rocket from a lander could theoretically travel half way around the Moon, the effects of surface blasting on the Moon, for example, would be something to be concerned about.

Dust. The lunar surface has a layer of fine particles that are disturbed and placed into suspension easily. These particles cling to all surfaces and pose serious challenges for the utility of construction equipment, air locks, and all exposed surfaces.

Lunar dust consists of pulverized regolith and appears to be charged. The charge may be from the fractured crystalline structure of the material or it may be of a surficial nature, for example, charged particles from the solar wind attaching themselves to the dust particles. It was reported that the dust particles levitated at the lunar terminator (line between lunar day and lunar night) may be due to a change in polarity of the surficial materials.

Ease of Construction. The remoteness of the lunar site, in conjunction with the high costs associated with launches from Earth, suggests that lunar structures be designed for ease of construction so that the extra-vehicular activity of the astronaut construction team is minimized. Construction components must be practical and, in a sense, modular, in order to minimize local fabrication for initial structural outposts.

Simple and conventional devices with no moving parts are preferred in the extraterrestrial environment over ones that involves multiple degrees of freedom in an exotic configuration involving a yet to be developed artificial intelligence control. Another misconception is that construction on the Moon, for example, is simply a scaling of the effects of similar operations on Earth and that theoretical predictive tools, especially those performed with computers, can accurately predic events. It is also critical to realize that astronauts do not make for efficient long-term construction crews. Automated construction is critical.

Use of Local Materials. This is to be viewed as extremely important in the long-term view of extraterrestrial habitation. But feasibility will have to wait until a minimal presence has been established on the Moon. Initial lunar structures will be transported for the most part in components from the Earth.

The use of local resources, normally referred to as ISRU (in situ resource utilization), is a topic that has been studied, now more intensely because of the possibility of actually establishing human presence on the Moon, Near-earth-orbit [NEO] and Mars. We can expect that ISRU will be the foundation for a long-term robotic and manned presence in the Solar System.

Water. The single most critical resource is water. As a need for human and plant life, it is without substitute. Its elementary components, hydrogen and oxygen, are fundamental to many processes that are needed in an industrial infrastructure. Water in some form has been identified on the Moon, and, perhaps remarkably – or not – on many of the planetary bodies in the Solar System. Water, in addition to other local elements, will set the parameters of the local infrastructure.

14.5.2 Discussion and Conclusions – Habitats

There is a vast literature on the exploration of the Moon and Mars, along with research on what eventual habitats will look like, especially on the Moon. While the Moon and Mars have quite different environments than do Mercury, Venus or Titan, there are certain engineering criteria that all habitats must fulfill so that robots and humans can survive on any extraterrestrial body. The formalism of engineering design is valid regardless of the target for that design. The physical laws are the same and, as long as the environment is fully defined, engineering can address the need.

14.6 Discussion and Conclusions - Overall

Of course, there are several additional issues that need to be considered. There are the costs associated with long space flights and the sustenance of humans and machines far from home. There are the logistics of supplies. Physiological constraints of humans and plants require further understanding. We are as yet unsure of the robustness of the human body in any other than full g. Even small radiation dosages can prove fatal when applied over the years that space activity requires of individuals. Psychological limitations can be challenging. The closeness required for long space flights cannot be tolerated by any but the very few who can endure small spaces for long periods of time. This is coupled with the risks of such voyages and distance from home and family.

It is almost certain that the first human settlements will be on the Moon and Mars, preferably in that order since the Moon's proximity to Earth gives it a special role for our development of survival techniques and technologies that will serve us when we choose to go further to Mars. It is also near certain that once we are able to survive in "Earth-Moon-Mars space" that the outer and inner Solar System will relatively rapidly become our proverbial backyard.

The foundation infrastructure that we will have to develop in order to settle the Moon and Mars will likely be sufficient for entrepreneurs and pioneers to do the same for Mercury, Venus and Titan. These are three locations that are ours to settle once we activate our spacefaring abilities with the Moon and Mars. We just have to decide to do it. AQ1

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