Chapter 7

The Terraforming of Venus

In times to come when the Parasol was dismantled and the sun's light shone again on Venus, a world shaped by men and women would be revealed. The lifeless, sterile ocean far below, an acidic ocean that might have boiled away in the still intense heat but for the high atmospheric pressure, would teem with life.

Pamela Sargent

7.1 A Fair Imagined Venus

Of all the Sun's family of planets, Venus is the most striking to look at from Earth. When well-placed, it is the brightest point source of light in the sky and is only constrained from being more spectacular by its proximity to the Sun and hence its transient appearance near the horizon before sunrise or after sunset. Venus has thus always been a planet with contrary natures: to the Greeks it was two stars — *Phosphorous*, the Morning Star and *Hesperus*, the Evening Star. Today we know that its brilliant cloud decks, with their superficial promise of abundant water beneath, actually disguise a gloomy, dry and baking hell.

Venus, Earth and Mars have often been regarded as a trio — planetary partners, formed close to each other from roughly the same material. The Earth sits in the middle, being a planet that has been continuously habitable for over 3.8 billion years. The other two, Earth's inner and outer companions, were therefore the logical candidates on which to focus most conjecture over the possibilities of extraterrestrial life. Venus in particular, closest in its proximity to the Earth and closest in size and mass also, was often referred to as the Earth's "Sister Planet", if not its twin. And yet Venus was never subject to the intense scrutiny and speculation that was applied to Mars; it never acquired the Martian place in modern myth.

The reason was of course due to the elusive nature of the world, perpetually veiled under its pale-yellow clouds. Not the briefest glimpse of the Venusian surface has ever been possible to a terrestrial observer (at least until the use of radar) and visible astronomy never shows much more than a blank crescent. Venus simply did not display anything resembling those permanent markings and seasonal changes of detail that excited such constant debate over Mars. All rational thought about the planet's environment had to explain the clouds first before deducing conditions on the surface. The nature of the planet thus depended on the nature of its disguise, often a very weak chain of reasoning linking the two, leaving astronomers free to paint imaginary pictures of Venus based on very sparse evidence. The models that resulted, some of which were of a potentially habitable world, were more a tribute to the fertility of imagination, than a practical ability to penetrate Venus' obscurity.

In 1918 the Swedish astronomer Svante Arrenhius published perhaps the most well known pre-space age speculation on the Venusian environment [1]. Assuming that the clouds were composed of water droplets, it seemed natural to deduce a warm and humid surface: *"We must therefore conclude that everything on Venus is dripping wet."* The planet of Arrenhius therefore was one with lots of water and a powerful hydrological cycle driven by the fiercer Sun; a world of huge cloud formations and violent rains — what land was present resembling Carboniferous-type swamps, choked with the growth of plants, thriving at temperatures of ~ 47 ^{o}C. It was only a short step beyond this for science fiction writers to complete the picture and populate the swamps with giant creatures resembling dinosaurs and the inevitable intelligent humanoids. This watery hot-house and its variants were, for the next forty years, the most popular images of Venus in science fiction.

However, the failure of astronomers between the wars to spectroscopically detect water vapour in the Venusian atmosphere, and the discovery of the presence of CO_2, suggested a dry planet. The clouds were therefore variously proposed to be composed of fine dust [2], maintained aloft by perpetual winds; photochemically produced polymers of formaldehyde [3]; or a hydrocarbon smog, generated from a boiling ocean of oil [4]. The wet Venus model was not completely abandoned either [5], for if the cloud tops were cold enough (e.g. ice crystals at -40 ^{o}C) then there would be little water vapour above them to be detected. Moreover, if the planet was *totally* ocean covered, a CO_2 atmosphere could persist, isolated from silicate rocks with which it might combine by a layer of sediments on the sea floor. One of the last visions of Venus that preceded the dawn of reality was therefore of a planet with a world-girdling ocean of Perrier and perhaps life of its own.

As it transpired, all these models had greatly underestimated the hostility of the real Venus. In the decade of the 1960's, microwave observations of the planet and data returned from a succession of Soviet and US space probes revealed the ground truth that the clouds had obscured. The surface of Venus swelters under an atmosphere almost 100 times as dense as on Earth at temperatures hot enough to melt metals such as zinc and lead; those once inviting clouds are tainted with corrosive sulphuric acid; and the planet spins backwards on its axis so slowly that its sidereal day is longer than its year. A deadlier place could hardly be imagined. Whilst the real Venus has been compared to visions of the medieval Hell, conditions are actually far more lethal than anything Dante imagined. There would be very little torture being exposed to the Venusian environment, only near-instant death followed by one's body being reduced to a charred stain on the ground within seconds.

The disappointment with the planet nature had finally to offer was eloquently summed up in 1968 by British science fiction author Brian Aldiss [6]. In the foreword to a book appropriately entitled Farewell Fantastic Venus! he wrote, *"... a story has ended. It is a long story, because man has been telling himself it for many centuries: the story of a fair imagined Venus... An unsatisfactory sibling she has proved at last... Her name is most beautiful. And yet: the Cytherian landscape, under the thick oppressive Cytherian cloudbanks, must be uglier than anything Earth can offer. Venus just has not come up to expectations."*

The fair imagined Venus was no more, but not everyone was prepared to surrender to an everlasting farewell. One of the scientists responsible for uncovering the real description of Venus was Carl Sagan. In a review paper published in *Science* in 1961 [7], just before the first probes would reach Venus, he described a planet similar to that we know today and proposed that it did not necessarily have to remain the way it was. His suggestion that the Venusian environment might be modified by *"microbiological planetary engineering"* was the first significant discussion of terraforming in the academic literature.

7.2 The Revealed Venus

7.2.1 Physical Parameters

Venus has the most successful history of exploration by robotic visitors from the Earth, involving the deployment since 1961 of a variety of flyby probes, orbiters, atmospheric descent probes, balloons and landers.

The Terraforming of Venus

As this text is being written, the mission of the NASA orbiter *Magellan* is nearing its close, having mapped the Venusian surface with radar to unprecedented resolution. Thus, whilst we have had a reasonable general knowledge of the planet for over twenty years [8,9], detail continues to be added to the picture [10,11].

The physical parameters that define the modern view of Venus are displayed in Table 7.1 and some of them do indeed point to the planet being a "sister" of Earth. Venus is 95% the Earth's radius and density and is 81% as massive; its gravity is 88% and escape velocity 93% of the terrestrial value. It is 72% of the distance of the Earth from the Sun and so when the two planets are at closest approach, they are separated by just ~ 42 million km. Judging by these characteristics, and the fact that an atmosphere was observable, it was not surprising that some pre-space age astronomers speculated over a habitable planet.

TABLE 7.1 PHYSICAL PARAMETERS OF VENUS

Parameter	Value
Age	4.6×10^9 years
Mean Distance from Sun	1.08×10^8 km
Sidereal Period	224.7 Earth days
Mean Orbital Velocity	35.03 km/s
Eccentricity	0.0068
Insolation	2620 W/m^2.
Mass	4.87×10^{24} kg
Mean Radius	6051.8 km
Mean Density	5240 kg/m^3
Surface Gravity	8.60 m/s^2
Escape Velocity	10.4 km/s
Sidereal Rotation Period	243.02 Earth days
Solar Day	117 Earth days
Obliquity	177.4° †
Albedo	0.77
Atmospheric Mass	~ 5.08×10^{20}kg
Atmospheric Pressure	~ 95 bars
Atmospheric Scale Height	16.2 km
Effective Temperature	-44 $^\circ$C
Mean Surface Temperature	464 $^\circ$C
Magnetic Moment	< 10^{12} Tm^3
Surface Area	4.60×10^8 km^2

† Inclinations of > 90° imply retrograde rotation.

Other parameters however distinguish Venus as a truly alien world. Its orbit has the lowest eccentricity of any of the planets and its spin axis the lowest obliquity, barring Mercury (177.4° retrograde ≡ 2.6° prograde). Venus therefore has no seasons. Once radar observations were able to identify surface features, it became clear that the planet rotates extremely slowly in a retrograde, East-to-West sense in a period of 243 terrestrial days, which is *longer* than the Venusian year of 225 days. As seen by a Venusian observer therefore, the solar day (the time taken for the Sun to make one complete circuit of the sky) is $\approx (243^{-1} + 225^{-1})^{-1} \approx 117$ days. Remarkably, this long diurnal cycle has very little influence on surface temperatures and has the greatest effect on the upper atmosphere where most sunlight is absorbed, driving an East-to-West circulation with wind speeds at the cloud tops of ~ 360 km/hr (see Plate 7.1). Thus the Venusian atmosphere "super rotates," circling the globe 60 times faster than the rotation speed of the solid surface below in ~ 4 days [8].

The closer proximity of Venus to the Sun means that it receives an insolation 191% that of Earth, but since its albedo is much higher, due to the unbroken nature of the clouds and the chemical composition of their constituent aerosols, the planet actually absorbs only 63% as much solar radiation. The effective temperature of Venus therefore (that at which it radiates into space) is only -44°C: 26°C *colder* than the terrestrial value. Yet Table 7.1 indicates that the surface temperature of Venus is an enormous 464 °C, and since no liquid water can exist above the critical temperature of 374 °C, whatever the ambient pressure of water vapour, the surface must also be totally dry. Thus, even though many of the physical parameters of Venus are Earth like, the most crucial environmental parameters are far from being so.

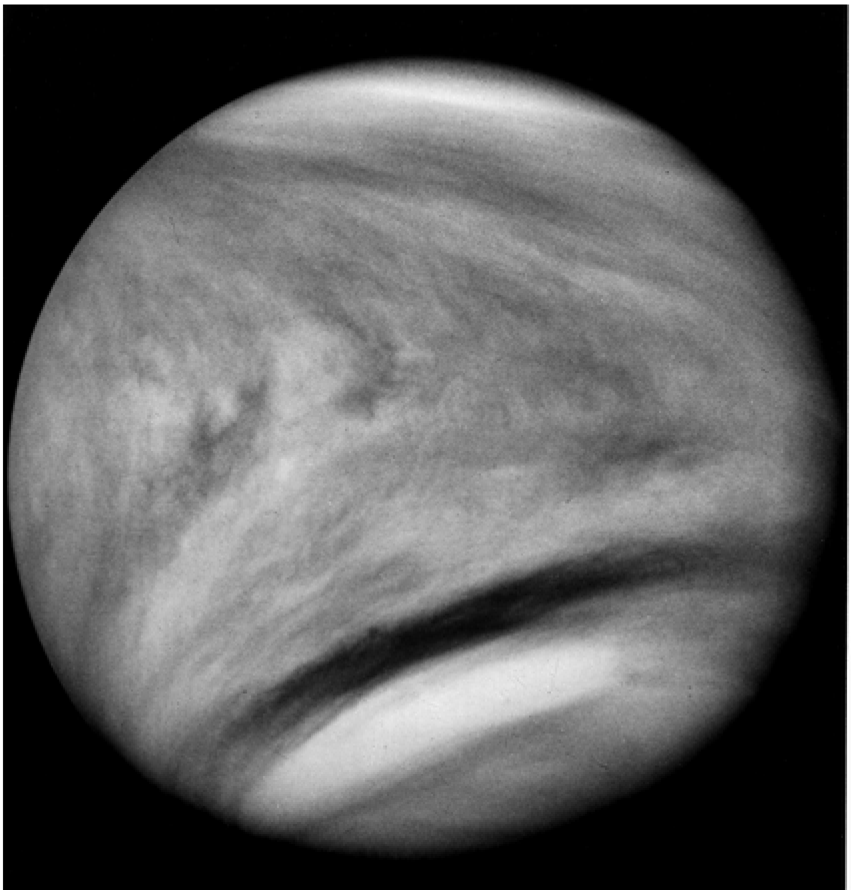

Plate 7.1 *Venus seen in ultraviolet light by the Pioneer Venus orbiter. The clouds totally obscure the surface and features can be seen to blow around the planet in 4 days. (Photo courtesy of NASA.)*

7.2.2 The Atmosphere

The reason for this enormous departure from the expectations of the pre-space age modellers is the presence of a massive atmosphere, exerting ~ 95 bars of pressure at the surface, equivalent to a depth of ~ 1 km beneath the Earth's oceans. Its composition is shown in Table 7.2; the two bulk gases being carbon dioxide (93.6 vol%) and nitrogen (3.5 vol%). Other species, which are either the products of volcanic outgassing or photochemistry, are present in trace amounts only and this includes nearly all the Venusian inventory of water which amounts to only ~ 10^{-5} the quantity on Earth, equivalent to just a ~ 5 cm global layer. Venus is therefore even drier than Mars.

TABLE 7.2 VENUS - COMPOSITION OF THE LOWER ATMOSPHERE

Species	Abundance by volume
CO_2	0.963
N_2	0.035
SO_2	~ 150 ppm
H_2O	~ 100 ppm
Ar	~ 100 ppm
COS	< 40 ppm
H_2S	< 40 ppm
O_2	< 30 ppm
H_2	< 25 ppm
CO	~ 20 ppm
Ne	~ 14 ppm
He	~ 12 ppm
Kr	~ 1.5 ppm
HCl	~ 0.4 ppm
HF	~ 0.005 ppm

Data from various sources. Minor constituents are approximate as disagreements exist between measurements.

The greenhouse effect of the atmosphere is very strong (ΔT_{green} = 508 °C) and arises from the large quantity of CO_2 that is present, augmented by the infrared absorption of water vapour, SO_2 and cloud particles. Thus, despite the fact that 77% of the Venusian insolation is reflected back into space, and most of the rest is absorbed tens of kilometres above the surface, the lower atmosphere is so effective at trapping heat that thermal equilibrium is only obtained with a temperature at its base as hot as 464 °C. The high winds of the upper atmosphere where gases are much less dense do not reach the surface where circulation is thought to be sluggish. Nevertheless the large heat capacity of the lower atmosphere is sufficient to buffer any temperature change during the long Venusian night, explaining the lack of diurnal temperature variations.

The Venusian cloud layers lie at altitudes of 45 - 60 km, where temperatures range between ~ 94 °C at the base to -48 °C at the top [8]. Layers of haze exist above and below the clouds. A temperature profile of the atmosphere is illustrated in Fig. 7.1, showing the height of the cloud layers and haze layers and the temperature inversion which marks the top of the troposphere at a height of ~ 100 km. The clouds are not as dense as those on Earth being more equivalent to a thick mist of density ~ 2 mg/m^3 of air (by contrast, terrestrial rain clouds are as dense as ~ 400 mg/m^3). They are thought to consist primarily of aerosol particles of size < 10 μm which are composed of a strong aqueous solution of 85% by weight sulphuric acid [12]. Other minor contaminants are thought to be necessary to explain the ultraviolet spectrum of Venus, including elemental sulphur, hydrochloric acid and perhaps chlorine.

Spacecraft measurements of the concentration of cloud particles are consistent with a source at the top and a sink at the bottom of the cloud layers [12]. Sulphuric acid is generated photochemically, starting with the action of ultraviolet radiation on sulphur dioxide above the clouds (a similar process converts SO_2 to H_2SO_4 on Earth — see Equations 4.11). It then becomes incorporated in aerosol droplets which, after about a year, sink to the base of the cloud layer where they evaporate. Ultimately, the heat of the lower atmosphere dissociates H_2SO_4 to SO_3, which then undergoes thermo chemical reduction by reacting with CO back to SO_2. The Venusian clouds therefore are maintained in a dynamic, sulphur-cycling, steady state and have little in common with terrestrial clouds, being more akin to photochemical smog in mode of formation and composition.

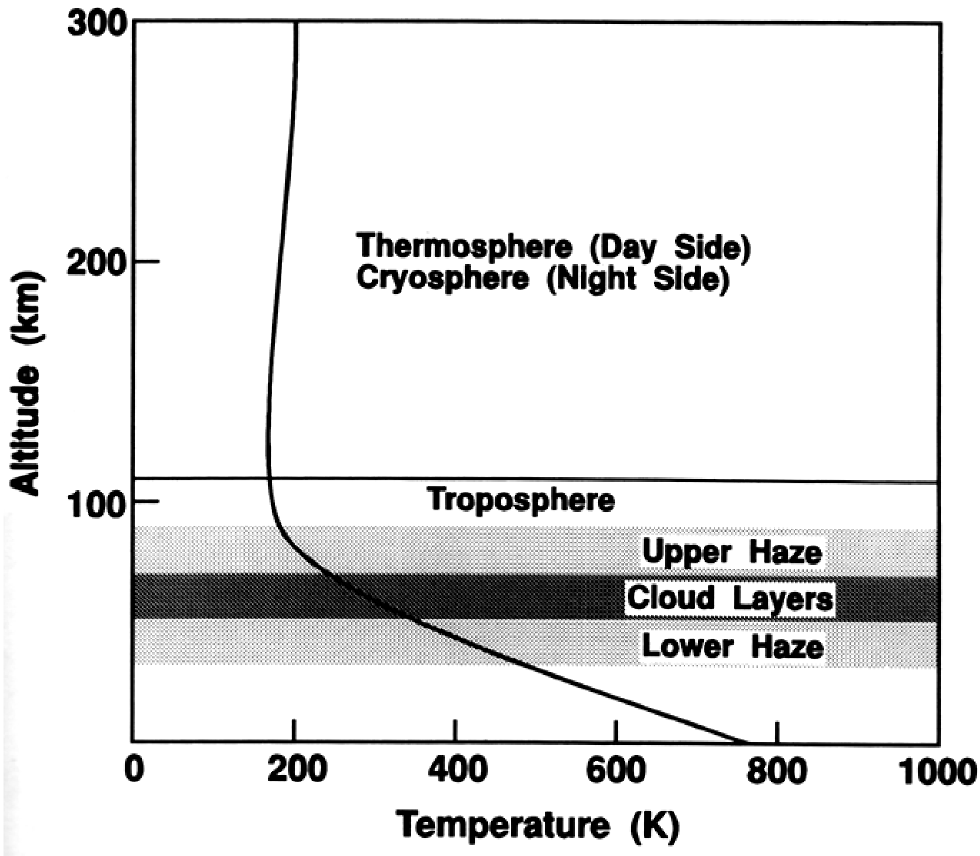

Figure 7.1 *Temperature profile of the atmosphere of Venus. In the troposphere the atmosphere is heated mainly by the greenhouse effect and temperature falls with altitude. The temperature profile in the underlying thermosphere/cryosphere is averaged: during the day, solar radiation is absorbed directly and temperature rises with altitude; during the night, heat is radiated to space and the upper atmosphere cools. (Reproduced with permission from Ref. [8].)*

7.2.3 The Surface

When looked at from the global point of view, Venus is a very flat planet [9]. Its topography is *unimodal*, with 80% of the surface at elevations within 1 km of the mean. This is illustrated as a hypsogram in Fig. 7.2 and shows as a large single peak centred on 0 km; it contrasts strongly with the *bimodal* topography of the Earth, with its two peaks corresponding to ocean floors and continents. Venusian geomorphology subdivides into two basic types of terrain: low, rolling volcanic plains, dotted with thousands of individual volcanic constructs cover 85% of the planet and the remaining 15% consists of highlands [13].

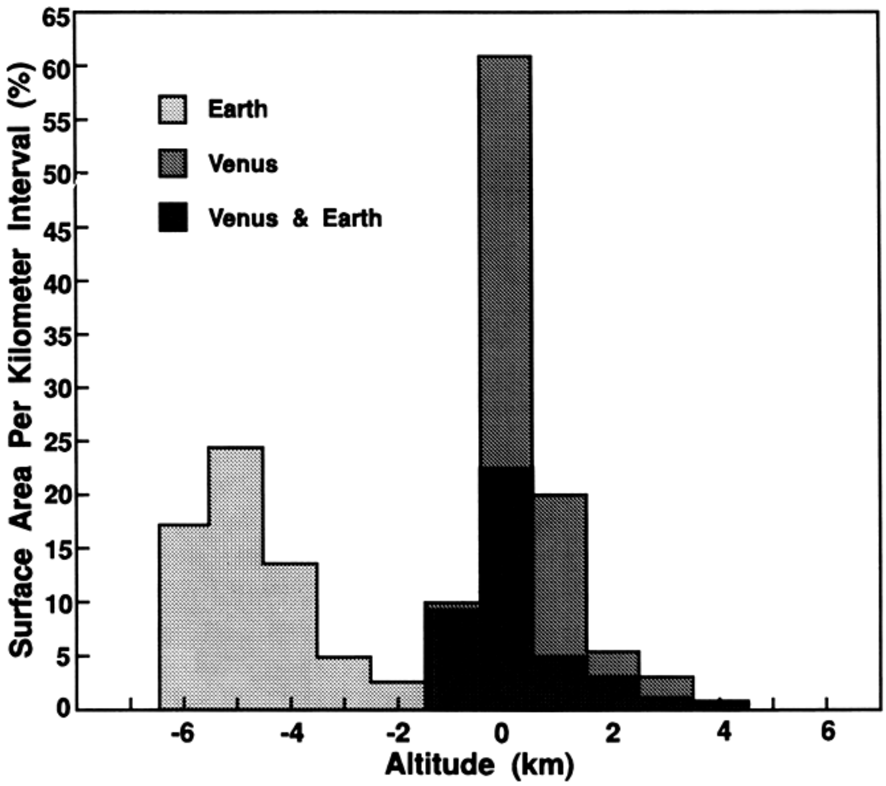

***Figure** 7.2 Comparison of surface relief of the Earth and Venus. The contrast is marked and thought to reflect differing styles of volcanism and tectonics. The bimodal distribution of the Earth shows two peaks at –5 km and 2 km, representing the ocean floors and the continents, respectively. Venus is a flatter planet, exhibiting just one peak with 60% of the planetary area within half a kilometre of the mean radius. (Reproduced with permission from Ref. [9].)*

There are two main highland areas that are often referred to as Venusian "continents." The largest is *Aphrodite Terra*, which is roughly the size of Africa, lying parallel and just South of the equator from 70 - 200°E (see Plate 7.2). It consists of two mountainous regions in the West, Ovda Regio and Thetis Regio, separated from an Eastern highland area, Atla Regio, by a lower lying region grooved with a series of rift valleys. The deepest of these, Diana Chasma, is the lowest point on Venus, being > 2 km beneath the mean radius and ~ 4 km below the surrounding terrain. The other substantial highland area is *Ishtar Terra* [14], situated in the North of Venus, between 60 - 75°N and 300 - 30°E (see Plate 7.3). This is a geologically complex region the size of Australia, made up of a 3 - 4 km high plateau, Lakshmi Planum, and adjacent mountains. Lakshmi is as large as Tibet and rises on a steep escarpment from the plains to the South. It is bounded to the West and

North by the Akna and Freyja Montes and to the East by the Maxwell Montes — the highest place on Venus, reaching altitudes of ~ 11 km above the mean radius (see Plate 7.4).

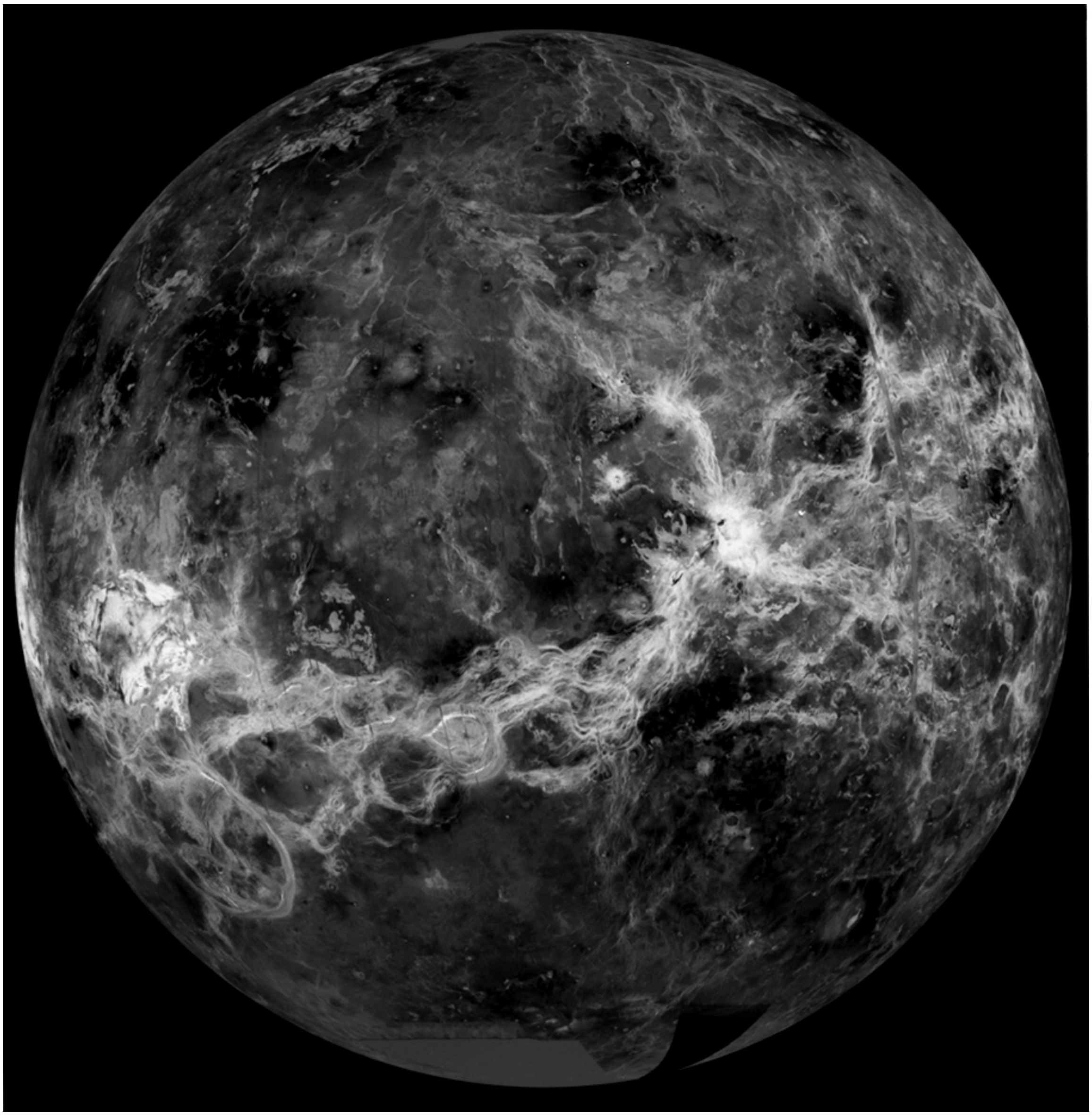

Plate 7.2 *Venus with its atmosphere removed. A global mosaic of Magellan synthetic aperture radar image data. Aphrodite Terra, a large Venusian 'continent', runs from the lower left of the image towards the centre. (Photo courtesy of NASA.)*

Volcanism is the most prevalent geological phenomenon on Venus [15], its influence being distributed globally (although not randomly) as opposed to being concentrated near plate boundaries as on Earth. *Magellan* images have shown a variety of volcanic features, including flood lavas, volcanic cones, domes and *coronae* — structures which appear unique to the planet and which manifest as domes surrounded by an annulus of ridges and grooves. The great majority of these features are consistent with being made from basaltic lava and the rocks sampled by the Soviet *Venera* landers also approximated to basaltic composition. Venus also appears to be tectonically active showing widespread evidence of crustal deformation of both a compressional and extensile nature. Rift zones are seen to extend for considerable distances and to connect certain highland regions, however there is little evidence for an Earth like mode of plate tectonics with creation and destruction of crust being concentrated in specific zones. In this sense therefore Venus may be more like Mars, being a one-plate planet dominated by hotspot volcanism and tectonics (see Plate 7.5).

Plate 7.3 *Western Ishtar Terra, latitudes 55º - 80ºN, longitudes 300º - 30ºE, as viewed by Magellan. The large dark area left of centre is the plateau Lakshmi Planum, bordered by the Vesta Rupes escarpments to the South, and the Akna and Freyja mountains to the West and North. The bright area to the East is that of the Maxwell Montes, the highest region on Venus. (Photo courtesy of NASA.)*

There are impact craters that have been discovered on Venus that have allowed the surface to be dated at between 200 - 700 million years old. This is older than the average age of the Earth's surface, but much younger than Mars. The impact data is explicable if Venus either underwent a catastrophic resurfacing ~ 500 million years ago and has been largely quiescent since, or experiences a more continuous, local resurfacing at a rate of ~ 0.5 km^3 of new rock per year [15,16]. This is roughly equivalent to the current intraplate (away from plate boundaries) volcanic flux on the Earth.

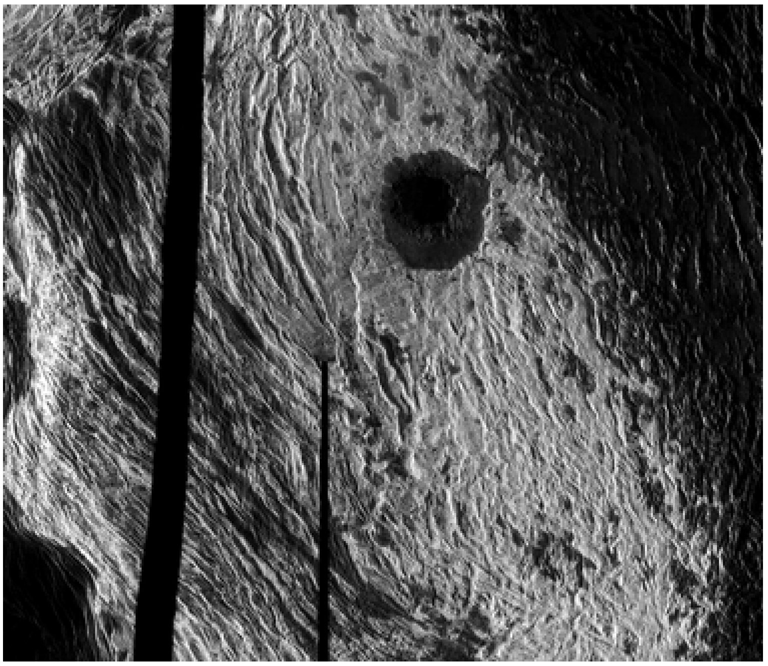

Plate 7.4 *Cleopatra Crater atop the Maxwell Montes, latitudes 64.8° - 67.1°N, longitudes 3.7° - 12°E, as viewed by Magellan. This is the highest region on Venus at > 10 km above the mean planetary radius. (Photo courtesy of NASA.)*

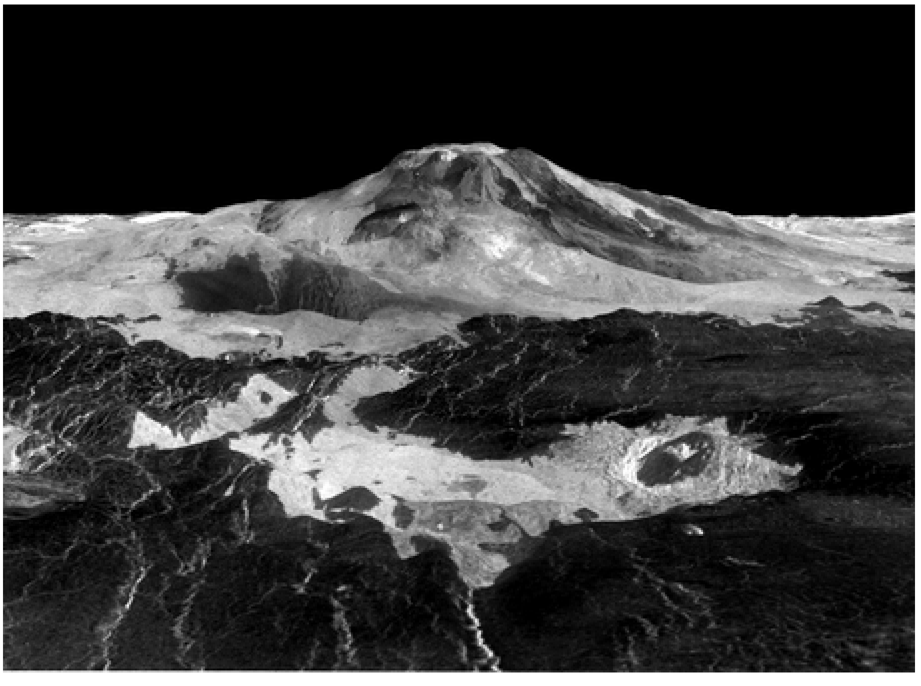

Plate 7.5 *Maat Mons is a 5 km high volcanic construct on Venus, seen here in a perspective view of Magellan data, with a 10x vertical exaggeration factor. Maat Mons lies in the Atla Regio region, seen right centre in Plate 7.1. (Photo courtesy of NASA.)*

7.2.4 Climatic History

As with Mars, *past* conditions of Venus are also relevant to determining possible terraforming strategies. Was Venus once a more hospitable planet than it is now? Was it once wetter, cooler and enveloped in a thinner atmosphere?

Even if less water condensed in the pre-planetary nebula in the present vicinity of Venus due to the heat of the newborn Sun, the subsequent dynamics of accretion should have ensured that the terrestrial planets formed from a well-mixed swarm of planetesimals. Venus could therefore have incorporated and outgassed as much water per unit mass of planet as the Earth. If instead, oceans are imported as the result of a cometary bombardment late in planetary formation, then there is similarly no reason to expect that Venus should have missed out on what was received by the Earth. Possible past loss of water on Venus is indicated by the deuterium to hydrogen ratio in the atmosphere which has been measured to be ~ 100 times that of terrestrial ocean water. (Deuterium, being a heavier isotope of hydrogen escapes less readily into space). Venus could therefore have had > 100 times as much water as remains presently, although the reliability of this evidence is questionable as water introduced subsequently by comet impacts could have wiped out any isotopic signature of the planet's original inventory [17].

In the early history of the Solar System, the Sun may have been only 70% as luminous as today so the solar flux at the Venusian orbit would have been 134% the current flux on Earth (1.34 $S_\oplus$). The classical picture, from about 1960, of the evolution of the Venusian atmosphere is that it suffered a climatic runaway — the "Runaway Greenhouse" — from the outset. This was due to the powerful greenhouse effect of water vapour and the strong positive feedback between surface temperature and the amount in the atmosphere. Venus therefore may always have been too hot to allow water to condense on the surface, outgassing producing a massive steam and CO_2 atmosphere [18]. If Venus originally had an inventory of water equivalent to that in the Earth's oceans then the partial pressure of water vapour would have been ~ 240 bars and the surface temperature a colossal ~ 1200 ^oC. This amount of water would have suppressed the formation of any atmospheric cold trap containing water close to the surface. The upper atmosphere would therefore have been wet and water molecules vulnerable to photodissociation by ultraviolet radiation. Loss of hydrogen to space and loss of oxygen swept up in the outflow, or by reaction with surface rocks could have deprived Venus of its water in a few hundred million years.

Preliminary calculations suggested that the runaway greenhouse effect could occur at a solar flux of only ~ 1.1 $S_\oplus$ — at this insolation, a planet would either go straight to the runaway state upon outgassing, or suffer the complete evaporation of any pre-existing oceans [18]. However, there are problems with this scenario [19]. The first is that early climate models did not take into account atmospheric heat transport by convection and so systematically overestimated surface temperatures. The second is that the scenario encounters difficulties in getting rid of enough Venusian water. This is because when the lower atmosphere contains < 20% H_2O by volume, a cold trap can form (such as at the base of the stratosphere on Earth) preventing water rising to high altitudes and so the upper atmosphere dries out. Water loss then becomes a much more gradual process. If Venus always had a background atmosphere of ~ 95 bars of CO_2 and N_2, then the Runaway Greenhouse model cannot explain the loss of the last ~ 20 bars of H_2O.

The solution suggested by James Kasting and colleagues is known as the "Moist Greenhouse" model [20], which proposes that the early Venusian atmosphere did condense to form oceans at temperatures between 100 - 200 ^oC. These were prevented from boiling by the pressure of the overlying atmosphere that would have contained (at saturation) 1 - 15 bars of water vapour and other non-condensable gases such as CO_2 and N_2. Originally therefore, most of the ~ 240 bar inventory of water would have been liquid and most of the 95 bars of CO_2 would have been solid — sequestered as carbonate minerals due to the chemical weathering of silicate rocks in the hot aqueous conditions. The moist greenhouse atmosphere therefore consists of > 20% water vapour, leading to a rapid loss of water to space. This would have continued so, long as there were oceans remaining to top up the water content of the atmosphere and to act as a medium in which to form carbonates. Ultimately therefore, the oceans would have evaporated completely and only after the desiccation of the surface would gaseous CO_2 from volcanic recycling of carbonates have accumulated in large quantities. The end result was the hot, dry planet we see today.

Fig. 7.3 shows the results of Kasting's model as a curve of solar flux against mean surface temperature [20]. It assumes a fully saturated N_2-O_2-low CO_2 atmosphere with a background pressure of 1 bar and ignores clouds other than by adding a small fixed increment to the planet's albedo. The model therefore yields an upper limit on the surface temperature expected for a given solar flux. Moist greenhouse conditions were found to occur at an insolation of 1.1 $S_\oplus$ and runaway greenhouse conditions (where $T_{surf} > 374$ °C and the liquid phase can no longer exist) at 1.4 $S_\oplus$. The young Venus therefore would almost certainly have been in the moist greenhouse state, especially if the cooling effect of clouds was greater than assumed by the model.

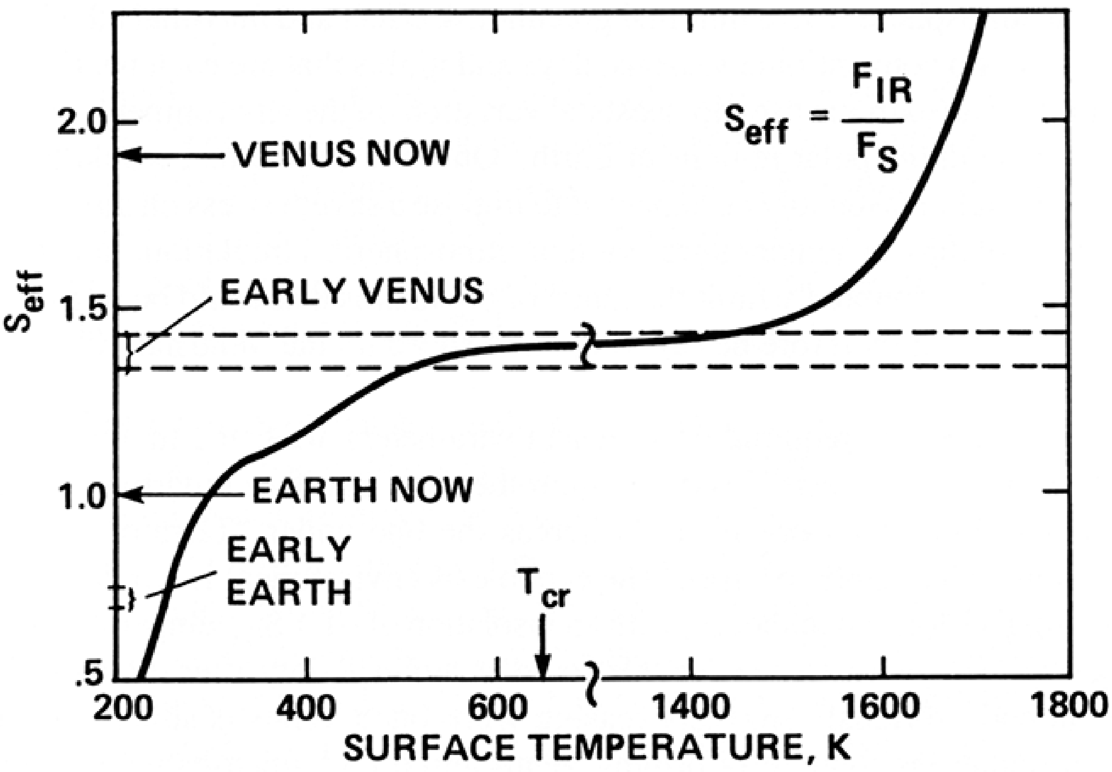

Figure 7.3 *Relationship between the surface temperature and insolation for an Earth-like planet. Insolation is in units of the present solar flux at Earth's orbit; the two dashed lines bracket the flux expected for early Venus. At temperatures higher than the critical point of water (T_{cr} = 647 K), liquid water is unstable and the planet enters the Runaway Greenhouse state. (Reproduced with permission from Ref. [20].)*

The Terraforming of Venus

It is interesting to note therefore that during the first 500 million years of planetary history, the environments of Earth, Mars *and* Venus may have been much more like each other than at present. *All three* would have possessed large bodies of stable liquid water on their surfaces and hence the possibility of the origin of life. Admittedly, Venus at best would only have been suitable for extremely thermophilic organisms such as *Pyrodictium*, and even then only for a comparatively short time. However, the parameters of the early Venus nevertheless provide some guide for the requirements of Venusian ecopoiesis.

7.3 The Requirements of Terraforming Venus

As a planetary engineer might see it, the principal problems with Venus are its proximity to the Sun, its massive atmosphere, aridity and slow rotation. To make the planet habitable therefore involves having to *remove* almost all the gaseous CO_2 (virtually the entire atmosphere), only processing < 1% of it into oxygen. In contrast, to provide an adequate hydrosphere we must *add* a substantial quantity of water, probably at least 2 - 4 orders of magnitude over what is already present. After Venus has cooled, measures to prevent it from relapsing into a runaway greenhouse state would be needed such as a reduction in the planet's insolation and the designing of an atmosphere with a minimal greenhouse effect and maximal albedo. Although Venus would have no conventional seasons, days and nights that are each nearly two months long would impose an extreme pseudo-seasonal variation on the environment, most similar to the light/dark cycle in the polar regions of Earth. On Venus, the effect would bear upon the entire globe and might reasonably be expected to impose a severe stress on any biosphere that is created: large swings in temperature, violent atmospheric circulation and long periods without light would undoubtedly limit the range of organisms that could be introduced. Planetary engineering might therefore also be called upon to speed up the Venusian day.

TABLE 7.3 VENUS - TERRAFORMING REQUIREMENTS

		Modification required for:	
Parameter	**Present value**	**Minimal ecopoiesis**	**Terraforming**
Surface Gravity:	0.88g	Not possible	
Solar Day:	117 days	Unnecessary?	Substantial reduction
Axial Inclination:	2.6°	Unnecessary	
Insolation:	2620 W/m^2	Reduce to 1507 W/m^2	Reduce to 1370 W/m^2
Albedo:	0.77	High as possible	
Mean Surface Temperature:	737 K	~370 K reduction	~440 K reduction
Surface atmospheric pressure:	~ 95 bars	< several bars	380 - 3700 mbar
CO_2 Partial Pressure:	~ 91 bars	< several bars	< 10 mbar
O_2 Partial Pressure:	< 9.5 mbar	Unnecessary	95 - 500 mbar
N_2 Partial Pressure:	~ 3.3 bars	Unnecessary	Unnecessary?
Hydrosphere:	0%	> 0%	>> 0%
UV Flux 0.2-0.3 μm:	~ 27 W/m^2	Reduction	Zero

The primary modifications required of Venusian parameters are listed in Table 7.3: the column under “Minimal ecopoiesis” lists the requirements of a surface environment suitable for extremely thermophilic microorganisms, whereas the one under “Terraforming” defines a planet that would be habitable for man. The ecopoiesis environment is similar to the mildest version of Kasting's Moist Greenhouse, with an insolation of ~ 1.1 $S_{\oplus}$, temperatures of ~ 100 ^{o}C and scalding seas. However, since even this could only be attained after substantial planetary engineering, nobody seriously suggests ceasing work once Venus is suitable for microbes. Virtually all speculations about terraforming Venus therefore aim for a human-habitable environment.

Since Venus orbits some considerable distance sunward of the inner edge of the ecosphere (see Section 3.4.2), long-term habitability may demand a degree of artificial regulation of planetary parameters. This conscious intervention might be minimized by not requiring that the planet be cooled down to present terrestrial temperatures. A world maintained at ~ 10 - 20 ^{o}C warmer, with a smaller equator-to-pole temperature gradient would still be habitable — perhaps similar to the Cretaceous Earth or the tropical Venus of Arrenhius. Such a strategy would have the additional advantage of leaving Venus with distinct, but not unpleasant or dangerous, differences as compared with the Earth. It is this notion of creating habitable planets that are more than duplicates of Earth, and which will have a palpable uniqueness, that is of particular intellectual and aesthetic appeal.

Terraforming Venus will involve manipulating ~ 100 times the atmospheric mass and perhaps ~ 10 - 100 times the mass of water involved in terraforming Mars. In these terms, it is undoubtedly a more demanding task, reserved for a more distant future. However this has not prevented speculation over how it might be done — in fact quite the contrary. As an intellectual exercise in planetological problem solving, Venus has one great advantage over Mars and that is virtually its entire volatile inventory (the atmosphere) is visible and accessible to measurement. Some of the most crucial data on which to base a terraforming thought experiment are much better constrained. Less uncertainty is involved in the basic scientific aspects of the exercise, but the greater magnitude of the undertaking does force us to match this by proposing a more impressive engineering capability. Papers on terraforming Venus therefore tend to present broad-brush scenarios, drawing from a wider variety of concepts. In contrast to Mars, there is less of a tendency to focus on a small part of the problem at the expense of the whole; conversely however, the terraforming techniques that have been proposed for Venus have been studied with less rigour and are usually more vague and speculative. Disentangling terraforming techniques, tools, and applications from the contexts of the scenarios in which they are used is thus more tedious and is not attempted here. Instead, these scenarios are listed chronologically in Table 7.4 alongside their chosen strategies for modifying the atmosphere, creating a hydrosphere, controlling temperature and changing the duration of the day.

We structure the following review, in which a freer rein must be given to the imagination than hitherto, around techniques for dealing with the dense Venusian atmosphere. Other problems are addressed when they arise out of the scenario under discussion.

7.4 Aerial Photosynthesis

In 1961, Carl Sagan wrote in the journal *Science*: *"After the physical environment has been thoroughly investigated and if, indeed, Venus proves to be without life, there will exist the prospect of microbiological planetary engineering. To prepare Venus for comfortable human habitation, it is necessary to lower the surface temperature and to increase the partial pressure of molecular oxygen. Both ends could be accomplished if a means were found to dissociate carbon dioxide to oxygen and elemental carbon."*

The Terraforming of Venus

These words are commonly considered to have opened the first speculation on terraforming, published outside science fiction, and based on an approximation to factual data. It took the form of a one-page speculative tailpiece to a nine-page review paper on the newly emerging understanding of Venus [7]. Sagan correctly identified many of the basic characteristics of the Venusian environment, such as the dense CO_2 atmosphere, powerful greenhouse effect and high surface temperatures. Nevertheless, although the planet he described was almost as deadly as the modern Venus, the extremity of some of its parameters were still very much understated. The surface temperature was assumed to be ~ 327 °C and the atmosphere composed of ~ 3 bars of CO_2 and ~ 1 bar of N_2. The clouds were considered to be made of ice crystals at the top and water vapour at their base, perhaps sandwiching a zone where liquid would have been stable. These differences between the Sagan's model Venus of 1961 and the real planet must be taken into account when evaluating both his terraforming proposal and the "urban myth" that it gave rise to.

TABLE 7.4 VENUS TERRAFORMING SCENARIOS

	Terraforming technique or tool proposed for:			
Author/date/reference	**Modification of the atmosphere**	**Creation of a hydrosphere** (~depth/m)	**Temperature control**	**Modification of the solar day**
Sagan, 1961 [7]	Photosynthesis	None	None	None
Oberg 1981 [30]	Photosynthesis + imported H_2	$2H_2 + O_2$ (~ 880 m)	Parasol	Mirror/parasol system
Adelman, 1982 [40]	Impact erosion	None	None	Impact spin-up
Marchal, 1983 [47]	Reaction with crust	None	Dust rings/cloud	None
Gillett, 1984, 1985 [33,34]	Photosynthesis + imported Fe & H_2	$2H_2 + O_2$ (~ 200 m)	Brine oceans	None
Fogg, 1987 [24]	Photosynthesis + imported H_2	$2H_2 + O_2$ (~ 880 m)	Parasol	Dyson motor
Smith, 1989 [49]	Reaction with crust	Imported water (~ 2200 m)	Parasol	Impact spin-up
Gillett, 1991 [38]	Imported Ca & Mg	Imported water (~ ? m)	Brine oceans	None
Birch, 1991 [32]	Freezing out of CO_2	Imported water (~ 140 m)	Parasol	Mirror/parasol system

It was the cloud layer that Sagan considered to be the last possible ecological niche on Venus and one where biological activity might succeed in transforming the atmosphere. He envisaged sowing the clouds with photosynthetic microorganisms that would grow and generate oxygen in the usual way:

$$CO_2 + H_2O \rightarrow (CH_2O) + O_2 \tag{7.1}$$

Now since the oxygen evolved in photosynthesis comes from water and since, in contrast to the Earth, there is much more CO_2 than water present, regeneration of water is required to stop the process grinding to a halt. Sagan suggested that this would occur naturally when organisms sank into the lower atmosphere where they would be roasted and charred to carbon:

$$(CH_2O) \rightarrow C + H_2O \tag{7.2}$$

The overall effect therefore would be precisely Sagan's stated aim — the dissociation of carbon dioxide into carbon and oxygen:

$$CO_2 \rightarrow C + O_2 \tag{7.3}$$

The carbon would accumulate as a layer on the surface and the oxygen in the atmosphere. Eventually sufficient CO_2 would be broken down as to reduce the greenhouse effect and the surface temperature. A point would be reached where rain can reach the surface and start accumulating in polar seas. This draws water vapour out of the atmosphere cooling Venus still further, eventually precipitating torrential rain over the entire globe (see Plate 7.6). (The analogy with Poul Anderson's 1954 short story "The Big Rain" [21] was not overtly stated by Sagan, but was subsequently made explicit by others.) The original mechanism for removing CO_2 would now no longer function. However an aqueous surface allows other mechanisms for disposing of CO_2 to come into play, such as the chemical weathering to form carbonates (see Equations 2.17 & 2.18) and the burial of organic carbon in sedimentary basins.

Plate 7.6 *The "Big Rain" gathers into boiling torrents on the Venusian surface in this artist's impression of the Sagan scenario. We now know, amongst other difficulties, that there is too little water in the planet's atmosphere for such an*

event to be engineered. However, scenarios which import volatiles to Venus (an unfortunate necessity) also predict such a phase of atmospheric precipitation. (Artist: David Hardy.)

Sagan described the possible climax of this process: *"With a few centimetres of precipitable water in the air, surface temperatures near room temperature, a breathable atmosphere and terrestrial micro flora awaiting the next ecological succession, Venus will have become a much less forbidding environment than it appears to be at present."*

Not surprisingly, many people found this predicted transformation of an entire planet to be startling, especially in view of the fact that little human work or technology seemed to be needed. The technique is thus a classically ecocentric one: the terraforming tools being living systems exhibiting fantastic leverage (useful work out >> useful work in) and requiring merely the energy of Venusian sunlight. Sagan however was careful not to predict a timescale for completion of the process, other than to state that it might be, *"... a relatively short period of time."*

He was also cognizant of the fact that the necessary simplicity of his thought experiment overlooked many potential complications that would need to be investigated before it could be seriously used as a basis for action. Not the least of these is that although microorganisms can be found in rainwater, we do not know of any species that prefers a completely aerial lifestyle. Venusian organisms would need to be able to conduct appreciable photosynthesis and would need to reproduce before sinking beneath the habitable layer. A large thermal range of metabolic activity is therefore desirable, as is the ability to fix nitrogen from the atmosphere as nitrates or ammonia will not be present in any significant quantity. The question of other non-volatile trace elements required for metabolism and cell structure is also important; if sufficient of these cannot be obtained from airborne dust blown up from the surface, then the clouds would have to be fertilized artificially.

The microorganisms Sagan nominated as being worthy of further investigation in this regard were the cyanobacteria, in particular members of the *Nostocacae* family. These are oxygen-evolving photoautotrophs, capable of nitrogen fixation and survival in environmental extremes. Cyanobacteria of some kind are thought to have been responsible for the oxygenation of the Earth's atmosphere and so are a logical choice for Venus. Another candidate Venusian pioneer was proposed in 1970 by Joseph Seckbach and W.F. Libby of the University of California at Los Angeles [22,23]. They performed experiments on a number of unicellular species in an environment of pure CO_2, under pressure, and in an acidic nutrient medium at elevated temperatures. *Nostoc* species did not fare well, but a Rhodophyte (red alga) *Cyanidium Caldarium*, a resident of hot acidic springs, was found to thrive and to grow better than under ordinary air (see Plate 7.7). However Seckbach and Libby were proposing *Cyanidium* as a potential inhabitant of acidic polar seas on Venus (which have been subsequently disproved), not any aerial habitat. Being a eukaryote and not a bacterium, it has no capability to fix nitrogen.

The feasibility of aerial microorganisms surviving in the presently known Venusian atmosphere was examined further by Fogg [24]. There exists a 12 km-deep layer within the atmosphere, between altitudes of ~ 47 - 59 km, that is potentially habitable. From top to bottom, temperatures range between 0 - 100 ^{o}C and the pressure is ~ 1 bar. A crucial question is whether cyanobacterial populations would be able to survive in this zone for long enough to grow.

In the absence of convection, the sink rate of microscopic sized spheres through a viscous fluid is described by Stokes' Law:

$$v = 2gr^2(\rho_1 - \rho_2) / 9\eta \qquad (7.4)$$

where v is the sink rate, g is gravity, r is the radius of the sphere, ρ_1 is the density of the sphere, ρ_2 is the density of the medium and η is the coefficient of viscosity of the medium.

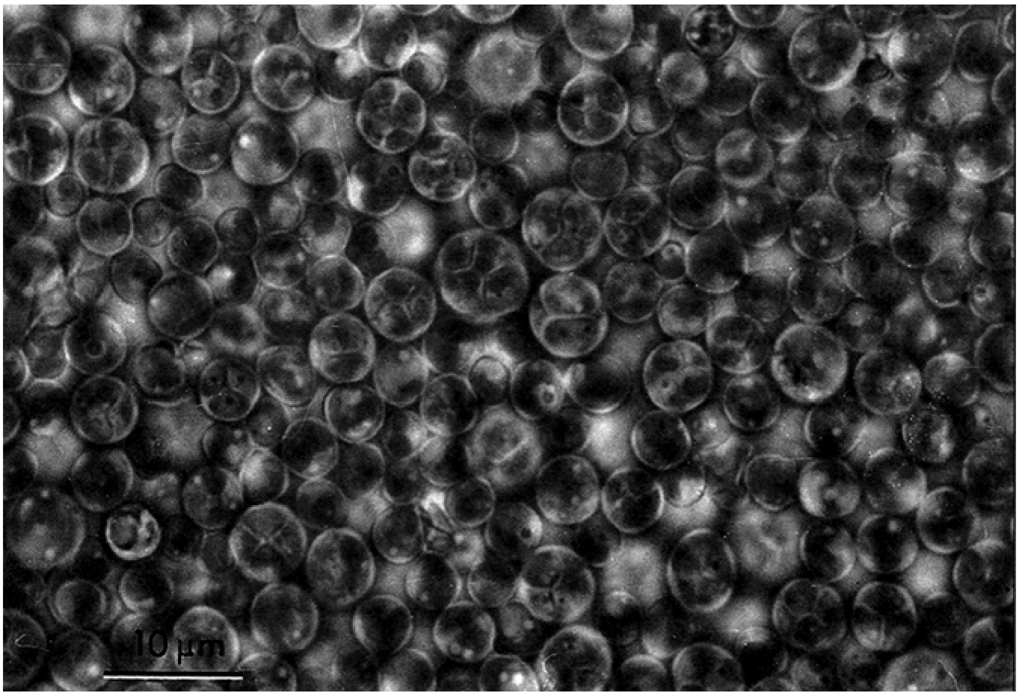

***Plate** 7.7 Cyanidium caldarium. A rhodophyte alga that grows best at temperatures of ~ 45 °C and at a pH as low as 2 - 3; experiments have shown that it also thrives under pure CO_2. Cyanidium species could be some of the first members of the Plant Kingdom to pioneer Venus, perhaps in hot, acidic, polar seas. (Micrograph courtesy of E. Imre Friedmann.)*

For the case in question we estimate $\rho_1 = 1000$ kg/m^3, $\rho_2 \approx 2$ kg/m^3 and $\eta \approx 1.38$ N s/m^2. Assuming cyanobacteria can be modelled as spheres, then we find a 4 µm diameter cell drifts downwards at a rate of $v \approx 5.5\times10^{-4}$ m/s, taking 251 days to traverse the habitable layer. If organisms are contained within 10 µm-wide aerosol particles, the sedimentation time falls to ~ 40 days, whereas large watery 100 µm cloud droplets (similar to those in terrestrial clouds) would last ~ 10 hours. In calm conditions therefore there appears to be ample time for many generations of progeny from an initial progenitor. Unfortunately, convective downdraughts within the clouds would act to shorten the lifetime of some droplets by carrying them down at a faster fate than terminal velocity. At the same time, up draughts would reprieve some algae-containing droplets from heat sterilization by carrying them upwards and laterally where further growth and reproduction can occur. We can tentatively conclude therefore that, unless the Venusian clouds are very turbulent, suitable microorganisms could survive and establish a steady state population.

Since an aerial ecosystem cannot be expected to be as crowded with life as an aquatic analogue, a cell number density of 10/cm^3 is perhaps reasonable, this is 10 - 100 times less than the number density of oceanic phytoplankton and is of a similar order to the abundance of the larger sized Venusian cloud particles. This raises the obvious question as to whether such a dispersed biota will be able to intercept an appreciable fraction of the planet's insolation. Fortunately, the much greater transparency and depth (z) of the habitable zone, might compensate for the greater dilution of biomass. The extinction coefficient of 4μm diameter cells at a density of $10/cm^3$ is $k \approx 1.26\times10^{-6}/cm$; thus the fraction of sunlight being intercepted is a respectable $1 - e^{-zk} \approx 0.78$. Larger cells or greater number densities that might occur if water is added to the clouds during terraforming (see Section 7.5.1) would further improve on this estimate.

It is likely that microorganisms better suited to genuine Venusian cloud deck conditions can be found amongst the inventory of Earth. However, it is a far cry from life in a liquid nutrient medium in a laboratory flask to a dispersed existence permanently aloft in cloud droplets. Workable aerial ecosystems will have to tackle both the buoyancy and nutrient supply problems and thus be designed and realised by genetic engineering. These difficulties can be solved conceptually [25], but since natural evolution has not succeeded at it, despite the selective advantages of being able to intercept sunlight above a ground-based canopy, the task will perhaps also be a tall order for genetic engineers.

Nonetheless, Sagan's proposal represented a bold leap of the imagination, its enduring importance being that it shattered the taboo that confined discussion of terraforming to the pages of science fiction. When applied to the Venus of the early sixties, his model, superficially at least, did seem to offer a cheap, simple and elegant way of terraforming an alien planet.

7.4.1 Time Scale: Fantasy and Feasibility

By the early 1970's the first Soviet *Venera* probes had succeeded in landing on the Venusian surface and of briefly returning data before being rendered inoperable by the harsh environment. It was now clear that the atmosphere contains ~ 30 times as much CO_2 as Sagan had originally thought, the surface temperature is > 100 °C hotter and the clouds contain as much sulphuric acid as water. This revised knowledge added such an extra burden of difficulty to the original terraforming proposal as to cripple it entirely. As Pollack and Sagan stated recently [26]: *"Even if a microbiological approach to engineering Venus were feasible however, the surface would be buried by hundreds of metres of fine graphite or organic particles sedimenting out of the atmosphere; and ~ 65 bars of O_2 would be generated — the first at least inconvenient for, and the second lethal for human settlers on an engineered Venus. Such microbiological schemes at best carry planetary engineering on Venus only part-way towards human habitability."*

In fact it is by no means clear that the process could reach completion at all, as it is unlikely that the surface carbon layer would be stable in the presence of so much oxygen. An equilibrium might be set up in which the amount of carbon deposited at the surface would be balanced by a similar amount returned to the atmosphere by combustion. Eventually therefore, once the process had proceeded partway down its intended path, it would grind to a halt and nothing else would happen [27].

However, such was the euphoria generated by Sagan's original proposal, with its vision of Venus as a planetary free lunch that it is perhaps understandable that some enthusiasts were reluctant to let the dream fade. This would not normally have mattered except for the fact that some of them were well-known popular science writers who chose to embellish the dream instead. Rather than digesting the implications of updated information and perhaps proposing alternative terraforming strategies, certain writers eulogised *"Sagan's Plan"* to such a baroque extreme that it could not fail to take root amongst the section of the public interested in such things. Terraforming therefore has a genuine "urban myth" associated with it — not as well known as the tale of the poodle in the microwave oven, but just as enduring and apocryphal. It is beautifully summed up by the following enquiry sent to the British Interplanetary Society by a member of the public in 1988.

> *Sir,*
> *As early as 1961 an idea was put forward by Carl Sagan involving sending unmanned spacecraft into Venus's orbit carrying on board colonies of blue-green algae in small torpedo-like rockets. The purpose was to introduce these organisms into the Venusian environment for the purpose of breaking down the carbon dioxide atmosphere.*
> *Within a year, the surface of Venus would be partly visible to telescopes on Earth. As oxygen replaces carbon dioxide the Sun's infrared radiation, hitherto trapped, will escape into space and the temperature of the lower atmosphere will decrease considerably. Water will collect from the atmosphere's vapour as rain that will eventually reach the planet's surface...*
> *The new oxygen atmosphere will combine with sunlight to create, high in the stratosphere, a layer of ozone. Sagan's entire scheme, requiring no greater expenditure than that involved in a dozen or so spacecraft and a few thousand small algae rockets, would bring the staggering riches of a second world in our possession.*
> *My question is, if it were possible to send Venera 9 and 10 in October 1975 into Venus' atmosphere and land, why has the scheme put forward by Sagan long ago not been attempted?*

The enquirer's question at the end is well put — why indeed? A whole new Earth *in just a few years* for the cost of a few rocket nose cones filled with cyanobacteria — the prospect is so staggering as to be irresistible. Of course, it is actually complete nonsense and is one "urban myth" that deserves finally to be put to rest. It is thus of use for our more serious purposes here to consider, fundamentally, why it is untenable and how it grew out of Sagan's original concept in the first place.

One of the mythmakers was Adrian Berry, the science correspondent of the British newspaper *The Daily Telegraph* who devoted two chapters to Venus in his best-selling book The Next Ten Thousand Years [28], published in 1974. (Most of the statements in the above letter are paraphrases of Berry's words). Another was SF author Jerry Pournelle whose speculation "The Big Rain" [29], published in *Galaxy* magazine in 1976, and later reprinted in a compilation of "Science Fact" articles in a book entitled A Step Farther Out. Both pieces appeared not to have taken into account Venus' changed circumstances and were unsupported by calculation. In particular, both attached numbers to the project's timescale — something which Sagan had not done himself. Berry felt that significant results were achievable within, *"... perhaps as little as two or three years..."* Whilst Pournelle predicted that, *"... we could probably get the job done in this century, using present day technology."* And all of this for a cost that, *"... is unlikely to be greater than a medium sized war."*

These predictions were based on the fallacy that life, when introduced into an unpopulated environment, reproduces at an exponential rate. This however is only true at the start of growth as every environment has a carrying capacity defined by such parameters as energy and nutrient supply [27]. Since Venus is only illuminated with a finite supply of sunlight, it is simple to calculate the minimum possible time that it would take to photosynthetically process all of the CO_2 in the Venusian atmosphere into oxygen.

The globally averaged sunlight on Venus is 655 $W/m^2 \equiv 2.07\times10^{10}$ $J/m^2/yr$; since photosynthesis requires $4.77\text{x}10^5$ J to generate one mole of O_2 then, at ε = 100% efficient utilization of top of atmosphere sunlight, we find an oxygen production rate of $2.07\times10^{10}/4.77\times10^5 \approx 43396$ mol $O_2/m^2/yr$. There are ~ $1.13\text{x}10^{22}$ moles of CO_2 on Venus: to convert this to an equal quantity of oxygen we must deal with $2.46\text{x}10^7$ mol

CO_2/m^2. The total solar energy required is therefore $1.13\times10^{22} \times 4.77\times10^5 \approx 5.4\times10^{27}$ J/ε and the minimum timescale is $2.46\times10^7/43396 \approx 570$ years.

One hundred percent efficient atmospheric processing is not feasible. But let us optimistically assume insignificant atmospheric absorption of sunlight, no nutrient limitations, a full photosynthetic canopy, no heterotrophic activity (NCP = NPP) and 100% disposal of carbon, then we might achieve an efficiency approaching the theoretical leaf-incident maximum of ~ 5%. This raises the timescale to ~ 11,000 years; whereas if the aerial biosphere of Venus can only be made as efficient as that of Earth ($\varepsilon \approx 0.05\%$) the process would take ~ 1.1 million years.

The inescapable conclusion therefore is that, despite what some might like to believe, microbiological planetary engineering on Venus entails a timescale of at least several thousand years and possibly far longer. The modern view of Venus also makes it clear that a simple biological model for terraforming Venus would not give rise to a habitable planet — there is simply too much gas to process into a breathable atmosphere. However, some of those who examined the question seriously, still felt that biology might have some pivotal role to play in a larger scheme. To quote Oberg's comment on the popularisers of Sagan's original idea [30]: *"A more realistic view, possible in light of recently acquired data, would not fault the suggestion that organisms could be salted in the Venusian atmosphere, or even that they could thrive there, but it would contradict the cheerful image of breaking clouds and Earth like climes all due to one biological trick, in a short period of time."*

Biological tools after all do have certain advantages in being inexpensive, self-reproducing, and autonomous and of using *gratis* solar energy. In addition, there is something inherently appealing about the notion of life creating the conditions for more life. Assuming therefore that organisms suited to existence in the Venusian clouds can be found — or more likely made — and assuming that the reaction scheme in Equations 7.1 - 7.3 operates with good efficiency, then it is worth asking what can be done to overcome the scenario's other difficulties.

7.5 Importation of Reductants

If a massive loss of hydrogen and oxidation of the crust did occur in the early history of Venus, as a consequence of the photodisintegration of water, then Venusian rocks cannot be expected to absorb much more oxygen. A past loss of volatiles at a time when the planet was more Earth like, logically dictates an addition of material to restore the chemical balance to what it was; furthermore, since it was a reducing agent that was lost, it follows the importation of a reductant will be required.

7.5.1 Addition of Hydrogen and its Consequences

A principal problem with the aerial photosynthesis scenario is the huge potential ~ 67 bar oxygen excess that arises from dissociating CO_2. Oberg [30] suggested that fixation of the liberated oxygen could be achieved by reaction with large quantities of hydrogen, imported from the atmosphere of Saturn. (The idea was further examined by Fogg [24]). This has the advantage that water is the product and that Venusian air is thus converted into the stuff of future oceans, thus solving the excess-oxygen and aridity problems simultaneously. A breathable pO_2 in the final terraformed atmosphere requires removal of all but ~ 0.5% of the oxygen, a quantity of ~ 1.12×10^{22} moles. Double this quantity of hydrogen molecules are needed — a mass of ~ 4.5×10^{19} kg. This will combine with the oxygen to give ~ 4.07×10^{20} kg of water, a mass equivalent to 29% of the Earth's oceans which would cover Venus to a mean global depth of ~ 880 m. This is a very respectable quantity, especially in view of the fact that Venus is so flat (see Fig. 7.2) and would spread out to cover ~ 70% of the planet's surface with shallow oceans ~ 1 km deep.

The disadvantage of hydrogen importation is that the extra water vapour generated enhances the greenhouse effect (water is a more powerful greenhouse gas than carbon dioxide and two molecules of H_2O are being produced for every molecule of CO_2 removed). The end result would therefore be a moist greenhouse ~ 78 bar steam and nitrogen atmosphere and a surface temperature hotter even than it was before. The “Big Rain” therefore would not occur naturally and would have to be induced by shadowing Venus and allowing the planet to cool by radiating its heat into space [24]. This could be done by a parasol positioned at the Sun-Venus L1 point and scaled up in size by over an order of magnitude over those systems considered for the Earth in Section 4.2.6 and the Mars mirror in Section 6.3.1.1. The L1 point is ~ 10^6 km above Venus and for the entire planet to be within the umbra of the parasol's shadow, the structure must be ~ 25,000 km in diameter — a little more than double that of the planet itself. If made of 2μm-thick aluminium, it would weigh ~ 2.7×10^{12} kg (2651 million tonnes). This is equivalent to 180 years of the present terrestrial production: a quantity readily available from space resources, but nonetheless giving some impression of the relative industrial effort needed. (Whilst this mass seems great, it is actually trivial compared with that which must be handled in processing the Venusian atmosphere. Parasol designs more sophisticated and lightweight than a simple stabilised disk can be envisaged and are discussed in more detail in Section 7.7).

The time taken for the atmosphere to cool and precipitate can be estimated from:

$$dT_{atm}/d\tau \;\approx\; -\sigma T_{eff}^4 / H_v \qquad (7.5)$$

where $dT_{atm}/d\tau$ is the mean cooling rate of the atmosphere, σ is the Stefan-Boltzmann constant, T_{eff} is the temperature at which the planet radiates to space and H_v is the heat capacity of the atmosphere per square metre. For a 78 bar steam atmosphere, we estimate $H_v \approx 1.8\times10^9$ J/K/m^2; in addition, the latent heat of vaporization that must be lost is ~ 2.0×10^{12} J/m^2.

Equation 7.5 can only provide a rough guide to events since it is sensitive to a term to the fourth power (the effective temperature) which itself depends on uncertain parameters such as the level within the atmosphere from which heat is being lost, the convective coupling of the lower atmosphere with the radiating layer, the influence of the release of latent heat and the change of all of these with time. For cloud-free conditions, Moist Greenhouse models predict a radiating temperature of $T_{eff} \approx 272$ K, but including the presence of clouds would depress this substantially to perhaps as low as $T_{eff} \approx 200$ K [31]. Because H_2O is such an effective infrared absorber, steam atmospheres are generally expected to radiate from very high altitudes and so a value of T_{eff} closer to the lower of these two would probably be the most realistic. We adopt this range of T_{eff} = 200 - 272 K here and further assume (optimistically) that the Venusian surface has not heated up over its present temperature of 737 K; and that the temperature of the radiating layer stays constant whilst gradually lowering in altitude as the lower atmosphere cools by convection and precipitates.

The boiling point of water under 78 bars pressure is ~ 569 K (296 ^{o}C) and so a 168 K temperature drop is needed before precipitation can reach the surface. Thus, according to Equation 7.5 and our assumptions, the “Big Rain” commences 30 - 100 years after shading. The total time to cool Venus by 440 K to T_{atm} = 297 K

(24°C), condensing the water into oceans, is estimated to be 300 - 1000 years. This is not substantially increased by the need to cool the surface as the low thermal conductivity of rock ensures that cooling to a depth of a few tens of metres will effectively insulate the surface from the high temperatures beneath. Thus we can roughly equate $T_{surf} \approx T_{atm}$.

The induced cooling of Venus therefore will take some considerable time although it is still likely to be one of the most rapid steps involved in the overall project. If the shaded atmosphere can be made to radiate at higher temperatures by engineering means, then the timescale would be substantially shortened [32]. The likely rate-limiting process on the terraforming as a whole is the biological processing of the atmosphere which we estimated in the previous section would take ~ 10^3 - 10^6 years. Hydrogen only needs to be added in proportion to the oxygen that is released into the environment.

The quantity of hydrogen required is prodigious, but its mass is slightly less than that involved in Dyson's scenario for supplying Mars with ~ 450 m of water (see Section 6.2.4). This is because 89% of the mass of what is to become ~ 880 m Venusian oceans comes from indigenous oxygen and does not have to be imported. Additional difficulties are that the hydrogen would have to be either mined from a gas giant planet atmosphere and lofted out of a deep gravity well, or produced from the dissociation of water ice. A collateral benefit from the former process however [24] would be that ~ 1.4×10^{16} kg of deuterium and ~ 8.8×10^{12} kg of helium-3 would become available as by-products — valuable fusion fuels embodying a potential energy of ~ 3.8×10^{30} J ≡ 3 hours of the Sun's *entire* radiant output, or ~ 400,000 years of Venusian sunlight! It is in fact > 100 times as much energy as is needed to raise the mined hydrogen free of Saturn's gravity. (The energy to raise the hydrogen from a large planet dominates over that needed to liquefy the gas and send it in to the inner Solar System and is ~ 2.9×10^{28} J for Saturn and ~ 10^{28} J for Uranus). Thus, whilst terraforming projects require one to think big in terms of energy expenditure and mass transfer, the resources required remain trivial compared to those of the Solar System as a whole.

Of course, presently we can only dimly foresee how massive atmospheric mining might be possible. Oberg [30] imagines collecting the hydrogen via large ram scoops suspended in the atmosphere of Saturn by "skyhooks" — tethers suspended from orbit. The gas is then compressed into metallic form (something that is theoretically possible but has yet to be done in bulk) whereupon it is fired on a course to Venus by an electromagnetic cannon. Fogg [24] suggests Uranus as a better location for mining since only 35% as much energy is needed to escape the planet and less also to be put on a trajectory into the inner Solar System. He envisages numerous robotic aerostat factories transferring frozen hydrogen to orbit, it then being transported to Venus via a gigantic reusable ferry system. Both of these ideas are perhaps naïve in view of both the timescale of the project and the distance into the future when such a feat could be attempted. Some sort of automated, autonomous mining process, with quasi-biological properties such as the von Neumann machines of Dyson, seem to be most appropriate. As with Mars, we can imagine a solar sail propelled mass stream circling into the inner Solar System towards Venus, bleeding hydrogen into the atmosphere at the required rate. Such a scheme does not appear unfeasible over the thousands of years that are under consideration.

A summary of the Oberg/Fogg scenario is given in Fig. 7.4. Box **a** shows the addition of hydrogen and movement of various important compounds during the photosynthetic processing of the atmosphere, the net effect being to precipitate carbon at the surface and to exchange almost every mole of atmospheric CO_2 with two moles of water. If we postulate genetically engineered aerial algae which intercept 78% of sunlight passing through the habitable zone and utilize this at 5% efficiency; and assume further that 50% of sunlight is absorbed by clouds and the gases of the upper atmosphere and production is enhanced by a factor of two due to the fertilization effect of CO_2, then our Venusian aerial biosphere converts top of atmosphere sunlight at an efficiency of 0.78 × 0.05 × 0.5 × 2 ≈ 3.9%. (This also presupposes no nutrient limitations on growth: a particularly difficult problem, but one which might be tackled by contaminating the infalling hydrogen packages with suitable trace elements which would then disperse as dust in the upper atmosphere [24]). The time taken to process the atmosphere therefore becomes ~ 14,500 years, hydrogen must therefore be added to Venus at a rate of ~ 98,000 tonnes/s, which would release a minimum infall power of ~ 5300 TW, about ~ 1.8% of the total Venusian insolation of ~ 300,000 TW. An ongoing kinetic energy input much greater than this is not desirable.

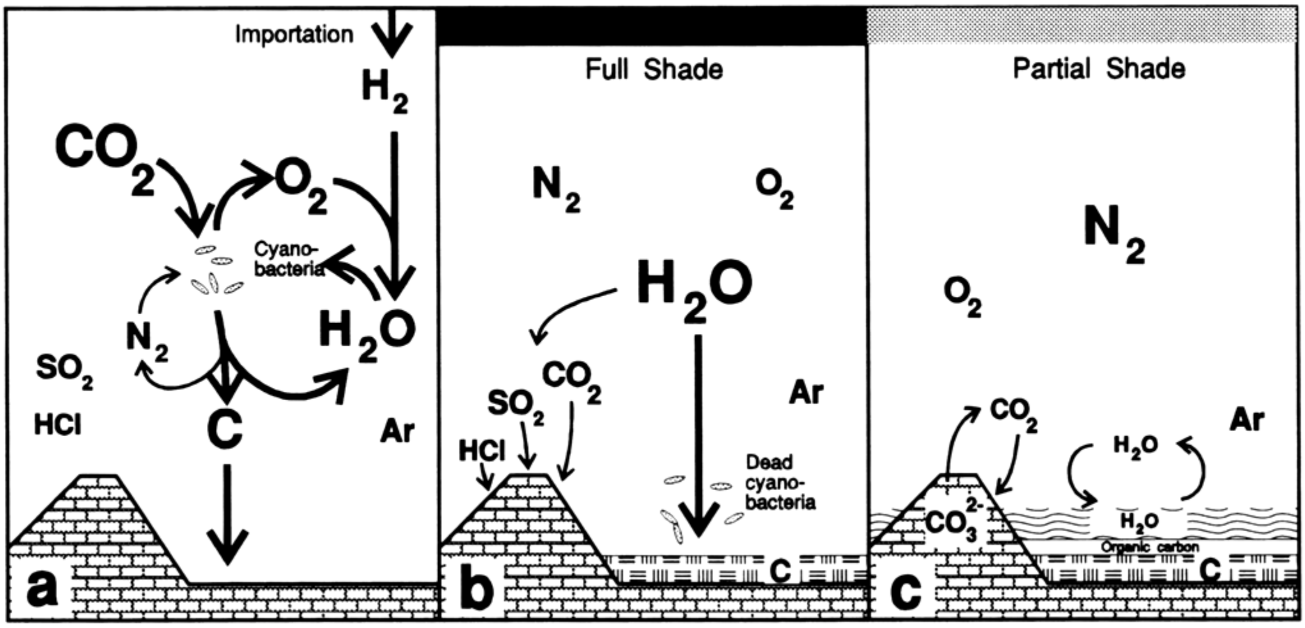

Figure 7.4 *Terraforming Venus in three stages according to the model of Fogg.*[24] ***a:*** *The atmosphere is processed by aerial algae (as per Sagan*[7]*), carbon is deposited at the surface and excess oxygen is reacted with imported hydrogen to form water.* ***b:*** *The "Big Rain" is induced by shading the planet with an L1 parasol. The resulting stream atmosphere precipitates.* ***c:*** *Oceans have formed beneath a nitrogen atmosphere containing residual oxygen and carbon dioxide. Venus is illuminated again, but with less than its natural insolation in order to prevent climatic runaway. It is now suitable for the reintroduction of life and final terraforming operations. (Reproduced with permission from Ref. [24].)*

The next stage, shown in Fig. 7.4**b**, is where Venusian sunlight is cut off by the L1 parasol to induce the "Big Rain" [24]. As discussed previously, a timescale of several hundred years is needed to clear the atmosphere and to fill the oceans. The non-stop precipitation of > 1 metre of scalding water per year would be expected to wash the ~ 120 m global blanket of carbon sediment into basins and to subject the exposed landscape to ferocious erosion. Toxic and acidic compounds are purged from the atmosphere at this stage, reacting in aqueous solution with rock minerals. Deprived of light the aerial algae die off.

Fig. 7.4**c** shows the state of affairs just before the re-introduction of life. The "Big Rain" is finished, 880 m of water is on the surface and a residual ~ 2.3 bar N_2/O_2 atmosphere, of breathable composition, is in place. Sunlight shines on Venus again, but the parasol is not removed entirely, only allowing through sufficient radiation to prevent a climatic runaway. Perhaps Venus can be allowed 52 - 58% of its former insolation (1 -

1.1 $S_\oplus$), or more if the temperature-albedo negative feedback is stronger than assumed by the Moist Greenhouse model. With nutrient-rich oceans covering 70% of Venus and the land overlaid by physically and chemically weathered soil, the planet would be ready for the establishment of a rich, diverse and Earth like biosphere (see Plate 7.8).

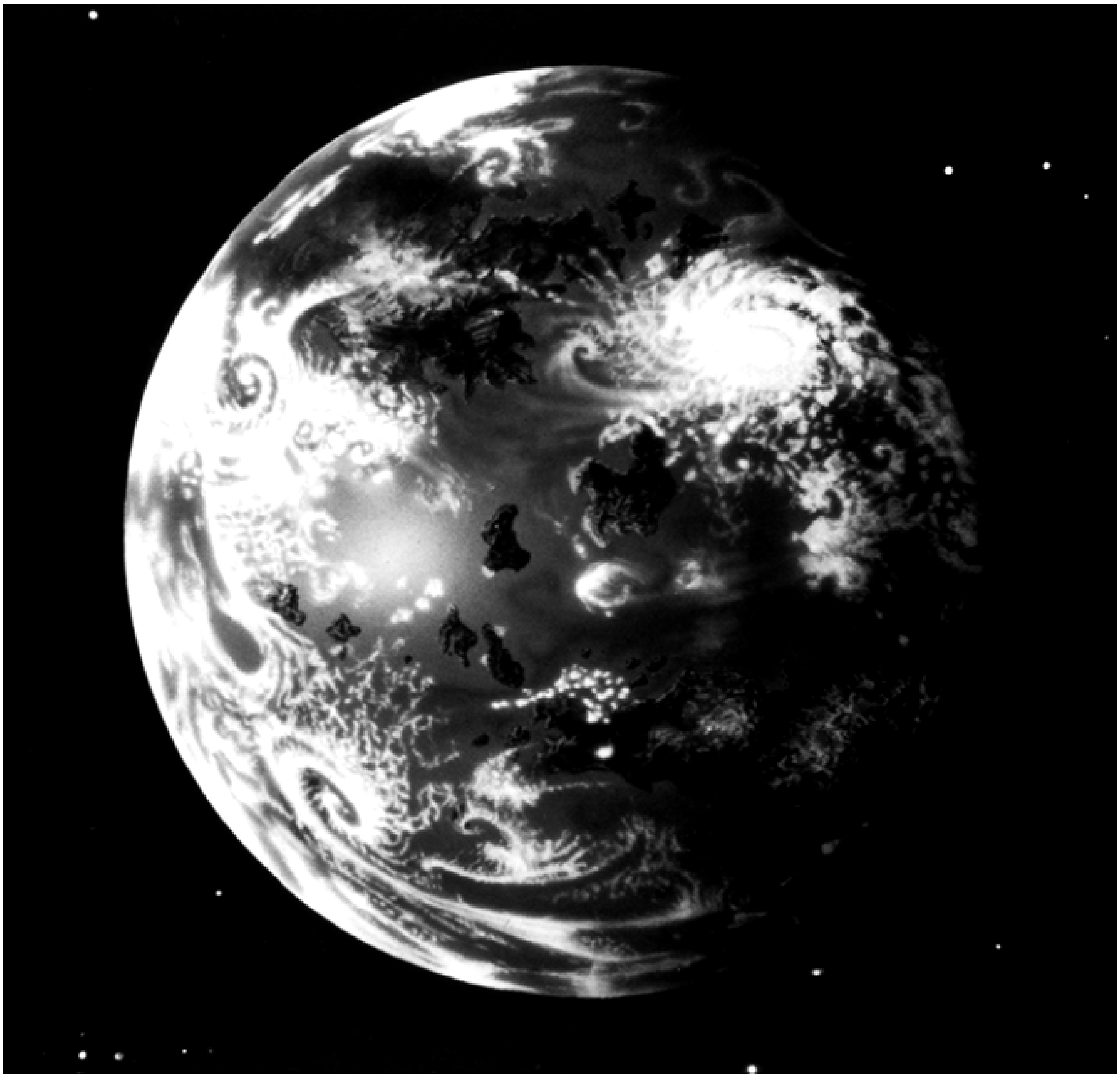

Plate 7.8 *If the surface of Venus is not drastically altered by terraforming, then newly formed oceans will flow around the existing topography. Ishtar (top left) and Aphrodite (bottom right) will stand out as continents. See also Fig. 7.13. (Artist: Ronald Brocklehurst.)*

7.5.2 The Iron / Hydrogen Compromise

The foregoing scenario creates on Venus a watery biosphere similar in volume to that of the Earth and sharing many of its qualities of a life support system. However, its stability does require the ongoing use of at least one terraforming tool, namely the parasol system. As with a fully terraformed Mars therefore, this conception of a terraformed Venus depends on the persistence of a human civilization, or some other sort of planetary consciousness (see Section 6.3.3). This is not seen as an objection by technocentrists, since space-based climate control devices can be considered part of a noosphere. However, it is undeniable that a planet that is naturally and *unconsciously* stable represents a better and more elegant end result — and to the ecocentrist, a *mandatory* one. This point has been well expressed by Stephen Gillett [33]: *"... I feel that terraforming is a pointless exercise if the resulting planetary environment is not stable over a significant period of geological time — that is, stable for hundreds of millions of years, not merely for thousands of years."*

The problem with a wet Venus therefore is that allowing the planet to relax into an equilibrium in the absence of a technological infrastructure risks re-enacting the runaway greenhouse effect. A way to avoid this might be to create a much drier Venus and to lessen the strength of both the water vapour greenhouse effect and its positive feedback with surface temperature. Gillett suggested therefore replacing most of the imported hydrogen with a non-volatile reductant that would chemically precipitate oxygen [33,34]. He creates some water, but has in mind a more arid planet with a minimal hydrosphere. Thus, before examining the choice of alternative reductants, we digress to consider the proposed advantages of this environment.

Gillett pointed out a potentially important clue for planetary engineers, namely the trace quantity of hydrogen chloride in the Venusian atmosphere, which must be buffered by, and hence implies, the presence of abundant NaCl-bearing mineral assemblages on the surface. The amount of NaCl is not well constrained, but it is reasonable to suppose that the Venusian inventory of chlorine is similar to that of Earth. Even in anhydrous conditions, it is likely that chloride minerals become partitioned in the upper crust since chloride and silicate melts are immiscible. The relevance of this likely abundance of water-soluble salts on Venus is that its oceans might rapidly become extremely saline, especially if planetary engineers restrict the mass of water from which they are formed.

A salt solution exhibits a lower vapour pressure above its surface than pure water and the ratio of these two pressures is defined as the *water activity* [35]. Seawater (3.2 wt% NaCl) has a water activity of 0.98, whereas a saturated sodium chloride brine (32 wt% NaCl) has a water activity of 0.75. These are conditions that can be found in saline lakes populated by extreme halophilic organisms such as *Halobacterium*. Lower values of < 0.5 are possible for saturated solutions of other salts such as $CaCl_2$ [36], but no life is known to be possible at water activities of much less than ~ 0.7.

Thus, Gillett proposed that oceans of saturated NaCl brine on Venus would substantially reduce the atmospheric concentration of water vapour, for a given temperature, compared to what obtains on the Earth [33,34]. He also speculated that if the water supply is further reduced, and precipitation occurs rapidly at the poles and on the cool nighttime hemisphere, Venus may not become fully enshrouded in vapour, forestalling any runaway instability. Evaluation of the maximum quantity of water that could be accommodated on a stable Venus would obviously require sophisticated modelling. Nevertheless, Gillett estimated that a terraformed Venus with low-mass brine seas might be stable with an albedo of ~ 0.2, a reduced greenhouse effect of $\sim 20\ ^{o}C$ and a mean global surface temperature of $\sim 55\ ^{o}C$. Only the poles and mid-latitude highlands would therefore be habitable for higher forms of life.

Whilst life in concentrated brine would not be very diverse, it could be highly productive as demonstrated by the microbial communities of many hyper saline ecosystems. There is also the prospect that, over the long term, a wider variety or organisms would evolve into the hyper saline niche. As Gillett asserts: *"Terrestrial marine life is abundant because normal marine salinity (an accident of the ratio of chlorine to water on the*

Earth) is ubiquitous, and has been so over most of Earth's history. Life adapted to concentrated, briny oceans like those proposed for Venus is rare on the Earth because these environments are rare and geologically ephemeral. Were they common and long-lived, life adapted to them would be abundant."

In Gillett's 1984 scenario therefore, aerial photosynthesis is adopted to process CO_2, *but* only 10^{19} kg of hydrogen is imported — less than a quarter of the amount assumed by Oberg and Fogg and sufficient to produce just ~ 200 m of water, equivalent to ~ 6% of the mass of Earth's oceans. If Venus has a terrestrial inventory of salts, and given that they are accessible for rapid dissolution, then saturated brine seas will form over perhaps ~ 20 - 30% of the planet's surface. However, to scavenge the remaining potential oxygen excess of ~ 8.7×10^{21} moles, we need an alternate non-volatile chemical reductant. Native iron is plentiful in the asteroid belt and some asteroids appear to be made from almost pure nickel/iron. Gillett suggested therefore that iron be used as the reductant as it would be expected to oxidise to Fe_2O_3 and could conveniently be dumped on Venus by diverting metallic asteroids to collide with the planet. A mass of ~ 6.5×10^{20} kg Fe would be needed which, when converted to the oxide, would cover the planet with a ~ 390 m layer. This compromise scenario therefore reduces the Venusian environment with an imported mixture of iron and hydrogen in a 2.3:1 molar ratio.

However, asteroidal iron may not be plentiful enough to provide this entire requirement. To illustrate this, Table 7.5 shows the estimated diameters and masses of the six largest known M-type asteroids [37] — objects the spectra of which suggest a fairly pure metallic composition. Their total mass amounts to only ~ 13% of the demand and objects of lesser size would not greatly add to this. In any case, M-type asteroids are likely to be sought after for space manufacturing and their use to make rust on Venus would be wasteful. Another problem, pointed out by Gillett himself, is that formation of the oxide is only thermodynamically favoured at low temperatures and even then forms slowly. A better choice than iron of non-volatile reductant is therefore required.

TABLE 7.5 THE SIX LARGEST M-TYPE ASTEROIDS

Name	Diameter (km)	Mass (kg) †
16 Psyche	249	5.27(19)
22 Kalliope	175	1.83(19)
21 Lutetia	114	5.06(18)
97 Klotho	109	4.42(18)
69 Hesperia	108	4.30(18)
76 Freia	79.1	1.69(18)
		8.65(19)

† Mass estimate includes a factor of 0.83 to take into account impurities and internal and external void space.
Note: m(n) ≡ m x 10^n.

7.5.3 Calcium and Magnesium from Mercury

Gillett [38] returned to the problem of chemically precipitating the Venusian atmosphere in 1991 and proposed these criteria for the material needed:

1. It must be sufficiently reducing to reduce CO_2 to carbon and an oxide.
2. The resulting oxide must be non-volatile, so that it precipitates.
3. The material should be abundant in the Solar System, preferably in bodies with shallow or nearly non-existent gravity wells.
4. It should not require extensive manufacturing or refining.

No known material fulfils all these requirements. Iron, for instance meets criterion 2 and, because sufficient metallic asteroids are not available, only partially meets criteria 3 & 4. Gillett chose therefore to propose the importation of alkaline earth metals instead, such as magnesium and calcium. From the chemical stand-point, these are ideal, having the interesting property of fulfilling criterion 1, i.e. *splitting CO_2 directly* and thus disposing of the need for photosynthesis altogether. For calcium, the reaction scheme is:

$$2\,Ca + CO_2 \rightarrow 2\,CaO + C \tag{7.6}$$

followed by:

$$CaO + CO_2 \rightarrow CaCO_3 \tag{7.7}$$

The overall scheme is therefore:

$$2\,Ca + 3\,CO_2 \rightarrow 2\,CaCO_3 + C \tag{7.8}$$

The reactions are similar for magnesium. All the products are non-volatile: two moles of metal dispose of three moles of CO_2, which become two moles of CO_3^{2-} and one of C. It is possible that the highly toxic gas, carbon monoxide, might be an unwanted by-product of the scheme, however this is probably not a serious problem as CO is a reactive compound that is unstable at low temperatures with respect to CO_2. Any residual carbon monoxide remaining after the processing of the atmosphere might be disposed of by certain strains of hydrogen-oxidising bacteria, which also possess the ability to metabolize CO [35].

The result of importing sufficient Mg and Ca therefore is to precipitate the Venusian atmosphere into a layer of surface solids equivalent to ~ 40 m of carbon and ~ 600 m of carbonate. Nitrogen remains gaseous and a breathable oxygen partial pressure might be produced by photosynthesis of residual CO_2 or importation of a small fraction of the waste oxygen produced from the metallic refining process. Since biology is not being used to dispose of the bulk of CO_2 (releasing oxygen), water, rather than hydrogen, is imported just in a sufficient quantity to create the saturated brine seas described in the previous Section.

Magnesium and calcium are abundant elements, but do not match criterion 4 — they are never found in native form and are always chemically combined, mostly in silicates. Magnesium metal on the Earth is manufactured by the electrolysis of molten $MgCl_2$, often prepared from salts dissolved in seawater. This is not an option in space and so the manufacture of pure Mg and Ca will involve processing huge volumes of rock. This entails having to solve the much more difficult problem of extracting the metals from silicates under anhydrous conditions. The process of *magma electrolysis* is under investigation in this regard [39]; however, although the separation of Fe, Si and O from the melt are relatively easy, the higher temperatures and tendency of the melt to precipitate refractory oxides makes it more difficult to extract reactive metals. It is reasonable to assume however that such problems will have been solved and that space manufacturing will be a mature technology by the time a project as large as terraforming Venus becomes practical.

The Terraforming of Venus

Gillett [38] suggested that the best locale for Mg/Ca production, where the huge amount needed is present, is the surface of Mercury. Appropriate minerals are likely to be abundant in the Mercurian crust — such as anorthite, $CaAl_2Si_2O_8$, orthopyroxene, $(Mg,Fe)SiO_3$, and olivine, $(Mg,Fe)_2SiO_4$. The Mercurian environment is also rich in energy, the planet's insolation being 9147 W/m^2 ($\equiv 6.7\ S_\oplus$). The scale required of such a project is so vast that it involves processing ~ 0.5% the mass of Mercury, by either strip mining the entire surface to depths of > 5.3 km or lesser areas to a correspondingly greater depth. The parameters of the undertaking are given in Table 7.6: which includes the mass of free metal needed to reduce the Venusian atmosphere; the energy required to separate the metals from their host minerals (assuming only bond energies have to be overcome and ignoring demands for crushing and milling etc); and the energy to remove them from Mercury. Also shown is the time taken for the total Mercurian insolation to meet these energy demands. As with requirements discussed previously for other processes, these estimates assume ε = 100% efficient energy use and thus provide optimistic lower limits on the total energy and time needed to carry out the project. It is interesting to note however that the demand Gillett calculates of ~ 10^{28} J/ε is of the same order as that needed for both photosynthetic processing of the Venusian atmosphere and hydrogen importation.

TABLE 7.6 MASS AND MINIMUM ENERGY REQUIREMENTS TO REDUCE THE VENUSIAN ATMOSPHERE

Metal	Amount (kg)	Energy required (J) for:			Time for Mercury to intercept energy
		Separation from rock	Removal from Mercury	Total	
Mg	1.7(20)	4.5(27)	1.5(27)	6.0(27)	1100 years
Ca	2.8(20)	5.2(27)	2.6(27)	7.7(27)	1420 years

Note: m(n) ≡ m x 10^n.
Table taken from Ref [38].

A project of this scale requires not just a major scaling up of the industrial capacity familiar to the 20th century, *but a change in its style too*. As Gillett notes: *"Clearly, refining such a large amount of metal for a project as economically marginal as terraforming Venus will be feasible only with highly sophisticated machine replicating systems ('von Neumann machines') that are capable of 'growing' and also 'differentiating' like biological systems."* Thus, as with the task of mining enough hydrogen for Venus, the scale of the undertaking and the fact that the wanted material does not occur in a pure state in natural, moveable objects, forces us to consider a level of sophistication and automation in robotic technology, that is presently only characteristic of life. Whilst this vision is certainly plausible, it involves taking speculation to the horizon of what is scientifically foreseeable. Gillett therefore envisages the entire surface of Mercury being turned over to the production of magnesium and calcium ingots, each one equipped with a solar sail and guidance microcomputer (for which there would be abundant raw materials available from the by-products of electrolysis). The packages are slung off Mercury by electromagnetic mass drivers into the tail end of a mass stream of trillions of other such ingots, with their solar sails deployed, spiralling out towards Venus.

Problems left behind on Mercury are what to do with the kilometres worth of slag left over from magma electrolysis and the huge quantities of oxygen that are generated. Conceivably, much might be consumed in exports to other markets in the Solar System. The large thickness of powdered carbonate precipitated on Venus also poses questions. Since it is about three times the mean depth of water Gillett has in mind, it may not wash away into depressions very efficiently, preventing the weathering of normal rocks into soil. Moreover, the indigenous salt that is expected to salinate the newborn oceans might be mostly prevented from doing so.

Assuming such problems can be overcome, then Mg/Ca importation precipitates the Venusian atmosphere; this would be followed the importation of a modest amount of water and oxygen, finishing with smaller-scale planetary engineering on Venus itself to "fine tune" the newly habitable environment. The end result is the same briny Venus as portrayed in the previous Section. Thus, although Gillett's scheme employs some ambitious terraforming techniques, the image of his terraformed Venus remains coloured by avowedly ecocentric aims. His planet is less inviting and Earth like than the Venus of Fogg and is hot and largely dry — being suitable for advanced life only at the poles, but perhaps host to abundant, but specialized, thermophilic and halophilic organisms elsewhere. It would be a place of searing days and frigid nights (since the duration of the day is left unchanged), but most of all it is a world conceived of as being stable and having a biosphere free from the need for conscious control. Only as a last resort does Gillett advocate the use of ongoing technological measures to counter the problems of climatic runaway and the long solar day.

7.6 Impact Erosion

While the ejection into space of atmospheric gases by impacting objects is a problem for terraforming Mars (see Section 6.2.4) it could be a positive benefit on Venus. The energy required to accelerate the Venusian atmosphere to escape velocity is a "mere" 2.7×10^{28} J, equivalent to that released by the impact of a ~ 300 km diameter asteroid at the Venusian orbital velocity of 35 km/s. This led to some speculation that engineered impacts on Venus might be an convenient way to dispose of all that unwanted CO_2. In particular Saul Adelman [40] of the The Citadel in Charleston, whose paper concentrated on the use of impacts to spin up Venus, suggested that impact erosion of the atmosphere would also occur as a concurrent process.

Impact erosion is now a more rigorously modelled phenomenon [41] and two limiting types of atmospheric ejection are illustrated in Fig. 7.5. When a collision occurs at less than about twice the planet's escape velocity, or the impactor is less than a certain mass, then no more than a plug of gas is lost to space equivalent to the column mass traversed by the projectile. This is negligible compared to the mass of the atmosphere. More energetic impacts generate a vapour plume and shock wave that can exceed the gravitational binding energy of a large mass of atmosphere. However, the spherical geometry of a planet limits the portion of the atmosphere lost to space as being that gas above a plane tangent to the surface at "ground zero". This is a fraction of roughly 3×10^{-4} of the entire atmosphere.

Mars may be vulnerable to erosion by comparatively small objects (3 - 4 km diameter at > 10 km/s), but larger planets such as the Earth and Venus are not. Calculations applied to the Earth estimate that tangent plane ejection occurs for objects of > 5×10^{18} kg (~ 150 km diameter) at an impact velocity of > 20 km/s. The fraction of atmosphere lost falls rapidly with decreasing mass with no loss at all occurring for objects of < 2 km diameter [41]. Pollack and Sagan [26] extrapolated these data for Venus (since the terrestrial and Venusian escape velocities are similar) suggesting that as the surface atmospheric pressure is 100-times greater than on Earth, it takes objects 100-times as massive to cause analogous impact erosion. This means that tangent plane ejection on Venus needs ~ 700 km diameter impactors, hitting at > 20 km/s. Each such impact blows off $3\text{x}10^{-4}$ of the atmosphere and so a number, *n*, of such events would reduce the atmosphere to ~ $(1 - 3\times10^{-4})^{n}$ of its initial mass. Thus 3333 impacts large enough to cause tangent plane ejection still leave us with ~ 1/e of the mass of the atmosphere still in place: ~ 35 bars.

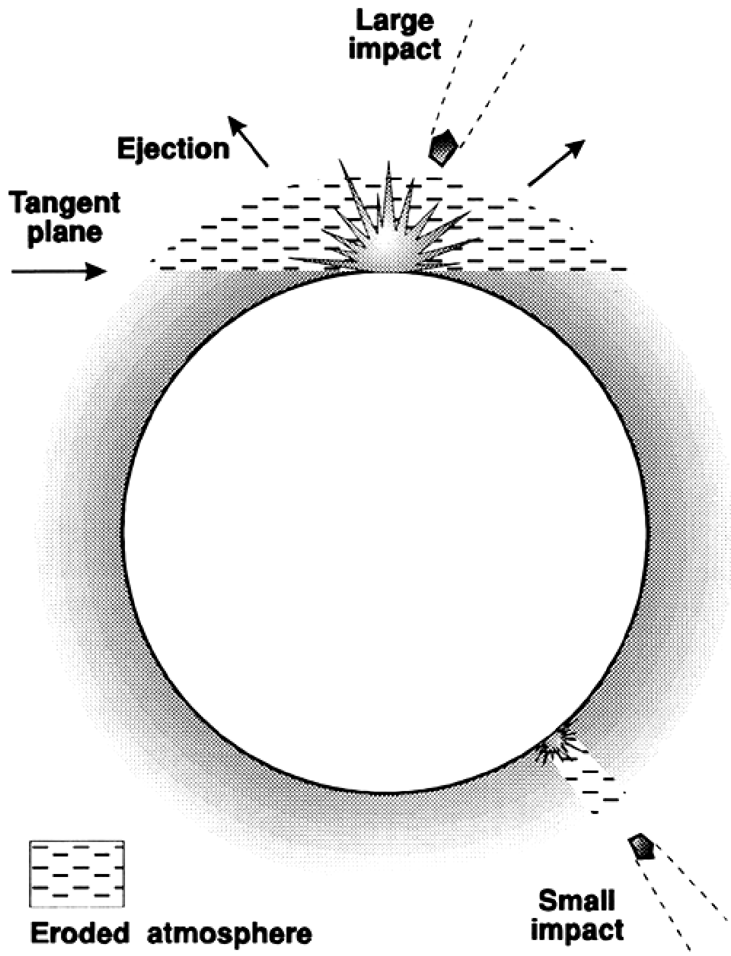

Figure 7.5 *Impact erosion of a planetary atmosphere. Sufficiently energetic events (impactors above a certain mass and hitting at > twice the planet's escape velocity) can eject all the gas above a plane tangent to ground zero. Lesser events cause much less atmosphere to be lost, no more than a plug of gas equivalent to that traversed by the projectile.*

There is nothing like this number of large asteroids available in the Solar System and using what there are would be wasteful. Impact erosion as applied to Venus is therefore an impracticable and inefficient terraforming technique.

7.7 Freezing Out Carbon Dioxide

Seeing that the time taken to cool Venus is short compared to other terraforming operations, it has been suggested by Freeman Dyson [42] that cooling should come first in the order of events. In this case, the cutting off of sunlight precipitates the atmosphere *physically*, rather than chemically, into CO_2 seas and ice sheets. These might accumulate in low-lying "ocean basins," allowing portions of the planetary surface to be selectively illuminated and inhabited. The much greater task of disposing of the CO_2 in a permanent fashion is therefore put off until some later date. A detailed scenario of terraforming Venus that commences with the freezing of the atmosphere has been proposed by Paul Birch [32] and we review some aspects of it here.

The present Venusian atmosphere is much easier to cool than Fogg's steam atmosphere because of the lower heat capacity of CO_2 and the fact that it is likely to radiate at slightly higher temperatures. With a heat capacity of $H_v \approx 9.3\times10^8$J/K/m^2 and assuming that the planet radiates at its current $T_{eff} \approx 229$ K, then Equation 7.5 predicts an initial cooling rate of ~ 5 K/yr. A period of just ~ 100 years is therefore indicated to reach Earth like temperatures. Of course, the situation is more complex than this since we wish to first liquefy and then solidify almost all of the carbon dioxide, requiring the loss to space of ~ 5.6×10^{11} J/m^2 of latent heat of vaporization and ~ 7.5×10^{10} J/m^2 of latent heat of fusion. This entails therefore having to freeze Venus down to very low temperatures and first covering the ices before warming the planet up again to comfortable temperatures. The results of Birch's modelling of this process are given in Table 7.7: showing the fall in temperature, partitioning of CO_2 between atmosphere, oceans and ice sheets and the time taken for each of five stages into which the process can be subdivided.

TABLE 7.7 COOLING AND CONDENSATION OF THE VENUSIAN ATMOSPHERE

Stage	Surface temperature (°C)	Surface pressure in bars of:			Time (years)
		Atmosphere	CO_2 oceans	CO_2 ice	
1. †	457 → 31	95	0	0	58
2.	31	95 → 76	0 → 19	0	27
3.	31 → -56	76 → 7	19 → 88	0	94
4. ‡	-56	7	88 → 0	0 → 88	17
5. §	-56 → -81	7 → 2.8 ¶	0	88 → 92	9
					200

† T_{eff} = 230 K.
‡ T_{eff} = 217 K
§ T_{eff} = 205 K
¶ ≡ 2 bars N_2; 0.8 bar CO_2.
Model according to Birch [32].

In Stage 1, the atmosphere cools over ~ 58 years to the critical temperature of CO_2 at 31 °C. At this point (Stage 2), it starts to rain liquid CO_2 and will do this for ~ 27 years at constant temperature until the atmospheric pressure falls to the critical pressure of CO_2 (the saturation vapour pressure at the critical temperature). Now (Stage 3), both pressure and temperature can fall, the rain continuing, accumulating ~ 88 bars-worth of liquid CO_2 in oceans which will flow to low-lying areas. This continues for ~ 94 years until the temperature falls to the triple point of CO_2 (-56 °C), whereupon the oceans start to freeze (Stage 4). Solidification takes ~ 17 years, followed by ~ 9 years for the precipitation of the last few bars of carbon dioxide as snow. This blanketing of solid CO_2 is not desirable on the Venusian uplands and so Birch proposes selectively illuminating these areas during this latter stage so that any snow that should settle will be sublimed and re-condensed on the lowlands. The entire freezing out process therefore takes just ~ 200 years and is not significantly affected by heat from underground as, over this timescale, the surface is effectively insulated from the higher temperatures below by a ~ 30 m layer of cooled rock. However, before considering what follows from here, we examine Birch's design for the terraforming tool implementing the cooling — an integrated space-based parasol/soletta system.

As was noted above, a parasol positioned at the L1 point needs to be a little over double the diameter of Venus to shade the entire planet. However, if the structure is fashioned as a flat disk, normal to the Sun's rays, it would receive a substantial photon thrust that would entail it either being balanced closer to the Sun (and hence made even larger in size) or ballasted with extra mass. Birch's solution [32] was to propose a more complex compound parasol/mirror design, the overall plan of which is illustrated in Fig. 7.6**a**. It is closely allied to the reflecting mega structure Birch proposed for Mars (see Section 6.2.3) consisting of a sunshade-parasol positioned between the planet and the Sun, being actively supported by light pressure from a polar orbiting, sun-synchronous, annular support mirror the other side of Venus. Sunlight pushes the support mirror about 30° behind the planet and by varying the balance of light pressure on the structure, sufficient torque can be exerted so that it precesses once per Venusian year, hence maintaining its facing with respect to the Sun. Light from the support mirror strikes the Venus-facing side of the parasol's inner cone (see Fig. 7.6**c**) which acts as a corner cube reflector, reversing the light and exerting a thrust which balances the parasol at just 250,000 km above the planet (a quarter of the distance to L1). The light that impinges on the edge of the cone however is only reflected once and is lost to the side. This actually makes the parasol stable: for should it move away from Venus, more of the support mirror's light is lost, reducing the photon thrust and allowing gravity to pull it back towards the planet; should it move towards Venus, then more of the support mirror's light is reversed, resulting in an increased thrust and a net force outwards. Similar considerations apply which stabilize the parasol against lateral or tilting motions.

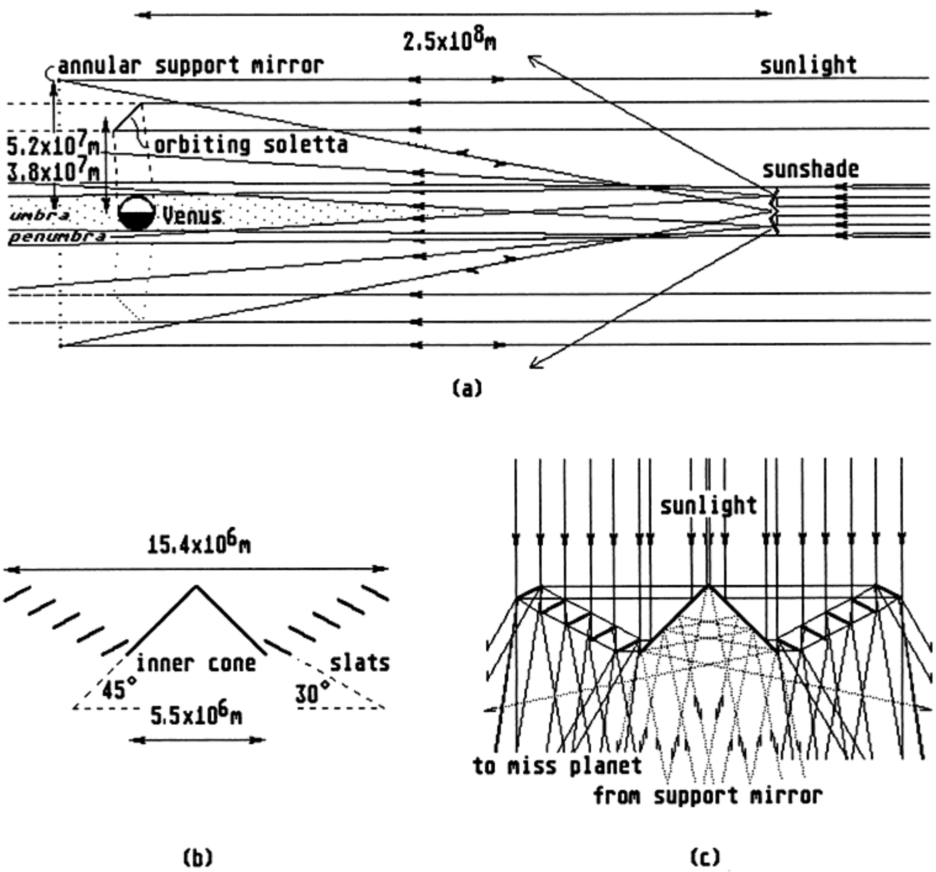

Figure 7.6 *Reflecting megastructure designed by Birch in order to shade Venus and provide an artificial 24-hour diurnal cycle. a: Overall assembly; b: parasol / sunshield structure; c: light paths through parasol / sunshield. See discussion in text. (Reproduced with permission from Ref. [32].)*

Because it is closer to Venus, Birch's parasol needs only to be ~ 1.27 the diameter of the planet to shade it fully. Its principal functional elements are a series of annular slats arranged *en echelon* and tilted at about 30^o (see Figures 7.6**b&c**); sunlight striking a slat is reflected to the next slat outwards where it is reflected a second time, almost along its original path. Alternate slats are however angled at ± 1^o to the nominal 30^o which results in light that passes through the parasol being deflected to either side by 4^o — sufficient to clear Venus. The photon thrust from this deflection is therefore very small and is one of the factors in the system's design that allows the parasol to be both reduced in weight and positioned closer to the planet. Since Birch assumes the use of hyper-thin 0.3 g/m^2 solar sail material, the total mass of the entire system, support mirror and parasol, amounts to just 76 million tonnes ≡ five years of terrestrial aluminium production.

Also shown in Fig. 7.6**a** is a solution to a problem that arises at the end of terraforming, namely that of providing Venus with an Earth like diurnal cycle. Birch proposes that this could be done by continuing to shade Venus behind the parasol and providing reflected sunlight with a polar orbiting soletta, maintained in a sun-synchronous orbit in the same manner as the annular support mirror. The soletta itself is a large structure orbiting at 37,000 km from Venus (after taking into account the influence of light pressure) and is tilted at about 45^o to deflect sunlight at right angles onto the planet. Intuitively, one might expect this angulation to be unstable and for the mirror to align itself along Venus' tidal field, but Birch suggests that this can be overcome by spinning the mirror about an axis through its centre and normal to the reflecting surface. If this is done once per orbit then each part of the mirror will be very nearly in a free orbit of its own. To compensate for the angle of the sunlight, an elliptically shaped mirror would normally be required to project a circular spot of light; however, because the mirror has to be spun, Birch proposes a larger circular soletta be used, 17,800 km across and with a filling factor of ~ 50% to cut down the intensity of sunlight to that of the Earth. Its estimated mass is just 4 million tonnes.

This method of illuminating Venus adequately provides a 24-hour day, but the path of the Sun through the sky, being at about 90^o to the ecliptic plane, would be most unearth like. The poles would be tropical, the Sun rising 3^o further East and passing overhead each day; whereas the equator would be partly tropical and partly arctic, a given location experiencing a cycle with extremes of the Sun either passing directly overhead or skirting all the way round the horizon. As Birch describes it: *"It is apparent that seasons on Venus will not be quite the same as on Earth. Unlike on Earth, where the Sun's track is confined to a band, on Venus it will at various times cover the whole sky. In general, a more uniform climate and gentler weather is expected."*

Following cooling, the 30% of Venus not covered by CO_2 ice starts to be colonized. The justification for this being that surface habitation can begin after a relatively short period of time, allowing the project some rapid return on investment. However, before sunlight is turned on again, the dry ice deposits must be covered and insulated. If only the highlands are illuminated, then it appears that an overlay of simple plastic sheeting would suffice, the manufacture of which could be done quite rapidly and inexpensively; (we already have the capacity to mass produce huge areas of such material; e.g. the population of the USA discards > 10^{10} m^2 of plastic wrapping each year [43]). However, since Birch aims to press on with the full settlement of the planet as rapidly as possible, importation of water ice from the Saturnian system is also initiated after cooling in order to provide Venus with a hydrosphere. Thus, water will start to collect in the lowlands too, *on top of the CO_2 glaciers*, to provide sunlit seas in which photosynthesis can occur, adding to the atmospheric oxygen generated by land-based ecosystems. Obviously, a much more sophisticated insulating cover is required to make such an arrangement stable even over the short term. Birch suggests an overlay of linked hollow blocks made from foamed rock would suffice, but this could prove an expensive and troublesome solution. It would be difficult to prevent extensive leaks of CO_2 occurring from the huge area that has to be managed, especially when much of it is hidden under water. Large masses of CO_2 ice could be vaporized by magmatic activity, quantities per event that would be small on a global scale, but disastrous locally as evidenced by the cloud of CO_2 produced in the Lake Nyos disaster in the Cameroons which suffocated a large number of villagers [44].

Water importation is done by releasing the icy moon *Enceladus* from orbit about Saturn (see Plate 7.9) by a combination of thrusting with a solar-powered steam rocket and gravitational assist manoeuvres with other satellites (a ΔV of 0.63 km/s is needed to initiate the process).

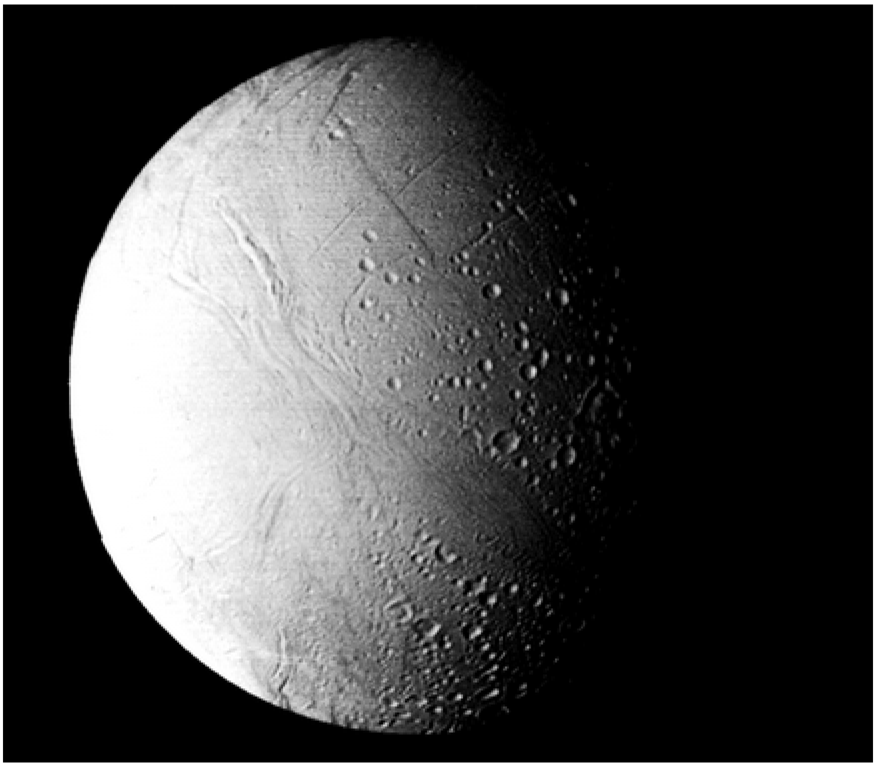

Plate 7.9 *Venusian seas of ~ 140 m mean depth might be provided from the icy substance of Enceladus, a 500 km diameter satellite of Saturn. Enceladus however is a fascinating world in its own right, in particular because of the mysterious flow marks on its surface. Whilst one can speculate over its sacrifice at a time when civilization develops the capability to move such masses across the solar system, could the destruction of one entire world in order to bring life to another be adequately justified? (Photo courtesy of NASA.)*

As Enceladus proceeds towards the inner solar system, it is first divided into two halves which pass over opposite poles of Venus into solar orbits like that of the planet, but inclined out of the ecliptic. They will return to the vicinity of Venus every 112 days (half a Venusian year) and if the sections are broken up into smaller chunks, sequential collisions between pairs of objects can be arranged so as to best dissipate their energy and angular momentum. The water then free falls onto the planet after each event (see Fig. 7.7), the total mass of the moon accumulating to a mean global depth of ~ 140 m. Whilst this is a feasible way of rapidly importing large quantities of water, Birch has to adopt some elaborate solutions for protecting the seas, ice sheets and planet-dwelling population below from the heat flashes of the collisions and the hot rain that follows. Life on Birch's Venus at this stage therefore might be at best inconvenient and at worst rather short!

Ultimately, heat leaking out of the crust will start to melt and destabilize the CO_2 ice, which will then either have to be refrigerated or exported from Venus. The former option is so inelegant as not to be any kind of long-term solution at all, whereas the latter returns us to the need to expend a similar magnitude of energy as consumed at the *beginning* of other scenarios (in this case ~ 2.7×10^{28} J/ε). The difference with Birch's concept is that it concentrates on establishing human settlements on the surface after some comparatively simple planetary engineering, leaving the bulk of the work until *later*. Birch believes that the massive effort that would accompany the export of a solidified Venusian atmosphere is not necessarily incompatible with an inhabited surface — although one might have doubts in this regard. When terraforming involves have to "do some violence" to a planet, the economic benefits of establishing a human population before the job is done might be outweighed by the expense of protecting them.

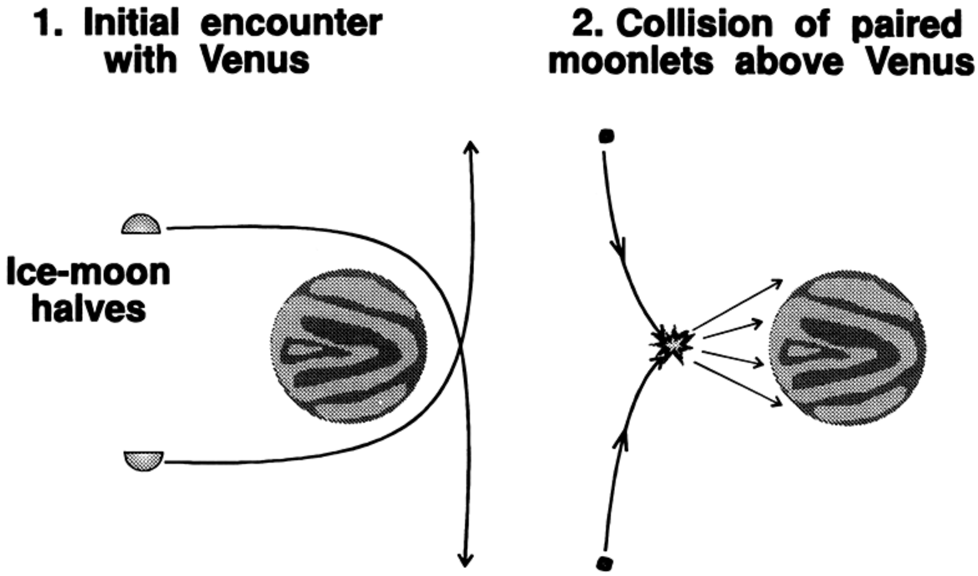

***Figure** 7.7 Mitigation of the effects of ice fall onto Venus. 1) Two halves of Enceladus diverted out of the ecliptic plane. 2) Paired moonlets colliding above Venus every half year; most kinetic energy and angular momentum is dissipated above the planet which captures most of the mass (Modified after Ref. [32].)*

Thus, if the freezing of the Venusian atmosphere is chosen as an initial step in terraforming — because of its ease and rapidity as a terraforming technique — then it may be better to follow this immediately with the necessary massive exchange of volatiles (92 bars CO_2 out, 12 bars of water in) and only then, when the environment is peaceful and safe, to make homes on Venus and to sow it with life.

7.8 Disposal of CO_2 by Chemical Weathering

All the scenarios described above have dealt with the Venusian atmosphere either by precipitating it in some form (carbon, carbonate or solid CO_2) *on top of* the present planetary surface, or by removing it from the planet altogether. One other potential method however, which is more in keeping with the Earth like aims inherent in terraforming, is to sequester Venus' carbon dioxide in the same reservoir where it resides on the Earth — the crust. The Earth is thought to have a similar CO_2 inventory to Venus (≡ 60 bars, according to one commonly cited estimate [45]) but instead of the bulk of it being in gaseous form, it exists as carbonate rocks — the product of the chemical weathering of silicates under aqueous conditions (see Section 2.7.3). Carbonate minerals must also exist on Venus in equilibrium with the atmosphere, but since the surface is already so hot, they can only be stable against thermal decomposition to shallow depths. However, the example of the Earth suggests that if conditions on Venus could be changed so as to promote aqueous chemical weathering to a significant depth then ample silicates are available to absorb all of the CO_2 within the present atmosphere. Thus, rather than chemically or physically precipitating CO_2, such a procedure would involve *chemically absorbing* carbon dioxide into the body of the planet.

The two major cations responsible for binding to carbonate are Mg^{2+} and Ca^{2+} and so the following generic weathering reaction is needed:

$$CaMgSi_2O_6 + 2\,CO_2 \xrightarrow{H_2O} CaCO_3 + MgCO_3 + 2\,SiO_2 \tag{7.9}$$

One can make a rough estimate of what depth of Venusian crust is required to soak up all the CO_2 by referring to the chemical analyses of surface material provided by the Venera 13 and 14 landers [46]. These suggest a rock containing ~ 10 wt% MgO and ~ 9 wt% CaO (averaging both sets of data); 1 m^3 of such material at a density of 2900 kg/m^3 therefore contains ~ 7250 moles of MgO and ~ 4660 moles of CaO and since one mole of oxide removes 1 mole of CO_2, its total absorption capacity, given total reaction of its constituents is ~ 11910 mol CO_2/m^3. Every square metre of Venusian surface must draw down an average of 2.5×10^7 moles of CO_2 and so the depth to which the crust must be weathered is $2.5\times10^7 / 11910 \approx 2100$ m.

The iron(II) cation can also form a carbonate mineral (siderite ≡ $FeCO_3$) but this is less common on the Earth because Fe^{2+} can readily be oxidised to the insoluble Fe^{3+}. On Venus however, the oxygenation of the environment might only occur at the end of terraforming and so it might be possible to absorb additional CO_2 by the formation of siderite. Venera data suggests an FeO content of Venusian basalt of ~ 9 wt% ≡ 3625 mol/m^3. This reduces the thickness of crust needing to be weathered down to ~ 1.6 km.

This depth appears insignificant compared to the planetary radius and is well within the topographic range of large-scale surface features (see Fig. 7.2). One might suppose therefore that by merely lowering the Venusian surface temperature into the stability range of liquid water, carbon dioxide might readily be taken up by crustal silicates. This possibility was first raised by French aerospace engineer Christian Marchal [47] who argued on thermodynamic grounds that cooling Venus would naturally result in the planet approaching a new chemical equilibrium like the Earth's, where carbonates dominate over carbon dioxide. The methods he proposed to cool the planet are sketched in Fig. 7.8; they include a dust cloud suspended at a balance point just beyond the Sun-Venus L1 point, which obscures some fraction of incoming sunlight, and an inclined ring system orbiting Venus itself. He envisaged both of them being created by moving a suitable sized asteroid into the appropriate position and then pulverising it to rubble. The difficulty with the former of these ideas is that the L1 dust cloud will not be stable over the long term and will require replenishment. The inclined ring might not be stable either as rings tend to collapse to a planet's equatorial plane due to torques exerted by the planet's oblate shape; substantial shading therefore only occurs if the planet has a significant obliquity — not the case for Venus. However, because of its slow spin, Venus is very near spherical and so an inclined ring might only collapse very slowly. Detailed modelling is obviously in order to evaluate this option; in neither case however do rings or dust clouds appear as effective, precise and controllable planetary engineering tools as parasols.

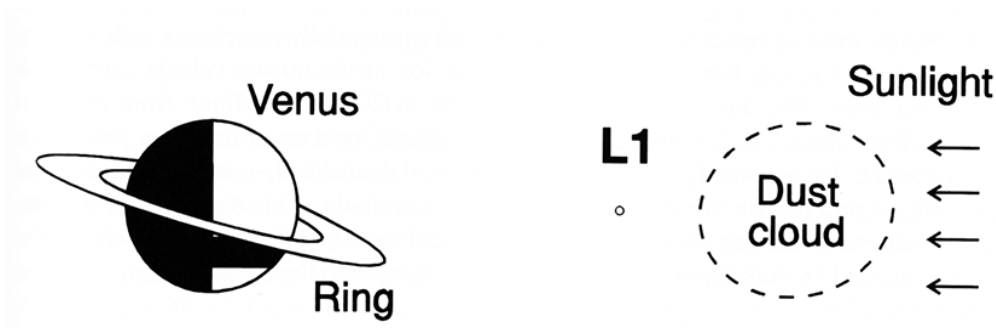

Figure 7.8 *Techniques of shading Venus proposed by Marchal: a dust cloud, partially obscuring the Sun, suspended at a balance point sunwards of L1; and an inclined orbiting ring. (Modified after Ref. [47].)*

A greater problem with Marchal's scheme is that weathering rates in typical terrestrial conditions are very slow and would take far too long to mop up 92 bars of CO_2. As Gillett has stated [38]: *"Reaction on such a scale has occurred on Earth due to long-term crustal churning by plate tectonics, but on Venus we have neither the mechanism nor the time."* Whilst no modelling of aqueous chemical weathering for Venus has been done, an analogous model for a warm, CO_2-rich, early Mars gives some indication of the timescale involved. Taking into account such factors as the partial pressure of CO_2, temperature, the cation content of rocks, the rate of evaporation and precipitation, the land-sea ratio and physical weathering, Pollack *et al.* [48] estimated a CO_2 draw-down rate of ~ 1 bar/10^7 years. Roughly extrapolating their equations to hotter moist greenhouse-type conditions on Venus, one finds that chemical weathering occurs at a much faster rate, but is ultimately limited by the rate at which physical weathering can expose fresh rock, giving perhaps only an order of magnitude improvement over the above figure. What limits the process even more is that Marchal omitted to advocate importing additional water to facilitate the process. The present ~ 5 cm of precipitable water in the Venusian atmosphere is wholly inadequate.

An amendment of this unpromising scenario has been devised by Alexander Smith [49]. He proposes bombarding Venus with several hundred "impact vehicles" fabricated from outer Solar System material and made from 75% rock and 25% ice. The total mass of these objects amounts to a very large 4×10^{21} kg, equivalent to the substance of a 1450 km diameter satellite at a mean density of 2500 kg/m^3. (The Uranian moon Oberon most closely matches this size.) Straight afterwards, Venus is shaded behind an L1 parasol and its sunlight cut off so that water can condense at the surface. The purpose of this bombardment is not to strip Venus' atmosphere (although significant impact erosion might occur) but to greatly enhance the rate of CO_2 sequestration into the crust. There are two improvements over Marchal's basic idea:

1. Venus is provided with ~ 2200 m of water, equivalent to 70% of the mass of Earth's oceans. This is an ample amount to hydrate minerals, provide Venus with a water table and wide oceans, and to allow for losses to space during terraforming.
2. Venus' crust is brecciated to great depths and substantially resurfaced with broken-up impact ejecta, the condensed silicate fraction of the impact vehicles and fresh lava flows. The surface area of rock accessible to CO_2-bearing fluids from shattered surface strata, via fractures down to hydrothermal systems at depth, is greatly increased. The proposed effect therefore is to artificially — and dramatically — increase the physical weathering rate on Venus by many orders of magnitude. This removes physical restrictions on the rate of chemical weathering and carbonate formation, which itself is optimised by controlling the planetary temperature with the L1 parasol.

The Terraforming of Venus

An additional effect of the impacts, which are targeted to strike at low angles, is to increase the spin angular momentum of Venus and hence its rotation rate. This question of spinning up Venus is however examined in Section 7.9 — suffice it to mention here that Smith estimated that his series of engineered collisions might leave the planet with a 60 - 72 hour day.

Smith was well aware that moving 4×10^{21} kg of material half way across the Solar System does not represent a near-term project. He therefore painted this picture of the economic background required before a feat on the scale of terraforming Venus might be attempted [49]: *"Before Venus can be converted to an Earth like state, permanent settlements will exist on the Moon, Mars and smaller bodies of the Solar System... A large population will live in space in artificial habitats, with space-based industry constructing habitats, space-craft and power stations... There will be some purely space-based trade which will be expanding... Terra-forming schemes which make use of iron asteroids, stony bodies or comets to alter Venus are not likely to be acceptable in a society which will see them as wasteful."*

This last point reflects the distaste some may feel about sacrificing smaller worlds, involving the loss of both their useful materials and bodily identity, for the purpose of terraforming a larger planet. Smith however sidesteps this by proposing instead that Venus be bombarded by no more than the industrial waste discarded over several centuries of mineral extraction in the outer Solar System. This would include ice processed to remove its deuterium content and waste oxides and silicates left over from the mining of rocky objects: *"In the inner Solar System the amount of waste will be small in proportion to the saleable material produced, almost anything will have some constructional value. In the outer Solar System transport costs and times prevent easy sale of by-products and the amount of waste remaining may amount to only half the material processed."*

Thus, according to Smith's scenario of space development, large stockpiles of unwanted material accumulate in the outer Solar System that eventually attain proportions relevant to terraforming. However the sheer quantity involved conjures a more eloquent description of Smith's future civilization than his verbal portrayal. If one calculates the fusion energy available from the deuterium taken from his 10^{21} kg of waste ice, it comes to a titanic ~ 9.3×10^{30} J, equivalent to ~ 6.7 hours of the Sun's total radiant output, ~ 1 million years of Venusian sunlight, or ~ 29 billion years of the primary power production of present terrestrial civilization! A need for this supply of energy suggests a civilization actively seeking the means to undertake projects on the grandest scale. Whilst the irony of gaining a new habitable planet for the price of a garbage disposal project is very appealing, one is left wondering over the original use of such a huge quantity of material.

Smith envisages this mass being divided into 4 flights of 200 fabricated impact vehicles; each individual impactor massing 5×10^{18} kg, being composed of a 3:1 rock/ice mix, with a mean density of 2500 kg/m^3 and hence a diameter of ~ 156 km. Furthermore, in order to maximise their collision velocity and thus their effectiveness at spinning up Venus, he suggests that the vehicles be placed in an eccentric retrograde orbit that meets an oncoming Venus at perihelion. A collision with a 156 km object, especially at the 100 km/s velocity Smith estimates (possibly a little high) is an extremely energetic event, releasing ~ 2.5×10^{28} J. If we refer back to Equation 6.9 and adopt $f_{conv} \approx 1.03$ for cratering on Venus, one such impact excavates an enormous basin ~ 4540 km in diameter: 2 - 3 times the size of observed major impact basins such as Hellas on Mars and the Mare Imbrium on the Moon and equivalent to ~ 3.5% of the surface area of the planet. However, we must bear in mind that each impact event in the scenario consists of the simultaneous arrival of 200 such objects, prompting Smith's remark: *"There will not have been, in that part of the history of the Solar System accessible for study, more than a handful of events comparable in effect to the arrival of impact vehicles."* This is almost certainly an understatement.

Suitably spread out, such impacts could easily excavate and overturn the entire planetary surface. However, because of their function to increase the rotation rate of Venus, Smith proposed that impacts are deliberately ordered in a pattern of five ranks, spaced several hundred kilometres apart contacting the planet along lines of longitude between latitudes of 45°N - 45°S. This means that impact effects overlap, excavating a trench roughly one eighth of a Venusian circumference wide and three eighths long. After the arrival of all four flights, ~ 60% of the Venusian surface has been directly excavated and the entire planet resurfaced with crust and mantle-derived ejecta and ~ 2200 m of rock and the same thickness of water from the impact vehicles themselves.

An additional effect not considered in the model is that a bombardment of this scale is likely to cause substantial impact erosion, although a reliable estimation of this effect is not possible since no modelling of such a large number of simultaneous hypervelocity impacts has been done. A crude upper limit (assuming tangent plane ejection for each impact vehicle) gives a loss of $95 - 95(1 - 3\times10^{-4})^{800} \approx 20$ bars; if water is lost in the same proportion, then ~ 470 m of imported water could be blown straight back into space — more than the entire inventory brought to Venus in some other scenarios. However, this magnitude of loss is probably a substantial overestimate as tangent planes over individual impactors will overlap.

Smith's summary of how he projects terraforming proceeding after the impact "Inferno" is shown in Table 7.8. The data represent a qualitative assessment of the subsequent evolution of Venus, rather than one based on quantitative modelling. The crucial uncertainty on which the viability of the entire scenario depends is whether the bulk of Venusian CO_2 is absorbed as rapidly as is suggested (~ 1000 years). If this is correct then more regular planetary engineering techniques (such as photosynthesis) can be applied to finish off terraforming and perfect the final atmospheric composition. However if the timescale is too optimistic by much more than an order of magnitude then the mechanism is no more attractive than other proposals for removing the atmosphere.

TABLE 7.8 TERRAFORMING OF VENUS — SUMMARY OF STAGES ACCORDING TO THE MODEL OF SMITH

	Stage						
	Impact	**Prelife**	**First Life**	**Forest**	**First Habitable**	**Mature Habitable**	**Long Term**
Temperature	Inferno	200 °C	40°C	20°C	20°C	20°C	20°C
CO_2 at start	90 bars	30 bars	5 bars	< 1 bar	Trace	Trace	Trace
Oxygen	None	None	Small	Rising	80 mbar	200 mbar	200 mbar
Oceans	None	Forming	Present	Present	Present	Present	Present
Plants	None	None	Single celled	Many	Many	Many	Many
Animals	None	None	None	Some	Many	Many	Many
Humans	None	None	None	Visitors	Resident	Resident	Resident
Duration	< 10 days	> 500 years	> 1000 years	> 5000 years	> 10000 years	> 10000 years	Indefinite
Time elapsed at start	Datum	10 days	1000 years	5000 years	15000 years	30000 years	50000 years
Ecology	None	None	Directed	Maintained	Maintained	Maintained	Stable?
Terraformed	No	No	No	Partially	Partially	Fully	Fully

Taken from Ref [49].

The Terraforming of Venus

Smith suggests that up to two thirds of Venusian carbon dioxide might be removed in the immediate aftermath of the impacts themselves by the entrainment of gas in the vast quantities of finely divided ejecta falling back to the surface. Rock vapour that condenses in the upper atmosphere, where it can cool efficiently by radiating to space, could absorb volatiles directly. Carbon dioxide, steam and mobilized rock at the surface would mix to form fluidised beds with large internal areas available for chemical reaction. The intention therefore is to engulf large quantities of gas and simulate the final stages of the cooling of igneous bodies as studied on the Earth, where the expulsion of hot volatile fluids and their migration through surrounding porous country rock can result in rapid and extensive weathering. On Venus, Smith clearly raises the possibility of accomplishing this rate of chemical reaction on a planet-wide scale.

There must be little doubt that the injection of such a large quantity of energy and volatile material into the Venusian environment, along with the comminution of so much crust is bound to have some dramatic effect. However, whether it will be of the magnitude Smith suggests is open to question. The total energy dissipated on Venus by the impact events is $\sim 2\times10^{31}$ J $\equiv$ 4.1 MJ/kg of Venus, theoretically sufficient to vaporize the entire planet! Of course, not all this energy will be converted to heat within the body of Venus; so, assuming a total heat deposition and retention efficiency of ~ 0.08 [50] and a specific heat capacity for an iron-silicate mixture of 600 J/kg/K, then the mean temperature of the planet is raised by ~ 550 ^{o}C. Since Table 7.8 implies that the bombardment takes place over a short period of time, negligible surface cooling occurs between events and so the result would be the creation of a global magma ocean overlying a steam atmosphere at temperatures of > 1500 ^{o}C, (a regime similar to that proposed for the terrestrial planets during the terminal stages of accretion [51]). Carbonates are not stable at these temperatures and so little of the hoped-for CO_2 absorption would occur.

Rarely for any terraforming scenario therefore, that of Smith *overstates* the engineering needed. His proposed absorption mechanism however, might still work if many fewer impacts are used, at lower velocities and over a much longer timescale. In this case, the effect on the rotation rate of Venus will be much less, but we shatter the crust rather than melting it, creating rather than obliterating the large surface areas needed for enhanced chemical weathering. Even so, the amount of carbon dioxide absorbed in the aftermath of the bombardment may still be low. The lack of any stable liquid water and the high temperatures and shock pressures generated by impacts may inhibit carbonate formation and cause some devolatilization of existing carbonates.

Nevertheless, there remains an immense potential for chemical weathering on the resurfaced Venus when precipitation commences. At ~ 360 ^{o}C the ~ 187 bars of water vapour in the atmosphere will reach saturation and the "Big Rain" will begin. Hot water with dissolved CO_2 will start to percolate through the thick airfall sediments blanketing the Venusian surface. Such conditions are ideal for rapid chemical weathering and some sunlight might be let through the L1 parasol at this juncture to maintain high temperatures and pressures in order to maximise the reaction rate. The steep geothermal gradient would be expected to drive a strong groundwater circulation drawing down cool, carbonated, liquid from above and propelling it back upwards to the surface via hot springs, geysers and mud eruptions. This convective cooling of porous strata would permit the downward migration of the water table at a faster rate than a conductive thermal wave. Carbon dioxide-bearing water might saturate substantial thicknesses of sediment therefore and once bedrock is reached (at > 2 km down) will be able to percolate to greater depths via extensive fracture systems left behind from the bombardment. It does not seem implausible that under these conditions, which would occur globally, weathering rates several orders of magnitude more rapid than on Earth would be obtained. Smith's heuristic timescale to reduce pCO_2 to 5 bars is ~ 1000 years. This does not seem implausible, but only with detailed modelling based on experimental data relevant to the conditions under discussion will we be able to ascertain whether it is realistic.

Once the physical removal of rate of CO_2 begins to fall, the temperature of Venus can be lowered to permit the introduction of life (see Plate 7.10). From this point, terraforming follows a more conventional course, discussed in many previous contexts, where photosynthesis and organic carbon burial is used to dispose of carbon dioxide and generate oxygen. From Table 7.8, it appears that substantial net O_2 production in Smith's scheme begins with what he calls the “Forest Stage”, reaching 200 mbar at the “Mature Habitable Stage”. This is estimated to take ~ 25,000 years and, if 55% of Venusian sunlight is allowed through the parasol, represents a combined photosynthesis and carbon burial efficiency of ~ 0.012%. If the efficiency of NPP of the Venusian biosphere is the same as that of the Earth (~ 0.05%) then to achieve this net rate of oxygen build-up assumes that 24% of the biomass produced is buried or stored in some fashion. This is a very high fraction compared to the norm for Earth, however Smith does make the point that the erosion of masses of loose sediment off the immature Venusian landscape and the presence of wide and shallow seas will favour burial. However, in reality, it is likely that a period of artificial biomass sequestration will be required (as on Mars, see Fig. 6.10). A global programme of active control of the biosphere, which is optimised and managed as a planetary engineering tool to produce oxygen (such as described for Mars in Section 6.3.2.1), might substantially reduce the time taken to complete terraforming.

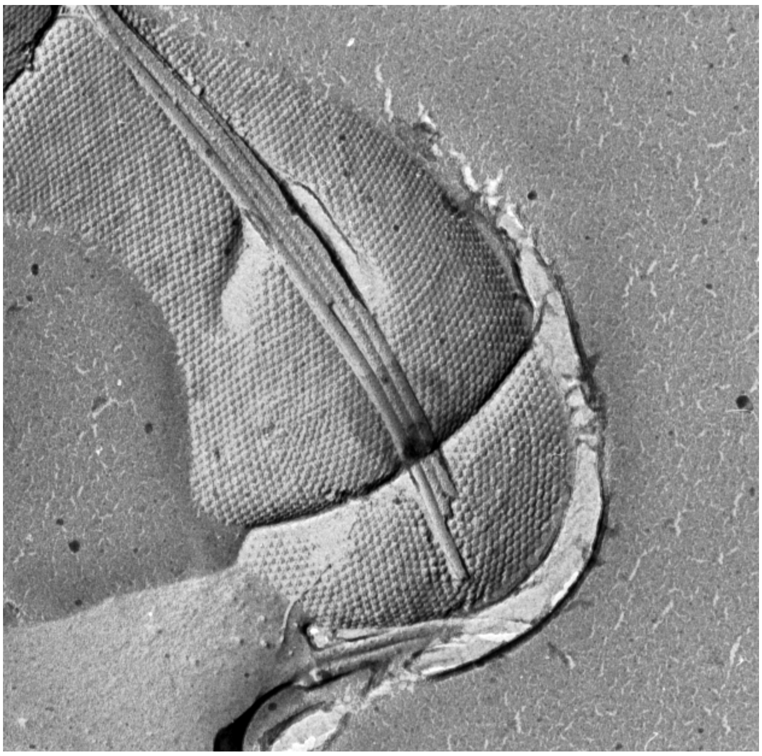

Plate 7.10 *Pyrodictium abyssi: mag: 57,000×, freeze etched, platinum shadowed. A thermophilic archaebacterium, lithotrophic (gaining energy from the metabolism of hydrogen and sulphur) and autotrophic (it can use CO_2 as a carbon source). Species of Pyrodictium might perhaps be the first organisms seeded on the cooling Venusian surface, as they can grow in the absence of light on inorganic chemicals. Volcanic hot springs at ~ 100 °C might host the first Venusian ecosystems. See also Plate 3.2. (Micrograph courtesy of Reinhard Rachel.)*

The Terraforming of Venus

As a final speculation, Smith considered how the style of Venusian geology might change over the long-term. In particular, he felt the escape of the heat deposited in the upper mantle by the bombardment would lead to some significant and beneficial outcomes: *"Where a mantle melt rises under a thick, comparatively cold Old Crust remnant it will undermine it. the ancient slab and its load of apron and airfall materials will be too heavy to remain supported by fluid, low density material, and the slab will probably be too rigid to break into smaller fragments. Instead it will rift and begin to sink... carry[ing] with it a load of some kilometres of partially carbonised rock, at temperatures which prevent it from dissociating until it is deep within the mantle."*

His long-range vision therefore involves the surface, blanketed and brecciated by the early terraformers, eventually being renewed over millions of years by tectonic and volcanic activity stimulated by those initial events. Whilst there is no certainty that crustal overturn would progress to an Earth like regime of plate tectonics, it may be possible to drive on Venus the kind of natural geochemical recycling that is lacking on Mars, but which is a life-sustaining feature of Earth.

7.9 The Problem of the Diurnal Cycle

Most thought experiments in Venusian terraforming have at least mentioned the potential problem posed by the planet's long solar day and some have discussed solutions (see Table 7.4). Sagan [7] passed over this in his original paper (the rotation rate was still uncertain in 1961) and Berry and Pournelle [28,29] speculated over a population of nomadic colonists migrating every two months between paired cities on opposite hemispheres. Oberg [30] tentatively proposed that an artificial 24-hour diurnal cycle might be provided by an arrangement of space-based parasols and mirrors — but this of course represents the sort of long-term technical fix the ecocentrist would oppose. A better solution would be to engineer an increase in the Venusian rotation rate, shortening the day so that it equals that of Earth. Gillett [34] however felt that, *"... it would be very difficult — i.e. expensive — to change and can probably be lived with."* The former of these statements is undoubtedly true, but the latter is open to question.

Intuitively it would seem that the temperature variation caused by 58 terrestrial days of sunlight followed by an equal duration of darkness would preclude the existence of all but the hardiest of organisms. Moreover, Venusian oceans, and even Gillett's briny seas may not be stable under the scorching heat of the long daytime. Another worry is that the slower rotation puts more of a demand on the atmosphere to transport heat between illuminated and dark hemispheres. Thus we might expect much more violent weather than on Earth. A clue to the magnitude of this effect can be obtained by calculating the fractional temperature rise in the atmosphere for a period of one solar day, assuming no heat lost to space [52]. The relevant expression is:

$$\frac{\Delta T}{T_{eff}} = \frac{S(1-A)gt_d}{4P_{atm}c_pT_{eff}} \qquad (7.10)$$

where A is the albedo, g is the gravity, t_d is the length of the solar day, P_{atm} is the surface atmospheric pressure, c_p is the specific heat capacity of the atmosphere and T_{eff} is the effective temperature.

Inserting into the equation values appropriate to the Earth, results in $\Delta T/T_{eff} \approx 0.80\%$ — the atmosphere has sufficient heat capacity to resist a large temperature change over the course of one day. For the present Venus we similarly find $\Delta T/T_{eff} \approx 0.72\%$ — the large heat capacity of the massive Venusian atmosphere cancels the effect of the long solar day. The general calm conditions at the surfaces of both planets, despite their very different parameters can thus be understood. However, if we look at the Venusian atmosphere above the 1 bar level, where most of the solar input is absorbed, and ignore the bulk of gas below, then the equation gives $\Delta T/T_{eff} \approx 68\%$. In this case, large temperature differences and hence vigorous heat transport between hemispheres is predicted and this manifests in reality as the rapid, 4-day, upper atmospheric circulation that has been observed [8].

If we model a terraformed Venus by the following parameters [24]: $A = 0.5$, $P_{atm} = 2.3\times10^5$ Pa (2.3 bars ≡ 2.1 bar N_2, 0.2 bar O_2), $T_{eff} = 276$ K, $c_p = 1000$ J/kg/K and $t_d = 10^7$ s (117 days), then Equation 7.6 gives $\Delta T/T_{eff} \approx 44\%$. This is close to the value calculated for the upper atmosphere of the present Venus and so we might reasonably conjure an image of the weather of the terraformed planet being analogous to lowering the present upper atmospheric circulation down to ground level. Hurricane-force gales might permanently blast the Venusian surface, the clouds of dirt lofted into these ever-present winds rendering the planet more like the pre-space age dust bowl model [2], rather than any second Earth.

This is not a certain conclusion, but it seems *unlikely* that the Venusian solar day can be lived with. We should therefore ask what the maximum tolerable length of day might be. If we take the terrestrial value of $\Delta T/T_{eff}$, then this would obtain on our nominal terraformed Venus with a solar day of ~ 47 hours. (This is because Venus has more gaseous nitrogen present than on Earth which, when left behind after terraforming, gives an atmosphere of over double the pressure). This might be raised by a further factor of 4 to $t_d \approx 8$ days if we accept Dole's criterion (see Table 3.4) which implies, assuming Earth like parameters, $\Delta T/T_{eff} \approx 3\%$. To implement such a change — a reduction in the real, or apparent, solar day from 117 days to < 8 days — requires planetary engineers to adopt space-based solutions, or the permanent answer of spinning up Venus. Establishing an *apparent* Earth like diurnal cycle with an extrinsic combination of mirrors and parasols has been most creatively studied by Paul Birch [32] and has already been described in Section 7.7. Here, we concentrate on proposals for reducing the duration of the *real* solar day by increasing the planet's rotation rate.

The moment of inertia of Venus is:

$$I_v \approx 0.33\, M_v R_v^2 \qquad (7.11)$$

where M_v and R_v are the mass and radius of Venus respectively, giving $I_v \approx 5.9\times10^{37}$ kg m^2. The angular velocity of the planet is at present a very slow $\omega_v \approx 3\times10^{-7}$ rad/s and so the magnitude of its rotational angular momentum is $L_v = I_v\omega_v \approx 1.8\times10^{31}$ kg m^2/s and its rotational kinetic energy is $E_v = ½\, I_v\omega_v^2 \approx 2.7\times10^{24}$ J.

When considering improving on these parameters, it makes most sense to further increase the spin rate of Venus in the *retrograde* sense, since the solar day (t_d) is always shorter than the sidereal rotation period (t_s). The relationship is:

$$t_d = (t_s^{-1} + T^{-1})^{-1} \qquad (7.12)$$

where T is the sidereal orbital period. The ratio t_d/t_s is smallest for long values of t_s; for instance $t_d/t_s \approx 0.5$ for the present Venusian parameters, however if the planet is to be given a 24 hour solar day then $t_d/t_s \approx 1$ and the benefit expressed by Equation 7.12 all but vanishes.

The Terraforming of Venus

The parameters of Venus at increased retrograde rotation rates are shown in Table 7.9 and give a numerical impression of the scale of the problem. It is seen that comparatively “minor” additions of angular momentum and energy can halve or quarter the duration of the solar day, but for it to be shortened into the preferred range of $t_d \leq 8$ days determined above, we must provide $\Delta L_v > 5\times10^{32}$ kg m^2/s and $\Delta E_v > 2.3\times10^{27}$ J.

TABLE 7.9 PARAMETERS OF VENUS AT DIFFERENT ROTATION RATES

Retrograde sidereal rotation period (days)	Duration of solar day (days)	Angular velocity (rad/s)	Rotational angular momentum (kg m^2/s)	Rotational kinetic energy (J)
243	117	3.0(-7)	1.8(31)	2.7(24)
81.9	60	8.9(-7)	5.3(31)	2.3(25)
34.6	30	2.1(-6)	1.2(32)	1.3(26)
8.3	8	8.8(-6)	5.2(32)	2.3(27)
4.1	4	1.8(-5)	1.1(33)	9.6(27)
1	1	7.3(-5)	4.3(33)	1.6(29)

Moment of inertia of Venus $\approx 5.9\text{x}10^{37}$ kg m^2
Note: $m(n) \equiv m\times10^n$

7.9.1 Tangential Collisions

Much the simplest concept for spinning up a planet involves engineering one or more low angle, inelastic, collisions with an extrinsic mass; ideally these should occur at and parallel to the equator to apply the optimum torque and the colliding mass should coalesce completely with the planet so as best to transfer its angular momentum. The first assessment of the application of this technique to Venus was done by Saul Adelman [40] who posed the problem so: *"If a sufficiently large object moving in the correct direction hits Venus, then the rotation rate will increase in accord to the conservation of angular momentum. But if the object is too large or moving to fast, then the planet might shatter. If it is too small or moving too slowly, it will be ineffective in changing the speed of rotation. So we want to use an object which is small by planetary standards, yet large enough to do the job."*

Adelman therefore proposed asteroids as terraforming tools — specifically large (175 km radius) iron asteroids which, due to their high density, pack a large mass into a small volume. Additionally, he proposed that impactors be directed towards Venus in retrograde orbits to maximise the relative collision velocity (see Plate 7.11). Objects directed from the asteroid belt or beyond, into an elliptical orbit that intersects the orbit of Venus at perihelion will be travelling at a velocity of between 44 - 49 km/s; since Venus will be moving in the opposite direction at 35 km/s then an impact velocity of ~ 80 - 85 km/s is expected. An illustration of Adelman's scheme is given in Fig. 7.9: the most unlikely part of it being that he imagines diverting asteroids at 2.8 AU from a circular prograde orbit into a retrograde elliptical one with a single 50 day impulse that not only stops the object in its tracks, but reverses its motion. The antimatter-powered rocket engines needed to accomplish this have to generate a gargantuan ~ 2.7×10^{11} TW (~ 1/1400 the entire solar luminosity) and are thus at best a somewhat gross solution to the problem of moving asteroids and at worst (and most probably) would vaporize themselves as soon as they were switched on! A more subtle and workable approach would be to thrust over much longer periods and use gravity assists from major planets in order to fashion the desired final collision orbit [32].

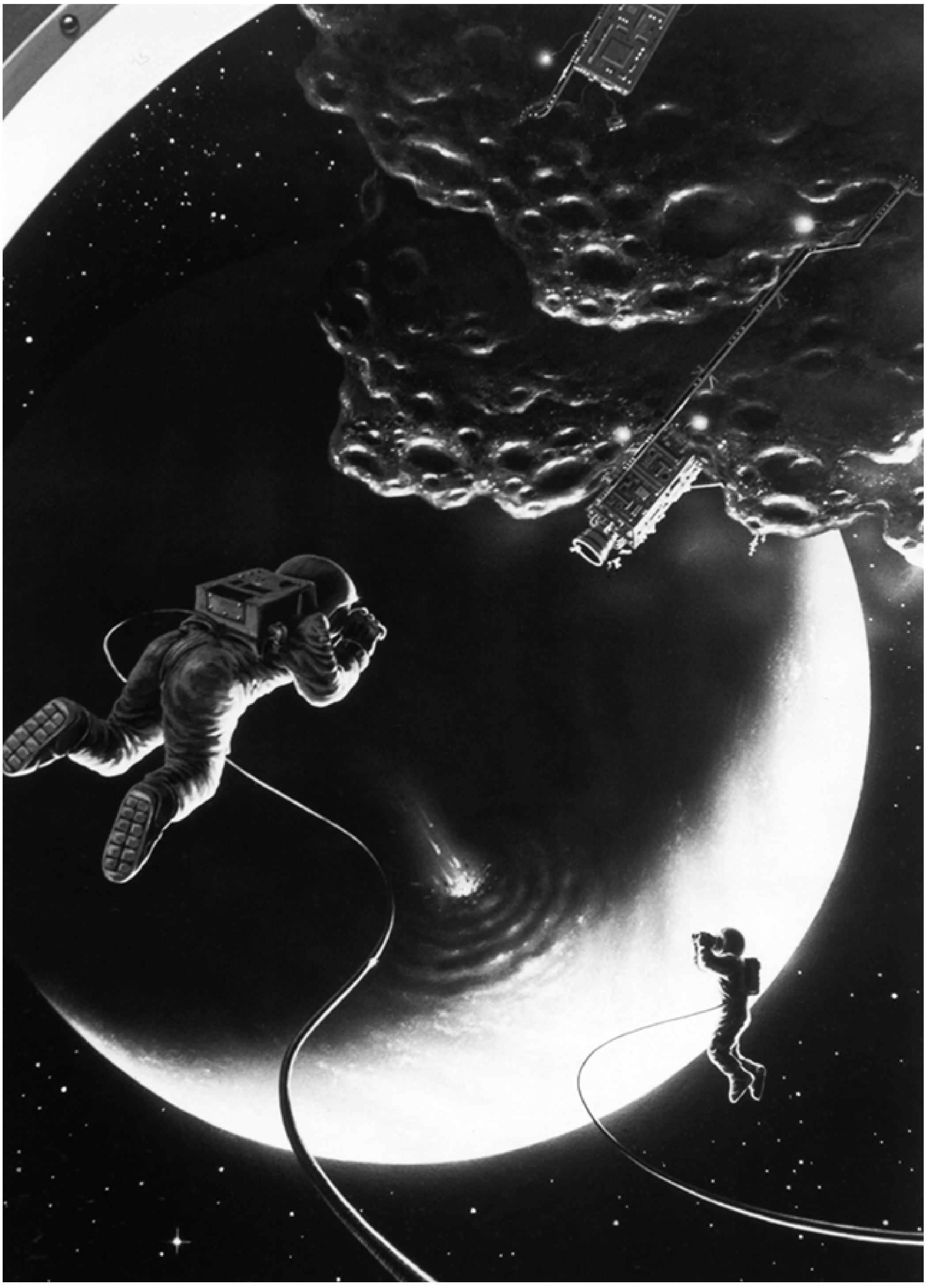

Plate 7.11 *If Venus is ever terraformed, then it will be subject to engineered impacts, either to import volatiles, spin-up the planet, or both. (Artist: David Hardy.)*

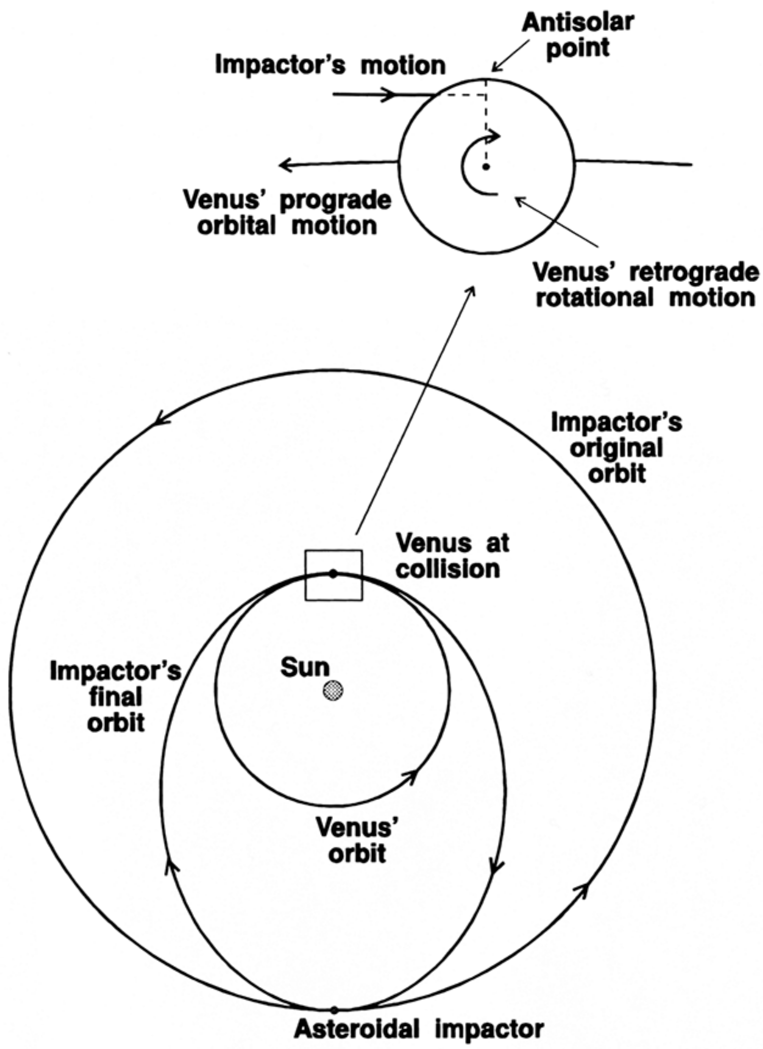

Figure 7.9 *Spin-up of Venus by collision with asteroids according to Adelman. Impactors are diverted into retrograde orbits to collide with Venus head-on at perihelion. The optimum impact trajectory is near-tangential to the equator and slightly in advance of the antisolar point. (modified after Ref. [40].)*

Given that collisions with large retrograde orbiting projectiles are possible, Fig. 7.9 shows that the optimum impact point will be tangential to Venus along the line of the equator at the antisolar point. However, since the impactor is not a point object and since the mass of planet beneath it must be such to ensure it does not burst through the thickness in its path, the collision must occur at some perpendicular distance between the impactor's path and the planet's spin axis that is less than the Venusian radius. Adelman chose this distance (R_i) to be 5800 km, 96% of the Venusian radius, allowing for a path length through the body of the planet of 10 times his nominal asteroids' diameter. Smith adopted an average R_i = 5000 km instead, to reflect the fact that some of his "impact vehicles" were hitting Venus at mid-latitudes.

In the limiting case of where we wish merely to alter the rotation rate of Venus and not affect the obliquity, the angular momentum vector of the impactor is aligned with the rotational angular momentum vector of the planet and the magnitudes of the two simply add so that we find:

$$I_v\omega_v' = I_v\omega_v + M_i v_i R_i \tag{7.13}$$

where ω_v' is the angular velocity of Venus after the collision, ω_v is the angular velocity before, M_i and v_i are the mass and impact velocities of the projectile respectively and other parameters are as defined above.

Now, Adelman's assumed population of 175 km radius metallic asteroids does not exist and so we repeat the calculations using the known inventory of such objects [37] listed in Table 7.5. Starting with asteroid 16 Psyche we estimate $M_i = 5.27\times10^{19}$ kg, $v_i = 80$ km/s and $R_i = 5800$ km: this gives $I_v\omega_v' \approx 4.25\times10^{31}$ kg m^2/s, $\omega_v' \approx 7.2\times10^{-7}$ rad/s, amounting to a sidereal rotation period of 101 days and a solar day of 70 days. The effect therefore is quite large, t_d being shortened to 60% of its former duration. If the next colliding object is 22 Kalliope, then we find $t_s \approx 84$ days and $t_d \approx 61$ days; following this with 21 Lutetia gives $t_s \approx 80$ days and $t_d \approx 59$ days. These are the three largest iron asteroids known and already it can be seen that their expenditure is providing diminishing returns; using up the other three objects in Table 7.5 improves the picture to just $t_s \approx 74$ days and $t_d \approx 56$ days. Asteroidal impactors therefore might reduce the duration of the Venusian solar day by half, but to shorten it further to an Earth like value would require the expenditure of most of the mass of the asteroid belt. This would be extremely profligate of accessible mineral wealth and since the momentum of a given mass of industrial slag is just as good as that of the same mass of valuable ore, Smith's proposal to use waste materials for the job of spinning up Venus makes sense. His 4×10^{21} kg dumped on Venus at 100 km/s could reduce the planet's solar day to as short as ~ 2.1 days; but we have already noted that an input on this scale probably has the undesirable side-effect of melting the entire Venusian crust.

Another limiting case worth studying is where we wish to use collisions to increase the Venusian obliquity, as the present value is too low to create Earth like seasons. In this instance, we want the impact to be tangential to one of the poles, or along a line of longitude, so that the angular momentum vector of the impactor is perpendicular to the rotational angular momentum vector of the planet. By vector addition we find that the magnitude of the angular momentum of Venus becomes:

$$I_v\omega_v = \sqrt{(I_v\omega_v)^2 + (M_i v_i R_i)^2} \tag{7.14}$$

and the change in obliquity is:

$$\theta_v = \arctan\left(\frac{M_i v_i R_i}{I_v\omega_v}\right) \tag{7.15}$$

To give an example, let us take 22 Kalliope and direct it into a tangential polar collision with Venus using the parameters $M_i = 1.83\times10^{19}$ kg, $I_v\omega_v = 1.8\times10^{31}$ kg m^2/s (the present value) and v_i and R_i as before. From the above equations we find that the solar day is little affected, falling to ~ 110 days, but that the obliquity has changed dramatically to an Earth like and pleasing $\theta_v \approx 25^\circ$.

It may be noted that the kinetic energy embodied by individual asteroidal impactors, of the size discussed, is greater than the entire rotational kinetic energy increment needed to adequately spin up Venus. However, since the collision is inelastic, kinetic energy is imperfectly conserved; the fraction that augments the planet's rotation is:

$$\frac{\Delta E_v}{E_j} = \frac{I_v(\omega'^2_v - \omega_v^2)}{M_j v_j^2} \qquad (7.16)$$

If we input the values appropriate to the collision of 16 Psyche discussed earlier we find $\Delta E_v/E_i \approx 7.5\times10^{-5}$. The great preponderance of the impactor's kinetic energy therefore is dissipated in the cratering process and in heating the crust and atmosphere.

The fact that the present obliquities and rotation rates of the planets (where unmodified by tidal effects) are thought to result from giant impacts occurring at the end of planetary accretion [53], suggests that similar, directed, collisions represent a workable planetary engineering technique. However, the process consumes a lot of mass and dissipates a great deal of energy. The simplified analysis here remains too optimistic since it assumes perfect retention of angular momentum in the body of the planet — something that is unlikely as substantial blow-off of mass into space would be expected.

7.9.2 The Dyson Motor

A method of altering planetary rotation rates with magnetic forces has been described by Dyson [54]. Originally this proposal was put forward in the context of the debate over the existence of extraterrestrial intelligence, his particular interest being in the potential observable characteristics of extraterrestrial technology. The first proposed use of his planetary spin motor was therefore to disassemble planets by centrifugal disruption to provide the mass for engineering projects on an *astrophysical* scale. Restructuring not just planets, but *entire solar systems*, is beyond the remit of this book; however Dyson's motor would serve just as well the more modest requirements of planetary engineering. Associating the idea with the terraforming of Venus was done in the scenario of Fogg [24].

Dyson's portrayal of his concept was mathematical and an abbreviated, qualitative description is given here. Its basic principle is to make a planet into the armature of a gigantic electric motor and hence to use magnetic forces to create the torques that alter its angular momentum. The salient features are illustrated in Fig. 7.10 and specifically show the motor arranged for operation on Venus; (thus the planet's rotation is shown as being clockwise and current generators are counted as being prograde if orbiting in the same direction and retrograde if in the opposite direction).

Metallic windings are laid down on the planetary surface along lines of latitude and current is passed through them in such a way as to generate a powerful quadupolar magnetic field with vertical field lines at the equator and poles. A pole-to-pole current flow that gives rise to a toroidal field passes through the body of the planet and returns extrinsically via the magnetospheric plasma. Angular momentum is transferred to Venus by surrounding it by a cloud, or ring, of orbiting "current generators" extending out to perhaps as far as ~ 100 times the planetary radius. A generator will cut magnetic field lines at ~ 90° and will experience an induced electromotive force in the direction $\mathbf{v_g} \times \mathbf{H}$ where $\mathbf{v_g}$ is the generator's velocity vector and $\mathbf{H}$ is the magnetic field vector. For prograde motion, this e.m.f. is directed normal to the plane of the generator cloud and in the same direction as the extrinsic pole-to pole current $\mathbf{I_g}$ which it helps to drive. The generator also experiences a mechanical force in the direction $\mathbf{I_g} \times \mathbf{H}$ which, in the prograde case, happens to oppose $\mathbf{v_g}$ and therefore acts as a *drag* force.

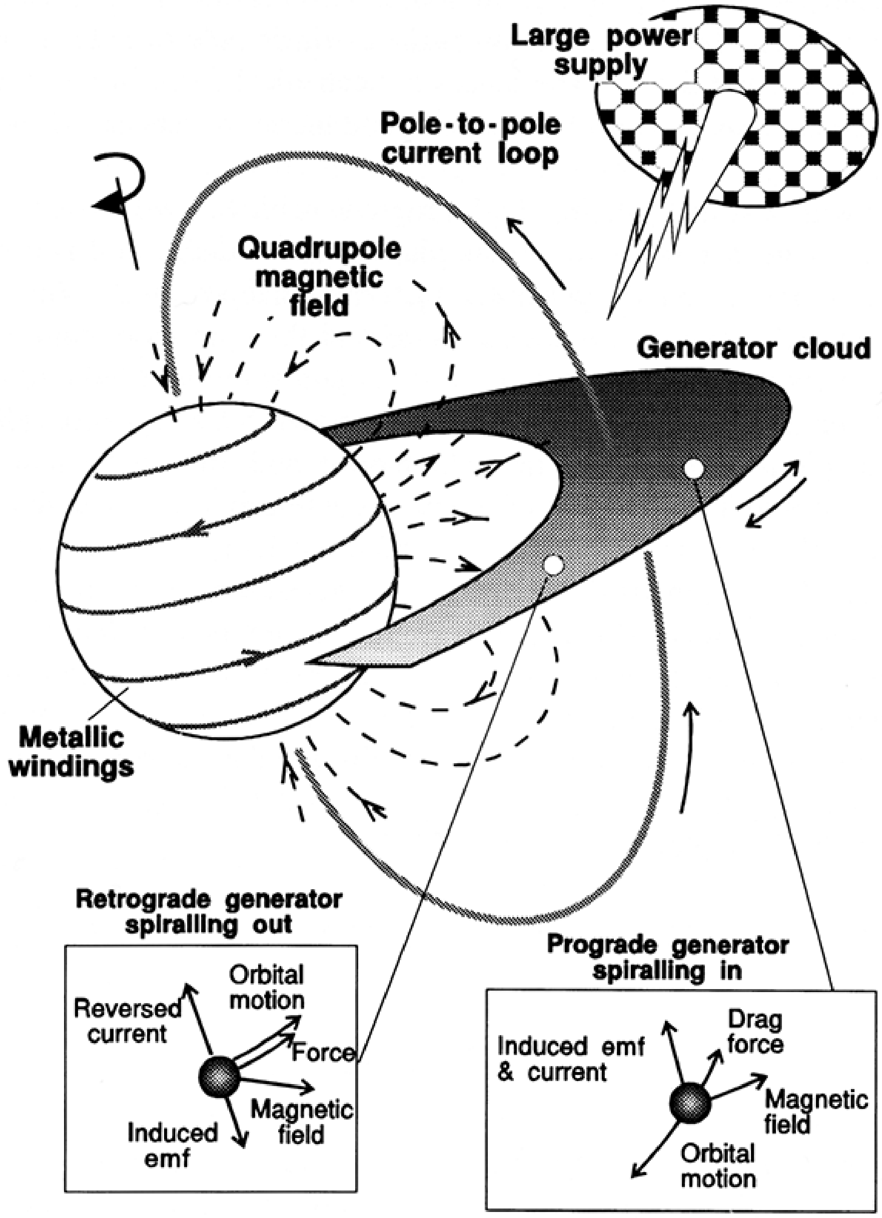

Figure 7.10 Schematic of Dyson's planetary spin motor [54]. Salient features shown are the latitudinal current flow, which generates the quadrupole magnetic field and the pole-to-pole current produced by the generator cloud. Directions of motion, magnetic fields, current pumping, induced emf and mechanical forces, on both prograde and retrograde generators are shown in the boxes. Not illustrated (due to the limitations of the 2D view) are generators in inclined orbits, facilitating the pole-to-pole current, or precessing in low orbit from prograde to retrograde direction. See discussion in text.

Thus such a generator will start its cycle in a high prograde orbit and will start to spiral inwards, transferring its lost angular momentum to the planet. The induced e.m.f. is used to generate current, the energy coming from the generator's gravitational potential. When in a low orbit, it generates current transverse to the induced e.m.f. and thus precesses into an antiparallel, retrograde, orbit. Now the generator pumps current *against* the induced e.m.f. (so that it still contributes positively to $\mathbf{I_g}$) and is hence subject to a mechanical *acceleration* force aligned with the orbital motion. It therefore spirals outwards back into a high orbit and since its angular momentum is increasing, but is opposite in sign to that of Venus, it continues to augment that of the planet. A continuous cycle of generators therefore maintains the torque accelerating Venus. At the outer edge of the generator cloud the magnetic field becomes too weak for generators to push against and so they unfurl a solar sail and escape free from the gravitational influence of Venus altogether [55]. Subsequent navigation, exploiting solar tidal forces, reverses the generator's angular momentum permitting re-insertion into the generator cloud in a high prograde orbit. The consequence of this cycle is that a tiny fraction of the angular momentum embodied in the planet's orbital motion, plus a minor contribution from the sunlight reflected by the solar sails, augments the spin angular momentum of Venus.

Dyson calculated the magnitude of the torque exerted by the motor to be [54]:

$$\mathrm{T} = \frac{4\times10^{7}}{15} R_v^3 H_0^2 \tag{7.17}$$

where R_v is the radius of Venus and H_0 is the magnetic flux density of the quadrupole field. Dyson felt that a value of $H_0 \approx 0.01$ tesla to be reasonable, *"... without requiring excessively massive conductors."* This is similar to that between the poles of a typical horseshoe magnet, but is ~ 25 times as intense as the surface magnetic field of Jupiter and ~ 200 times that of the Earth. The torque applied to Venus would therefore be T $\approx 1.5\times10^{22}$ kg m^2/s^2 and the angular acceleration: $A = T/I_v \approx 10^{-15}$ rad/s^2. To spin the planet up to $\omega_v' = 8.8\times10^{-6}$ rad/s ($t_d \approx 8$ days) therefore takes ~ 280 years and, more ambitiously, if we aim for $\omega_v' = 7\times10^{-5}$ rad/s ($t_d \approx 24$ hours) then this is done in ~ 2220 years. The power required for these operations would be roughly $T\omega_v' \approx 1.3\times10^{17}$ W and 10^{18} W respectively.

These power ratings are equivalent to about 0.4 - 3 times the Venusian insolation and could be collected by solar panels over the large area of the generator cloud itself or beamed to the vicinity of Venus from solar power satellites closer in to the Sun. This may be less expensive than harnessing enough energy in the outer Solar System to send ~ 10^{21} kg inwards to spin up Venus by impact. Operation of the Dyson motor is also less wasteful of both energy and the mass embodied in its components — huge quantities of the former are not dissipated heating the atmosphere and large volumes of crust, whilst the latter can be scrapped and reused for other purposes when the job is done. In addition, it is a much more precise planetary engineering technique than the impact method, being capable of providing any desired length of solar day including, if operated for long enough, an Earth like 24 hours.

Many aspects however of the Dyson motor remain obscure, such as for instance the number of generators and their design (their total mass is estimated [55] at roughly one millionth that of Venus ≡ 5x10^{18} kg [55]). The concept is therefore one of those that can be described theoretically, but remains uncertain when projected into the real world. As Dyson stated [54]: *"I do not need to emphasize the practical difficulties that would be involved in the implementation of this scheme. Two obvious difficulties are the avoidance of collisions between generators and the formation of conducting paths through the insulating atmosphere... My object in discussing the scheme is only to prove feasibility in principle. It is noteworthy in this connection that the required electric fields (of the order of 1 volt per centimetre) and current densities (1 microampere per cm^2) are well within the range of conventional plasma physics."[54]*

Thus whilst we can say that an ideal Dyson motor would be far preferable to impacts as a method of spinning up Venus, we cannot yet be sure of its ultimate feasibility.

7.9.3 Dynamic Compression Members

An even more ambitious concept for altering planetary rotation rates has been devised by Birch [56]. As with Dyson's work, it arises out of a wider exploration of the sort of infrastructure that could be constructed by an advanced space-faring civilization. It is thus similarly positioned far from present day engineering reality, whilst embracing the constraint of physical law and hence being feasible in principle.

A common feature of many of Birch's published concepts is that they depend on the application of forces by mass streams, or what he has called “dynamic compression members” [57]. Conventional engineered structures composed of static compression members or struts are limited by the finite strength of available materials or by problems of twisting or buckling. However, Birch has emphasized that dynamic structures supported by momentum do not rely on the strengths of chemical bonds and can therefore have specific strengths approaching the relativistic limit. The basic idea is sketched in Fig. 7.11. A *non-conservative* dynamic compression member does not recycle its components and thus requires a continuous extrinsic supply of momentum; whereas *a conservative* dynamic compression member involves countervailing mass streams traversing a distance between two reflectors. In the latter case, although the stream is moving rapidly, it requires no more energy once set up, other than to overcome losses at the reflectors. As Birch notes [57], a variety of dynamic compression members of either sort can be envisaged: *"The mass stream could take any convenient form: continuous cable; discrete pellets; plasma; electrons or other sub-atomic particles; light or other electromagnetic radiation. Likewise, the reflectors could be an arrangement of super conducting magnets, an active accelerator system or actual mirrors. The essential feature is a highly efficient reversal of the energy and momentum flows."*

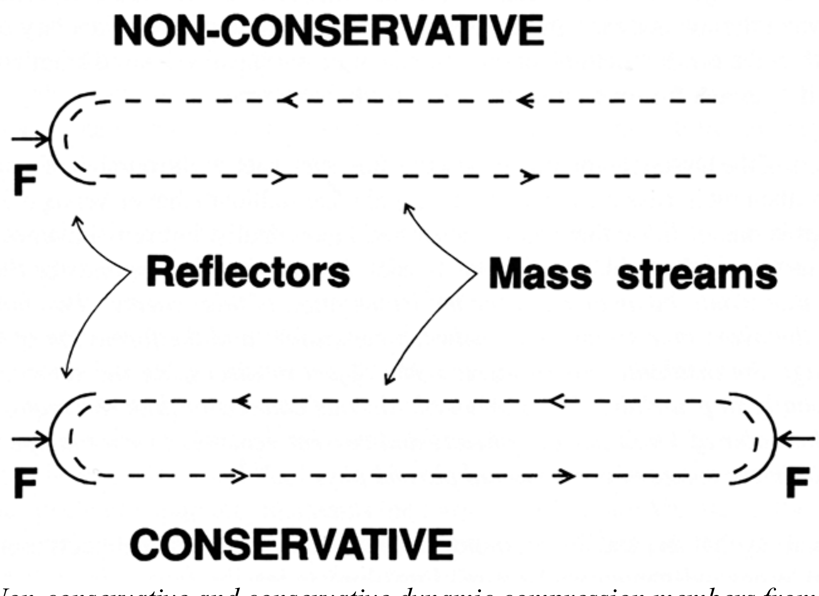

Figure 7.11 *Non-conservative and conservative dynamic compression members from Birch [57].*

We skip over the mathematical analysis of the concept here as it can be found in the cited references [and 58-60]. Suffice to say that one can point to numerous natural examples of dynamic support, such as the net force of air molecules that allows birds to fly and balloons to float and the force applied by a fountain of water that holds a ball up above the ground. In astronautical engineering, a solar sail is an example of a spacecraft propelled by a non-conservative dynamic compression member — the beam of light intercepted and reflected by the sail. The positioning and subtlety of design of Birch's reflecting mega structure for Mars and Venus (see Figures 6.5 and 7.6) are only possible because of their dynamic support by sunlight.

Birch's concept for changing the rotation rate of Venus [56] is based on the idea of applying a similar dynamic thrust tangential to the planet's equator. The infrastructure required however is even greater in scale than the Dyson motor and is illustrated schematically in Fig. 7.12. In all Birch's terraforming papers his stated aim is to get the job done quickly, in order to provide an economic return within a presently comprehensible project lifetime. He therefore starts his thought experiment with a greater space-based industrial capacity and more sophisticated technological capability than assumed by most other authors. In the case of Venus, he proposes to produce a 24 hour *prograde* solar day on Venus in just 30 years and so must have access to a minimum power of ~ 1.7×10^{20} W. The best region where such an energy flow ($\equiv 4.4\times10^{-7}$ the solar luminosity) can be trapped is close to the Sun. Thus, the arrangement depicted in Fig. 7.12 is based on a power generation system which Birch calls a "light sail windmill" [60]. This consists of an artificial orbiting ring dynamically supporting, via electromagnetic coupling forces, a track on which are mounted intricate arrangements of mirrors. These, and their super conducting mountings, are accelerated along the track by light pressure, thus converting solar energy into kinetic energy, which in turn can be re-converted into a form suitable for export into the Solar System at large. An arrangement of many such light sail windmills could usefully exploit a significant fraction of the entire solar output of ~ 3.88×10^{26} W.

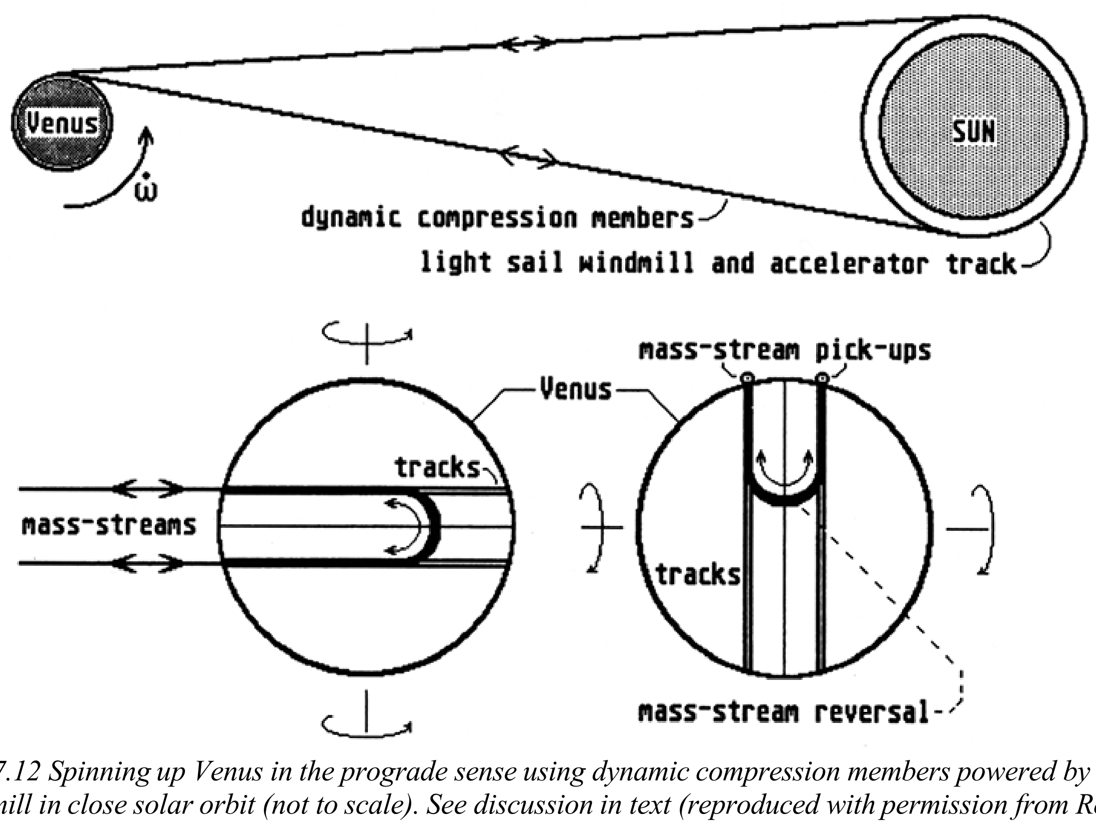

Figure 7.12 Spinning up Venus in the prograde sense using dynamic compression members powered by a light sail windmill in close solar orbit (not to scale). See discussion in text (reproduced with permission from Ref. [56].)

In the case under discussion [56], the kinetic energy of the windmill is coupled through a co-circular travelling wave accelerator to drive a pellet stream at velocities of >> 300 km/s. Having looped around the Sun, the pellets are launched on a course for the equatorial limb of Venus where they are caught and directed into a track girdling the equator. Once in the track the stream enters a reversing loop, where momentum and energy transfer occurs, before being launched back towards the Sun. Assuming loss less reversal and taking into account the pellet's high velocity, they are slowed only slightly on each pass, by twice the planet's circumferential velocity. This small change is compensated for by the pellet accelerator as the stream swings back around the Sun.

The equatorial tracks and reversal loops are fixed on the planet's surface, but the mass pickups must move at an opposite velocity to that of the planet's rotation in order to remain their position on the terminator. The launch point, where the streams are projected off the accelerator track, must also continuously change to track Venus in its orbit.

The net tangential impulse to be applied to the equator of Venus is $I_v\omega_v'/R_v \approx 7.1\times10^{26}$ N s and thus the force needed (for a 30 year spin up time) is ~ 7.5×10^{17} N. This is quite large and reduces the weight of Venus in the Sun's gravitational field by about 1 part in 10^5, temporarily and slightly expanding its orbit. At the opposite side of the Sun, this force is balanced by a counterweight of ~ 5×10^{15} kg (≡ 4 km asteroid) suspended in a gravitational field of ~ 240 m/s^2. Alternatively, a more massive counterweight could be used further out. Birch calculated that it would be sufficient to apply the force to the body of Venus over an area of only ~ 3×10^8 m^2, however since the force is actually *tensile* this estimate may have to be revised upwards [61].

The diameter of the reversal loop would be ~ 10,000 km, extending roughly between latitudes 45° North and South which means that the individual pellets of the dynamic compression member have to withstand accelerations at this point of their journey of ~ $2\times10^{10}\,\beta^2$ m/s^2 where β is the magnitude of the stream velocity as a fraction of the speed of light. If this acceleration is too great then the pellets themselves will not be able to maintain their integrity, suggesting to Birch the suitability of mass streams with $\beta < 0.25$. His estimated mass of the dynamic compression members is ~ 9×10^{11} kg/β^2, which is less than the counterweight mass if $\beta > 0.02$. Mass streams at a velocity between these two values ($\beta \approx 0.1$) are therefore indicated, composed of ~ 3000 trillion, 2.5 cm-wide, aluminium-coated corundum particles.

As with the planetary spin motor of Dyson [54], Birch's concept could be applied to planets other than Venus. However, Dyson's quoted remark about needing to solve practical difficulties before implementation of such a scheme apply also. Specific problems include difficulties in constructing the complex machinery that must be sited on the hostile Venusian surface and those posed by the design of the mass pickups — which must be large enough to protrude beyond the Venusian atmosphere and, towards the end of the procedure, must travel at up to 1580 km/hr. Extremely accurate alignment of mass streams is obviously called for along with precisely tuned movement of both projectors and mass catching apparatus. Freezing out the Venusian atmosphere, so that even nitrogen condenses, might considerably facilitate the task of feeding the mass streams into the equatorial tracks by reducing the size of the pickups and the pressure of intervening gas.

Given Birch's assumption that such engineering problems and unknowns can be solved, then perhaps his method of spinning up Venus might work. However, the notion that such a task might be accomplished in 30 years is so staggering that one can be left with the feeling of entering that region of the thought experiment envelope reserved for the "arbitrarily advanced" civilization mentioned in Section 3.1. It's a place where many have no wish to tread, as once a significant fraction of the solar output can be tapped routinely for industrial purposes, then the demands of terraforming begin to appear comparatively trivial. Although such an era may come, it appears remote to most terraformers and futurists in general.

7.10 A Comparison of Scale

Terraforming Venus will never follow the easy course mapped out by Berry or Pournelle [28,29]; but might Birchian infrastructure render the task as easy to a future civilization as perhaps a land restoration project on 20th century Earth? Maybe, but maybe not. What is clear however from the attention the problem has been given so far is that we can point to no preferred method of terraforming Venus. The planet presents us with a multitude of difficulties and choices; the "real" way of doing it can only be expected to crystallize with greater knowledge, understanding, industrial capacity and within the context of the technological style of that future civilization that is capable of taking on the project. What is true though now is that there is no scientific camp still advocating terraforming Venus with little more than microbes. Intensive planetary engineering will be *mandatory* for such a project to stand any hope of success: ecocentric ideas of exploiting environmental feedbacks and tweaking a planet to life with a minimum of technology, whilst there is a faint possibility of them working on Mars (see Chapter 5), won't wash at all on Venus.

A rough measure of the requirements of a Venus terraforming project can be gained by looking at Table 7.10. It compares features of the four comprehensive scenarios that have been offered, below that of the original Sagan model, and assumes that their predicted outcomes occur as proposed. A sense of scale is given by contrasting extrinsic mass transfers that are involved; the effect terraforming activities have on the Venusian surface and other solar system bodies; the timescale; and need for long-term planetary maintenance.

Major mass transfers to or from the planet appear to be essential. Unlike on Mars, there is no hope on Venus that intrinsic volatile inventories can provide for the requirements of a habitable environment. Although this fact seems to have taken time to be widely appreciated, it should not come as a surprise because what terraformers effectively have to do is to reverse that episode of mass transfer early in Venus' history where it lost its water to space. One can argue the relative merits of whether water should be re-imported or various reductants brought in instead, but this changes the amount of mass involved just within plus or minus an order of magnitude of the mass of the present atmosphere. It is also interesting to note that most of the terraforming techniques discussed have an total energy demand of ~ 10^{28} J/ε, where ε is the efficiency at which energy is coupled to the process. This includes photosynthetic processing of CO_2; hydrogen importation; Mg and Ca importation, CO_2 export and planetary spin-up. Whilst this energy is readily available in space (≡ half a minute of the solar output), it is equivalent to ~ 30 million years of the present primary power consumption of terrestrial civilisation. We might expect therefore that terraforming Venus may not be a realistic proposition until there exists a space-based civilization routinely using > 10,000 times as much power as now [24].

Not only will the project require a lot of energy, but the concentration of this energy implied by some terraforming techniques suggests a great deal of destruction on Venus or elsewhere in the Solar System. All scenarios either blanket the surface with a precipitate or, in the case of Smith [49], destroy it all together. Only Birch [32] finally reveals the existing surface of Venus, but only after an impractical process of initially creating his biosphere on top of frozen CO_2 and then removing this as fast as possible before it becomes unstable. Other Solar System bodies that are seriously affected by the project are Mercury in the scenario of Gillett [38] and Enceladus in that of Birch. Smith's vast quantities of industrial waste could only have been accumulated in the first place by the processing of a mass equivalent to several medium sized outer planet satellites.

TABLE 7.10 SCALE OF UNDERTAKING IMPLIED BY VENUS TERRAFORMING SCENARIOS

Scenario	Mass (kg) required to be:		Effect on Venusian surface	Effect on other bodies	Timescale[c]	Environment habitability	Long-term maintenance
	Imported	Exported					
Sagan	0	0	Blanketing with carbon	None	Long[d]	None	None
Fogg/ Oberg[a]	4×10^{19}	0	Blanketing with carbon	Slight – mining giant planet atmospheres	Long[a]	Good	Reduced insolation / diurnal cycle[a]
Gillett	2×10^{20}	0	Blanketing with carbonate	Strip mining of Mercury	Medium	Marginal	None
Smith	4×10^{21}	0	Total destruction and blanketing with debris	By-products of large scale mining in outer system.	Medium?	Good	Reduced insolation
Birch[b]	6×10^{19}	0	Blanketing with condensed CO_2 and covering.	Destruction of Enceladus	Short	Maintained	Reduced insolation / diurnal cycle[b]
	0	5×10^{20}	None		Medium?	Good	

Notes:
a. Minor differences between these scenarios are not important: Oberg implies shorter timescales, whilst Fogg used the Dyson method to spin up Venus thus removing the need for an artificial diurnal cycle.
b. Birch's scenario is divided into the proposed phase of initial habitability after freezing out the atmosphere and importing oceans and a later stage following exportation of CO_2. Spin up of Venus is also possible.
c. Timescale is loosely defined as: Short = < 1000 years; Medium = 1000 - 10,000 years; Long = > 10,000 years.
d. Erroneously claimed to be short by Berry and Pournelle.

Realistic terraforming timescales seem to be in the region of at least a few thousand years. The only really rapid planetary engineering option available is the freezing out of the atmosphere (~ 200 years); but then this still leaves us with the task of exporting ~ 5×10^{20} kg of CO_2 off Venus. The energy needed to do this is equivalent to ~ 2700 years of Venusian sunlight, so even with a large energy subsidy from elsewhere the time taken is likely to be substantial. If shortened to 50 years or so, as suggested by Birch, then the heat dissipated by the procedure into the Venusian environment is likely to cause problems such as vaporizing much of the solid volatiles before collection.

If Gillett's marginally habitable, briny-oceaned, Venus [34] proves not to be stable, or nothing is done about the duration of the solar day, then long-term artificial regulation of the planetary environment will be required to reduce the planet's insolation into the range of climatic stability and to provide an acceptable diurnal cycle. Unlike on Mars however, it is possible that the prevailing level of Venusian geological activity will provide adequate geochemical recycling of elements. Thus, although the biosphere Venus must also be embedded within a noosphere to remain vital, the conscious control of processes within the biosphere itself (beneath the top of the atmosphere) might be reducible to a negligible proportion. The ecocentric goal of establishing a self-regulating biosphere, intimately connected to planetary biogeochemical cycles (a version of Lovelock's Gaia, which we might call “Dione” after the mythical mother of Venus [24]), might therefore be more completely achievable on Venus than on Mars.

The Terraforming of Venus

Given all these caveats, will terraforming Venus ever be worth the effort? If there comes a time when the effort no longer appears so daunting, then the answer must surely be yes. Venus is the one world in the Solar System which, due to its mass and composition, really can be made into a New Earth (see Fig. 7.13) — not a clone of Earth, but its sister planet of myth.

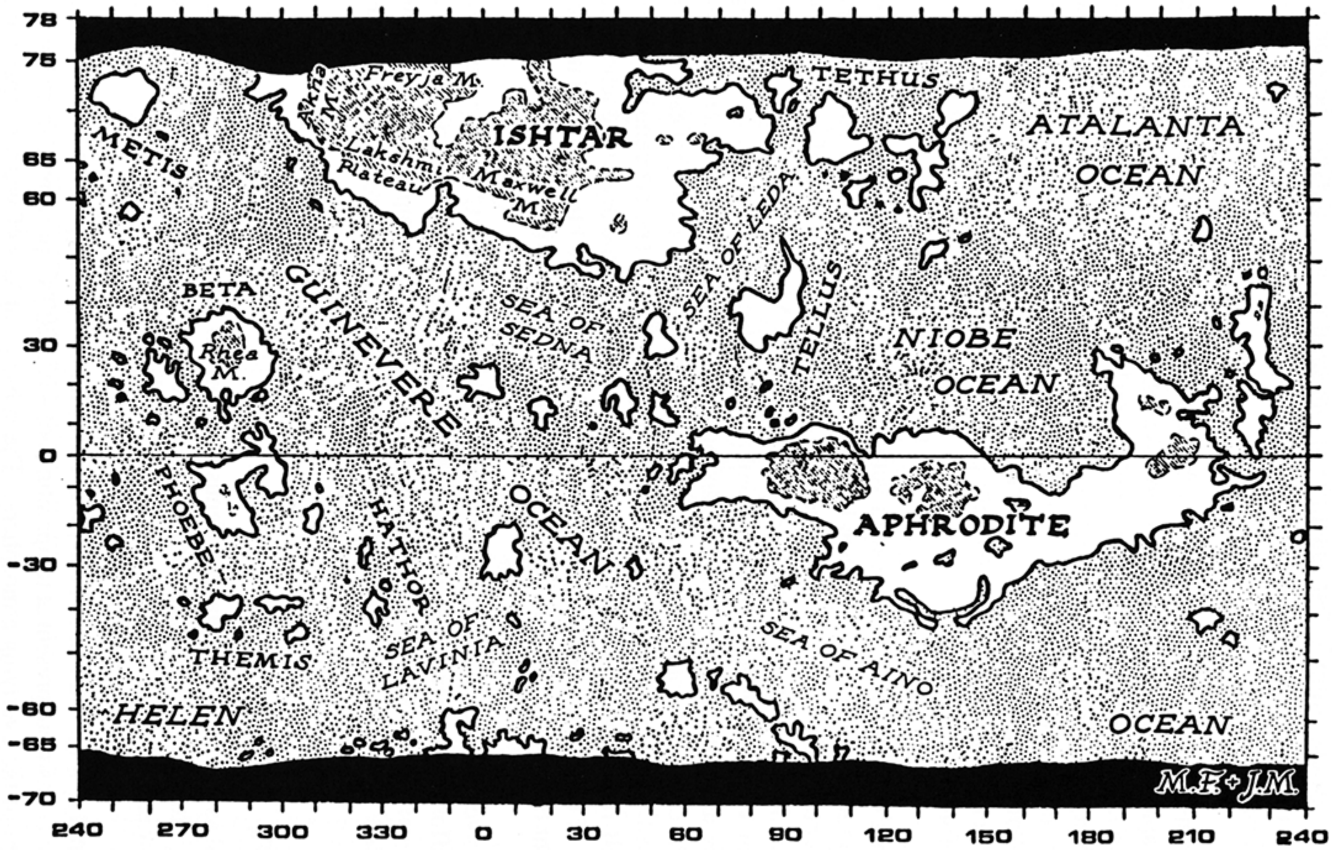

Figure 7.13 *Mercator projection of Venus after terraforming according to the model of Fogg. Flooding the planet 880 m of water covers ~70% of the surface with shallow ~1-km-deep oceans. Ishtar and Aphrodite would stand out as continents: the former with temperate and alpine climates; the latter being tropical. Not only is Venus closer in size to Earth than Mars, but its distribution of highlands and plains would lead to a more Earth-like geography once terraforming is complete. This rough sketch map is based on Pioneer Venus data and the same nomenclature: plains ⇒ seas and oceans; highlands ⇒ continents. (Lettering by Jack McArdle; reproduced with permission from Ref. [24].)*

7.11 Summary

- Once regarded as Earth's "sister planet," Venus is a world of inhospitable extremes. Conditions of high temperature and pressure at the surface render the planet unsuitable for colonisation or exploitation.
- In its early history, Venus may have been more Earth like. According to the Moist Greenhouse model, oceans were present at temperatures of ~ 100 - 200 °C, prevented from boiling by the pressure

of the overlying atmosphere. The subsequent loss of water to space and increasing solar luminosity has left Venus in its present hot and desiccated state.

- Terraforming Venus will be required for the planet to be of relevance to life. Planetary engineers must undo the consequences of its early episode of water loss, remove most of the atmosphere, take measures to prevent a future climatic runaway, and reduce the duration of the diurnal cycle.
- Early ideas of a purely ecocentric approach to terraforming Venus (by seeding its clouds with micro-organisms) are no longer considered viable. The nature of the task forces every modern proposal to follow a technocentric path, involving extensive planetary engineering measures, such as transfers of large quantities of material and a space-based infrastructure to control insolation and perhaps increase the planet's spin rate.
- If Venusian CO_2 is not to be removed from the planet, then it must either be chemically reduced and precipitated or made to react with rocks to form carbonates. Reduction and precipitation methods include photosynthesis plus imported hydrogen, which produces carbon and water; or imported alkaline earth metals (particularly Mg and Ca) which reduce CO_2 to carbon and carbonates. By importing water, brecciating the planet's crust and controlling planetary temperature to promote chemical weathering of silicates, it may be possible to sequester CO_2 within the body of Venus as carbonate minerals. All such techniques are likely to take some thousands of years.
- Cutting off Venusian sunlight physically precipitates the Venusian atmosphere in a comparatively short time (~ 200 years) forming CO_2 seas and glaciers. Whilst this somewhat reduces the hostility of the Venusian surface compared with what obtains at present, it only provides a temporary solution to the planet's CO_2 excess.
- Impact methods of increasing the rotation rate of Venus only realistically appear capable of halving the planet's solar day (to a diurnal cycle of ~ 60 terrestrial days). A substantial improvement on this involves too many large impactors and complete destruction, and possibly melting of the Venusian crust. An Earth like diurnal cycle might therefore be obtained artificially with space-based mirror/parasol systems. Planetary spin motors capable of directly spinning up Venus to the desired rate have been designed, but an assessment of their likely practicality is not presently possible.
- It is clear that terraforming Venus, in terms of the energy and mass flows that must be manipulated, is a task several orders of magnitude more demanding than that of Mars. For planetary engineers to make any significant impact on Venus, we must not just invoke a greater technological capability and industrial capacity — but a different technological style also. Autonomous machinery endowed with such biological properties as self-reproduction and differentiation may in order so as to process the enormous quantities of mass involved.
- Many terraforming applications, such as the various techniques of atmospheric processing and planetary spin-up have an energy demand of ~ 10^{28} J/ε, where ε is the efficiency at which energy is coupled to the process. Whilst this demand is huge compared with the present usage of terrestrial civilisation, it might not be so to one in space. 10^{28} J represents just 30 seconds of the Sun's output, or the fusion energy that might be released from the deuterium in a ~ 100 km cube of ice.
- As applied to Venus, all proposed terraforming techniques have their advantages, disadvantages and unknowns. Whilst we can discuss possible options available for planetary engineers (and learn by them), a choice of strategy cannot be made on behalf of the civilization that might undertake the project — one that would be highly advanced over our own. Thus, there exists no preferred scenario for terraforming Venus.
- The similarity of the Venusian mass and gravity to that of Earth, and the likelihood of ongoing geological activity, suggests the prospect of a particularly pleasing, Earth like, outcome of terraforming. If the necessary planetary engineering becomes practicable and affordable, then there exists the at-

tractive possibility of creating a second terrestrial-style biosphere within the Solar System. The economic worth of a habitable Venus is clearly enhanced over the planet's present state, although perhaps this will mean little if a majority of the future population take up residence in space habitats. However, the value of the challenge itself and its implications for the long-term survival and diversity of life, are likely to be substantial.

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