Chapter 5

The Ecopoiesis of Mars

The point is not to make another Earth. Not another Alaska or Tibet, not a Vermont nor a Venice, not even an Antarctica. The point is to make something new and strange, something Martian.

Kim Stanley Robinson

5.1 A Much-Loved Planet

Looking out into the Universe on a dark and clear night, and feeling that unique sense of awe the night sky provides, one can gain some appreciation of why ancient astronomers named celestial objects after their gods and heroes. This is particularly so for the planets which, month by month, could be seen to alter their position against the fixed stellar background. The serenity and regularity of their motion hinted at some order to the Universe, underlying the capriciousness and chaos of daily events. Whilst the study of the mystery of planetary motion was ultimately successful and was a major factor in the invention of modern science, planetary astronomy has not entirely shed all its mythical connotations. This is particularly the case with the planet Mars. Although Mars no longer conjures up images of the blood-red Roman god of war — modern myths have replaced it. We have the unforgettable Mars of Lowell [1], shaped out of necessity into a dour utopia by a race of planetary engineers; we have the anarchic arena of adventure that sprang from the mind of Edgar Rice Burroughs [2]; and the beautiful, stark and haunted world of Ray Bradbury [3], with its empty seas and slender, alien ruins.

Current knowledge of Mars, furnished by a succession of visiting space probes, has reshaped these myths but not abolished them. Space scientists and engineers are developing concepts not just for the future exploration of the Red Planet — but for its permanent settlement and eventual terraforming. Modern science fiction writers [e.g. Ref. 4] now set their human dramas on a planet as real as the Earth, a harsh frontier of a place that can not just be "won" in the traditional sense by the progressive settlement of individual patches of land, but can also be *transformed as a global entity* from a lifeless desert into a dynamic and living world. Mars therefore, more than any other of the planets, provides a focus for our desires and hopes. It is a metaphor for a future of noble and glorious possibility. *Lowell's planetary engineers can be us*.

5.2 Mars as an Abode of Life

Our knowledge of Mars is both extensive and paltry. Extensive enough, in the form of measurements from orbit (see Plate 5.1) and at two surface locations, to have generated many scientific papers and a range of books; paltry though since both the data we have and our comprehension of its importance is still incomplete. To a lesser extent, this is true of the Earth, and so for Mars too speculation must substitute for gaps in information and understanding so that what is known can be integrated into consistent hypotheses of planetary evolution. The speculative content of models of Martian evolution is of course greater than those for the

Earth, but we nonetheless have a good general view of the planet and the rough order of events that have brought Mars to its present state. This picture is sufficiently coherent and detailed as to permit rational investigation of the potential of Mars to host life.

Plate 5.1 *Mosaic of Mars composed of 102 Viking Orbiter images, processed as to simulate a point perspective from a distance of 2500 km. The centre of the scene (8°S, 78°W) shows the entire Valles Marineris canyon system, more than 2000 km long and up to 8 km deep, extending from Noctis Labyrinthus, the arc-like system of graben to the West, to the chaotic terrain in the East. Two of the large Tharsis volcanoes are visible close to the Western limb of the planet. To the far North and East are low-lying plains which may have been flooded in Mars' past, whereas to the South are found ancient uplands, covered by many impact craters. (Photo courtesy of US Geological Survey).*

Further data however is urgently needed to replace the Red Planet's many remaining mysteries with hard facts. The recent failure of the *Mars Observer* probe as it entered into orbit about the planet in August 1993 has been a sad blow for those interested in furthering Martian studies and planetary science generally. We must continue therefore to rely principally on observations returned from the *Viking* probes which visited as long ago as 1976. These data have therefore been worked over for 17 years and continue to be the prime source. The best and most up to date summation of Martian studies [5], written by 114 contributors, is a huge 1500 page tome published by the University of Arizona press in 1992. It appears that this will have to serve for longer than was intended as the standard reference work on the Red Planet. In this book we attempt only a thumb-nail sketch of Mars, concentrating on those issues most relevant to life and terraforming. The book mentioned above and the reference lists at the end of both this chapter and the next will be useful for those who wish greater detail of Martian planetology.

5.2.1 The Present

Taking all its parameters together, and considering the issue of habitability, Mars is seen to be the most Earth-like of the other planets (see Tables 5.1 and 5.2). Nevertheless, in its present state, it is far from suitable as a home for terrestrial life.

TABLE 5.1 PHYSICAL PARAMETERS OF MARS

Parameter	Value
Age	4.6×10^{9} years
Mean Distance from Sun	2.28×10^{8} km
Sidereal Period	686.98 Earth days
Mean Orbital Velocity	24.13 km/s
Eccentricity	0.0934
Insolation	589 W/m^2
Mass	6.419×10^{23} kg
Mean Radius	3389.9 km
Mean Density	3934 kg/m^3
Surface Gravity	3.71 m/s^2
Escape Velocity	5.03 km/s
Sidereal Rotation Period	24.62 hr
Obliquity	25.19^{o}
Albedo	0.25
Atmospheric Mass	2.18×10^{16} kg
Atmospheric Pressure	~ 6 mbar
Atmospheric Scale Height	10.8 km
Effective Temperature	-63 ^{o}C
Mean Surface Temperature	-56 ^{o}C
Magnetic Dipole Moment	< 8×10^{11} T-m^3
Surface Area	1.44×10^{8} km^2
Area of perennial N polar cap	8.37×10^{5} km^2
Area of perennial S polar cap	8.8×10^{4} km^2

Data from Ref. [6]

Mars is a rocky planet a ninth the mass of Earth, with about 40% of the gravitational acceleration; its area is roughly equivalent to that of Earth's land surfaces. Its red-ochre appearance comes from a layer of fine ferric-iron containing dust, particles of which are caught up by the winds and suspended in the atmosphere, giving the sky a salmon-pink colour. Being 50% further from the Sun, Mars' insolation averages only 43% that of Earth; this, and the fact that its tenuous atmosphere only gives a 7^{o}C greenhouse effect, combines to lower the planet's mean global surface temperature to ~ -56^{o}C. In the equatorial regions, temperatures may peak as high as 20^{o}C in the early afternoon, but plunge as low as -90^{o}C just before dawn. The temperature of the Winter pole can fall to below -130^{o}C.

What air is present is composed primarily of carbon dioxide with a little nitrogen, argon, and trace amounts of other species (see Table 5.2). The small amount of oxygen present is thought to have nothing to do with biology and is generated photochemically; its concentration is too low to generate an Earthlike ozone layer, so ultraviolet radiation can reach the surface. The length of day is very similar to the Earth; however, the Martian orbit is more eccentric and the year is almost twice as long, accentuating the effects of seasons — one of them being significant changes in atmospheric pressure as CO_2 condenses out on the Winter pole. There is no significant magnetic field, suggesting that either the planet's core is solid, or is perhaps composed of iron sulphide and therefore completely liquid [7]; in either case, the non axisymmetric fluid currents thought to be required to generate a strong magnetic field are not possible. The solar wind is thus only prevented from reaching the surface by interaction with the upper atmosphere — an additional process that can result in the loss of gases to space. Since Mars' column mass of atmosphere is only equivalent to a depth of ~ 0.15 m of water (as opposed to Earth's ~ 10 m) the level of cosmic ray irradiation of the surface is much greater.

TABLE 5.2 MARS - ATMOSPHERIC COMPOSITION

Species	Abundance by volume
CO_2	0.9532
N_2	0.027
Ar	0.016
O_2	0.0013
CO	0.0007
H_2O	0.0003
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	0.04 to 0.2 ppm

Data from Ref. [6]

Mars has no liquid water visible anywhere over its entire globe — indeed, its temperature regime and low atmospheric pressure makes the liquid phase unstable. An initial glance at the planet therefore reveals a place that is too cold and dry for terrestrial life, bathed in lethal radiation, with an atmosphere that is too thin and of an unsuitable composition.

An indigenous Martian biology appears unlikely. However Mars has revealed itself to be a world of compelling fascination and future visitors will find all the chemical requisites of life to be present. The planet has polar caps thought to be made from water ice which are seen to expand in Winter due to condensation of CO_2. Occasional water-ice clouds, too tenuous to precipitate, are seen to form (see Plate 5.2) and the Viking lander craft photographed a thin layer of hoar frost that condensed on nearby rocks during the night. The atmosphere therefore is sometimes saturated with water vapour — the absolute amount present however is very small (equivalent to ~ 0.01 mm thickness of liquid spread over the entire planet) due to the tiny water vapour pressure at such low temperatures. Mars is therefore very dry, but perhaps is so in part because it is very cold. As will be shown in the next Section, there are reasons to believe that the bulk of the planet's inventory of water is hidden from view.

Plate 5.2 *A cyclone at the edge of the North polar cap, photographed from orbit in mid-1978. Frost cover is visible on the ground below. (Photo courtesy of NASA.)*

Other elements essential for biology may be found within surface materials. The analyses conducted by the *Viking* landers suggests that rocks in the two sites studied are similar to terrestrial basalt lavas (see Plate 5.3); soils appear to be composed of clays with an admixture of salts (especially sulphates) [8,9]. Basalts on Earth weather into fertile soils, but do not normally provide concentrations of rare minerals. These locales however may not be typical of broad areas of the Martian surface [10] and it is possible that past geological activity may have differentiated useful minerals into deposits — possibly similar to some analogues on Earth [11]. Certainly, not all the Martian surface is primordial and there is an abundance of visible evidence of past volcanic and tectonic activity. Two thirds of the planet — the Southern hemisphere and some extensions over the equator — remain heavily cratered and date from the first billion years of Martian history [12]. The bedrock here is thought to be overlain by *regolith*, a layer of broken and unconsolidated strata. Other areas however have been resurfaced since then, as evidenced by the Northern lowland plains and the volcanoes of the Tharsis and Elysium regions. Some places show extensive erosion and mass wasting that may have exposed mineral formations deposited at depth.

Plate 5.3 *The terrain of Utopia Planitia, as seen by the Viking 2 lander. The region is a low-lying plain, strewn with blocks that may have been hurled as ejecta from the 90 km diameter crater Mie, the rim of which lies 170 km to the East. (Photo courtesy of NASA.)*

TABLE 5.3 MARS - MATTER RESOURCES

Known

- Atmosphere — CO_2, N_2, Ar, H_2O
- Ices — H_2O, CO_2
- Silicate Rocks
- Clays
- Salts

Possible Mineral Concentrations

- Hydrothermal deposits
- Evaporites
- Sedimentary deposits
- Layered igneous intrusions

Unlikely Mineral Concentrations

- Organic deposits
- Orogenic deposits

Mineral nutrients of all sorts therefore may be available from Martian rocks and soils. In addition to chemicals required directly by life, our rudimentary inventory of Martian resources (see Table 5.3) already appears adequate to the task of supporting some technology. Materials as diverse as rocket fuel and construction cements can be manufactured from the basic resources we know exist [13-15]. Once a proper inventory of Martian assets is done, its range of requisites for biology and technology will undoubtedly increase. Unlike the Moon, unlike Venus or Mercury, unlike individual asteroids or the satellites of the giant planets, Mars offers all of the requirements for space colonization on-site: a surface that can readily be settled, sufficient sunlight for photosynthesis, and both rocky and volatile resources. It has therefore long been a prime candidate (in the opinion of some, the *leading* candidate) for the establishment of the first permanent extra-terrestrial settlements with the capability to evolve into a self-sufficient civilisation. As the planet is constituted now however, human beings and their combined living and mechanical life-support systems will have to be structurally contained, along with all the disadvantages that this entails (see Chapter 2). Mars exterior to such biosphere habitats would remain lifeless.

5.2.2 The Past and the Future

A closer look at Martian geomorphology reveals a planet that may have been very different in the remote past and possibly much more habitable than at present [16]. The oldest Martian terrain shows abundant evidence that liquid water was once present and stable enough to carve recognizable river valleys (see Plate 5.4).

Plate 5.4 *The valleys of Thaumasia. Highly fractured ancient terrain at 48°S, 98°W is dissected by some of the densest drainage networks on Mars. (Photo courtesy of NASA.)*

Many of these *runoff channels* have been photographed from space and are seen to be present almost exclusively in the Southern upland regions [12]. This heavily cratered terrain covers about two thirds of the planet and is thus thought to date to the first billion years of Martian history when the impact flux was much greater than now (the period of what is called the *late heavy bombardment*). Runoff channels are almost ubiquitous in these regions and generally wind between craters forming extensive networks that drained into closed depressions. Mars at this time therefore almost certainly possessed numerous lakes and possibly standing bodies of water large enough to be called seas. Whilst there is controversy whether the channels were fed by rainfall runoff or groundwater seepage, it is clear that they could only have been formed on a warmer and wetter Mars than we see now. The pre-requisite for this more Earth-like Mars must have been a much more massive atmosphere. It is necessary to postulate such an atmosphere to: 1) provide the pressure to stabilize liquid water and 2) to provide an adequate greenhouse effect to warm the planet above freezing. The latter requirement is particularly problematic > 3.5 billion years ago because of the "faint young Sun" problem mentioned in Section 2.7.4 — Mars at these remote times may have received only ~ 70 - 80% the insolation it does today.

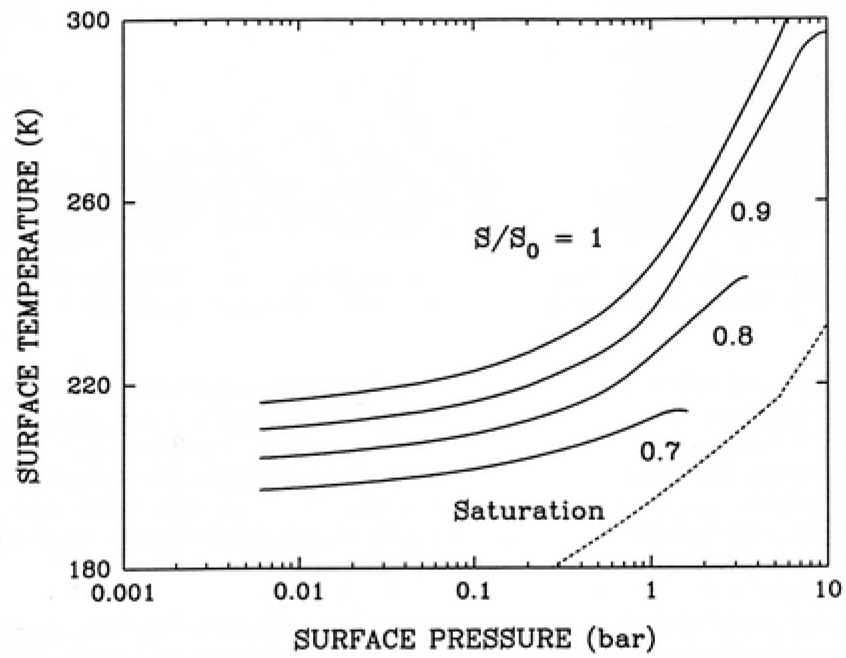

Figure 5.1 *Martian mean surface temperature versus surface pressure, calculated from a climate model with CO_2 condensation included. The four solid curves are the response of the model for four different solar luminosities, where S_0 is the present luminosity. The dashed curve is the saturation vapor pressure of CO_2. It is seen that only when $S/S_0 \geq 0.9$ can a CO_2/water vapor greenhouse effect warm Mars above freezing. (Reproduced with permission from Ref. [18].)*

A number of planetary scientists (among them the late James Pollack of NASA-Ames and James Kasting) have attempted to explain Mars' warmer past by adopting a climate model based on the geochemical carbon cycle and similar to that proposed for the Earth [17]. To investigate the concept, Pollack *et al.* constructed and ran a detailed radiative-convective computer model of an early Martian atmosphere composed of pure CO_2 in equilibrium with liquid water. Initial predictions of the model were that ~ 2.2 bars of CO_2 are required to warm Mars above freezing at the present time, whereas > 3.5 billion years ago ~ 5 bars would have been needed; a thinner ~ 0.75 bar atmosphere was predicted to have been capable of thawing the planet's equatorial regions, at least on a seasonal basis. An updated model by Kasting [18] (see Fig. 5.1), which includes the formation of CO_2 clouds, supports these conclusions for modern Mars; but where the insolation is < 86% the present value it appears that carbon dioxide and water vapour alone may not have provided the required warming. This is because CO_2 clouds increase the albedo of Mars, an effect that at low insolations eventually overcomes the increased greenhouse effect of more gas. Thus there is no definitive explanation for Mars' early warm climate, although it is possible that the young Sun may have been more luminous than is currently believed, or that other greenhouse gases were present. In any case, a quantity of gas > 100 times that present in today's atmosphere, and a lot more water than is visible, seems to be indicated in order to explain the structures exposed on the Martian surface.

Whether Mars possessed all this carbon dioxide and water depends on its original endowment of volatiles and how much of this outgassed from within the planet. The original inventory is extremely uncertain, but a number of attempts have been made to estimate it [19-26] and these are shown in Table 5.4. As one might expect, present estimates are very poorly constrained, to within two orders of magnitude, and depend strongly on the method of assessment. Geochemical models that scale the volatile inventory with the abundance of ^{36}Ar or ^{40}Ar, or by the ratio between ^{14}N and ^{15}N tend to conclude that Mars has only outgassed ~ hundreds of millibars of CO_2 and ~ tens of metres of water (globally averaged depth). Geomorphological approaches, such as estimating the amount of outgassing produced by volcanoes or the quantity of water needed to carve the planet's fluvial features arrive at an inventory of ~ several bars of CO_2 and ~ several hundreds of metres of water. Assuming that Mars formed from material with an equal fraction of volatiles as did the Earth, then its inventory is predicted to be ~ 27 bars of CO_2, ~ 1.2 km of water and 300 mbar of N_2 (the latter quantity is particularly significant because nitrogen is such an important limiting nutrient element with a present partial pressure on Mars of only 0.2 mbar).

TABLE 5.4 ESTIMATES OF TOTAL MARS VOLATILE INVENTORY

Study	CO_2 (mbar)	N_2 (mbar)	H_2O (metres)	Method of estimation
Present Mars Atmosphere	~ 7 mbar	0.2	~ 10^{-5}	Atmosphere only
Earth Scaling[a]	27000	300	1200	Equal volatiles per unit mass
Rasool and Le Sargeant [19]	198	3.1	5.9	^{36}Ar, ordinary chondrites
Anders and Owen [20]	140 - 525	2 - 8	9.4	K, ^{40}Ar, $^{36}Ar/^{40}Ar$
McElroy *et al.* [21]	1760	21.5	133	$^{14}N/^{15}N$
Clark and Baird [22]	187 - 410	8.6	88	^{40}Ar, 'excess volatiles'
Pollack and Black [23]	1000 - 3000	6.6 - 66	80 - 160	N, noble gases, Venus data
Carr [24]	10000 - 20000	100 - 300	500 - 1000	Geomorphology
Dreibus and Wanke [25]	(3000)[b]	(33)[b]	130	SNC meteorites, Martian CI
Greeley [26]	(> 1000)[b]	(> 11)[b]	> 45	Volcanism only

Table taken from Ref [16].

[a] Determined by assuming the martian ratio of volatiles of per unit mass of planet is the same as the Earth's. The Earth volatile inventory is assumed to be: 190 bars of CO_2; 2 bars of N_2 and 3200 m of H_2O.

[b] These values are not taken from the referenced source but were determined assuming that the ratios of volatiles are the same as the Earth scaling result.

It seems quite possible therefore that Mars did possess sufficient volatiles from which to constitute a dense carbon dioxide atmosphere in its early history which might have warmed the surface above freezing. However, Pollack *et al.* [17] pointed out that this would have been unstable in the presence of liquid water and silicate rocks — 1 bar of CO_2 being chemically converted into carbonate minerals in just ~ 10^7 years (Equations 2.17 & 2.18). Thus, to sustain a dense atmosphere for ~ 10^9 years, a *closed* geochemical carbon cycle must have operated like on the Earth where carbonates are recycled back into the atmosphere (see Equation 2.19 and Fig. 2.11). The mechanism they suggested was an intense early volcanism, with carbonate deposits being buried under fresh lavas and eventually reaching a depth where they are thermally decomposed. This process might have been possible due to the high internal heat flow that would be characteristic of a young, newly accreted, planet. An alternate suggestion that has been made is that the recycling could have occurred through the devolatilization of carbonate sediments by impacts [27].

Whichever mechanism was responsible for maintaining the proposed warm climate of early Mars, it seems to have ceased operating ~ 3.5 billion years ago, about the time that the late heavy bombardment was ending. Runoff channels younger than this date are rarer and more parochial in their distribution. It may be that since Mars is smaller than Earth, with a larger surface to volume ratio, its internal heat was lost at a faster rate. The vigour of Martian geology waned to the point where the recycling of carbonates, at a rate consistent with maintaining a warm surface, was not possible. As its atmosphere thinned by aqueous reaction with silicate rocks, Mars froze. This loss of CO_2 by chemical weathering could have continued after the average global temperature fell below freezing (albeit at a slower rate) in such locations as ice covered lakes supplied by groundwater [28] and transient moist pockets within soil [29]. Other mechanisms for removing CO_2 include adsorption onto mineral grains in the regolith, deposition of dry ice at the poles and possibly also impact erosion — the ejection of gases into space by the vapour plume of an energetic asteroid collision [30]. The relative importance of these processes is unknown, but carbonate formation and impact erosion seem to have the capacity to remove the largest amounts of gas. The picture is similar for nitrogen, the level of which would gradually decline in the absence of biological denitrification or return via volcanic gases. Energetic processes in the atmosphere, such as lightening and the passage of meteors, generate nitrogen oxides, which eventually react with surface minerals to produce nitrate compounds [31]. As nitrates are very soluble, they would be mobilized by liquid water and deposited by precipitation from evaporating brines. Nitrogen would also have been lost by impact erosion and would be more susceptible than CO_2 to the gradual leaking of gases to space. Being a smaller planet, Mars is more prone generally to lose gases by thermal and photochemical processes over the span of geological time. Quite how much of its volatiles have been lost in this way is unclear, although it appears unlikely that the planet could have been divested of several bars worth of CO_2 and several hundred metres of water.

Despite this long-term trend towards climatic cooling and sequestration of volatiles subsequent to ~ 3.5 billion years ago, Mars has been far from quiescent [12]. In the following ~ 1-2 billion years the Northern plains were formed, and the Valles Marineris — a huge rift valley the width of North America — was created by tectonic movements. A stationary hotspot under the crust created the Tharsis volcanic province, a 10 km high bulge capped by the largest volcanoes in the Solar System. The greatest of them, the 27 km-high Olympus Mons, appears to possess few impact scars and may therefore have been active up to the recent geological past. Of most interest to biology is the fact that the Martian surface preserves evidence of a different style of erosion by liquid water occurring at dates that post-date the Southern uplands. These are the *outflow channels* (see Plate 5.5), vast features tens to hundreds of km wide and thousands long, which have deeply incised the landscape [12,33]. They appear almost certainly to have formed by the erosive action of catastrophic floods, a hypothesis that is supported by the observation of “scabland” type features, such as prominent scour patterns and streamlined islands. The channels emanate from large areas of chaotic terrain, ground that appears to have collapsed due to withdrawal of material from below. This might be explained by the release of water confined in an aquifer removing support for the overlying rock and causing it to disintegrate. This could possibly have happened if, subsequent to the freezing of the planet, a thick layer of permafrost had formed confining an aquifer of liquid water underneath. This water might have gradually percolated from the highlands down to lower elevations until a point was reached where its pore pressure exceeded the overburden pressure. At this point, rock would start to liquefy and collapse — the aquifer ruptures and the water would be violently released [34]. An alternative mechanism could have been the intrusion of magma into crust rich in ground ice [35]. This again would have produced a high-pressure flow of water which could have been driven through permeable rocks out to the surface. Support for this idea comes from the location of the two most prominent channel complexes: one East of the Tharsis bulge and associated with the Valles Marineris and the other close to the Elysium volcanoes. There have been other hypotheses put forward to explain the appearance of the outflow channels, but the cataclysmic flood model accounts for all their features best. What is clear is that huge flows of water would have been required (10^7 - 10^9 m^3/s) to have caused the destruction that is observed — up to 10,000 times that of the Mississippi. And since some channels seem to have flooded several times and not all are of the same age, Mars may have experienced a number of such episodes, spread out over a considerable period of geological time.

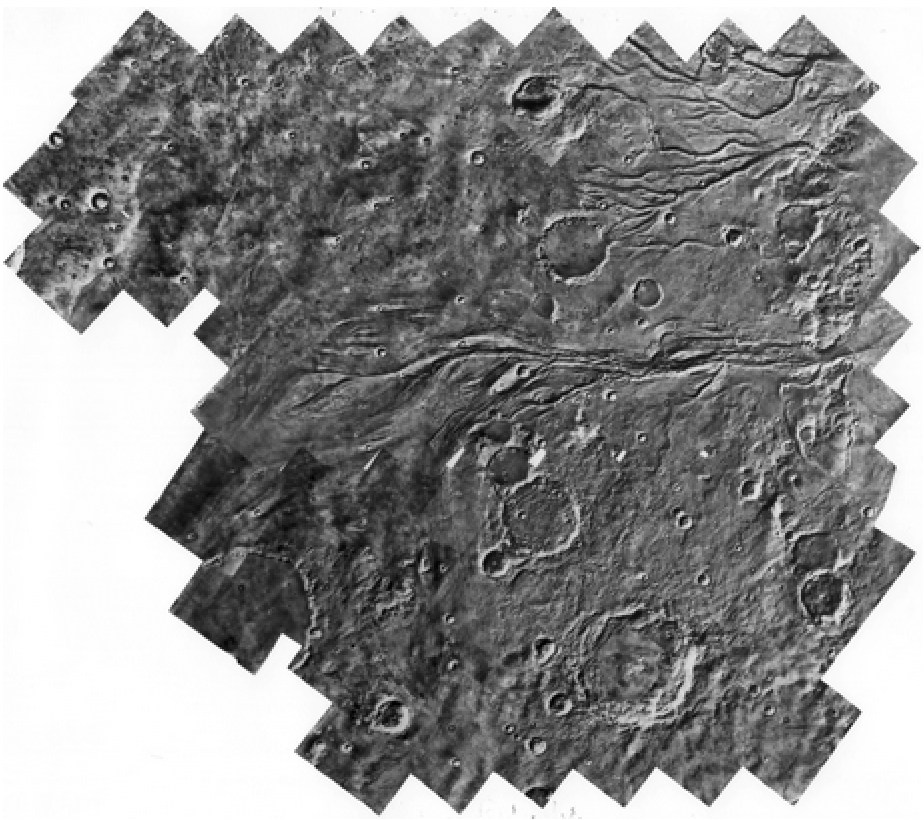

Plate 5.5 *Scoured landscape caused by floods originating in Lunae Planum to the West and flowing downhill and eastwards into Chryse Planitia. The scene is 300 km across and the outflow channels visible are Vedra Vallis to the North and Maja Vallis to the South. The flow seems to have converged on Maja to cut its gorge and teardrop-shaped islands are abundant at its western end. (Photo courtesy of NASA.)*

Mars would not necessarily have required the presence of a thick atmosphere and a warm surface to permit the formation of the outflow channels. This is because of the sheer volume of the flood which could have pooled on the Northern plains, depositing the sediments carried with it, long before freezing solid. The rapid formation of an ice cover would have retarded the cooling rate and would have allowed flow to continue underneath. Tentative evidence for a large expanse of water has been found in *Viking* photographs and it has been controversially proposed that features at the uplands-lowlands boundary might represent the wave-cut shorelines of a small Boreal Ocean [36]. The ice may perhaps still be situated on the Northern plains and is hidden from view by a covering of aeolian sediment. However, the speculative identification of glacial features near the South pole [37] that may be contemporaneous with the outflow channels, has led one group, headed by Victor Baker of the University of Arizona [38], to propose that the flood episodes, by flushing out large quantities of adsorbed CO_2 from the regolith into the atmosphere, brought about brief interludes of warm climate in which the ocean did not immediately freeze and was free to evaporate. An Earth-like, global-scale, hydrological cycle became possible, providing the water to recharge upland aquifers and the snowfall to feed the Austral ice sheets. The dry river valleys in the Southern uplands would have presumably have once more run with water; but since the additional erosion seems to have been slight, each warm "Maritime" episode would have lasted for less than a million years. Baker *et al.* proposed that the trigger for such events was powerful pulses of magmatic activity associated with Tharsis volcanism which destabilized ground ice. According to their calculations the Northern plains could have been inundated with ~ 70-450 metres of water (globally averaged depth) in just a few weeks to a few years, depending on the quantity and rapidity of the flooding (for more detail see Fig. 6.8 and Table 6.9 in the next Chapter). Each episode would have been less intense than the last as the planet's volcanic activity declined. Eventually, Mars would have become grounded in a permanent ice age, its atmosphere and hydrosphere permanently sequestered in the crust of the planet or lost altogether. This is the Mars we see today.

The episodic oceans hypothesis is admittedly highly speculative [39], being based on the interpretation of features on photographs taken from orbit for which there are other possible explanations. It was expected that *Mars Observer* would either confirm the validity of the concept or rule it out, by imaging the proposed shorelines and glacial landforms at higher resolution — but this was not to be. The hypothesis is mentioned here though for two reasons: the first is because it extends the potential habitability of Mars for those organisms capable of surviving the wait for the next warm spell and the second is because a terraforming model covered in Chapter 6 is based upon its proposed mechanism for rapid ocean formation. The timescale that characterizes the events described above is shown in Fig. 5.2 and is compared against the geological timescale of the Earth. Martian chronology is very uncertain and is based on crater counts and a less-than-certain analogy with cratering on the Moon. Nevertheless three major epochs in Martian history have been identified: the *Noachian*, when Mars may have been similar to the early Earth, warm and wet with running water; the *Hesperian*, a time of powerful volcanism, catastrophic floods and intermittent warm spells and the *Amazonian*, where the planet stuttered into quiescence, becoming the dry and cold place we see today.

An important question that is posed by this emerging picture of Martian history must be: where is the water now? —The amount of water ice visible at the present time is far to little to have been responsible for the planet's fluvial, and possibly marine, geomorphology. A possible answer is that much of the water inventory estimated in Table 5.4 may be situated under the surface, within the porous regolith. A stability diagram of ground ice on Mars, depicted on an idealized pole-to-pole cross-section of the planet, is shown in Fig. 5.3. The North and South polar caps are stable and so are the stippled lens-shaped areas underground, which extend to ~ 40° latitude. These locations are almost permanently below the frost point (~ 200 K) and ice can exist in equilibrium. In the equatorial regions though, ice can only exist over long periods if separated from the atmosphere by a diffusive barrier — otherwise it will gradually sublime and be redeposited at higher latitudes [41]. The tropical regolith of Mars may therefore be dehydrated to depths of ~ 500 - 1000 m. Also shown in Fig. 5.3 is the melting isotherm below which liquid water can exist. It is interesting to note that the vertical height depicted in the Figure is of the same order as the difference in altitude between the Southern uplands and the Northern plains (~ 3 km). It is easy to appreciate therefore how confined liquid water aquifers might be positioned in a gravitationally unstable position — a configuration that could have preceded outburst flooding as described above.

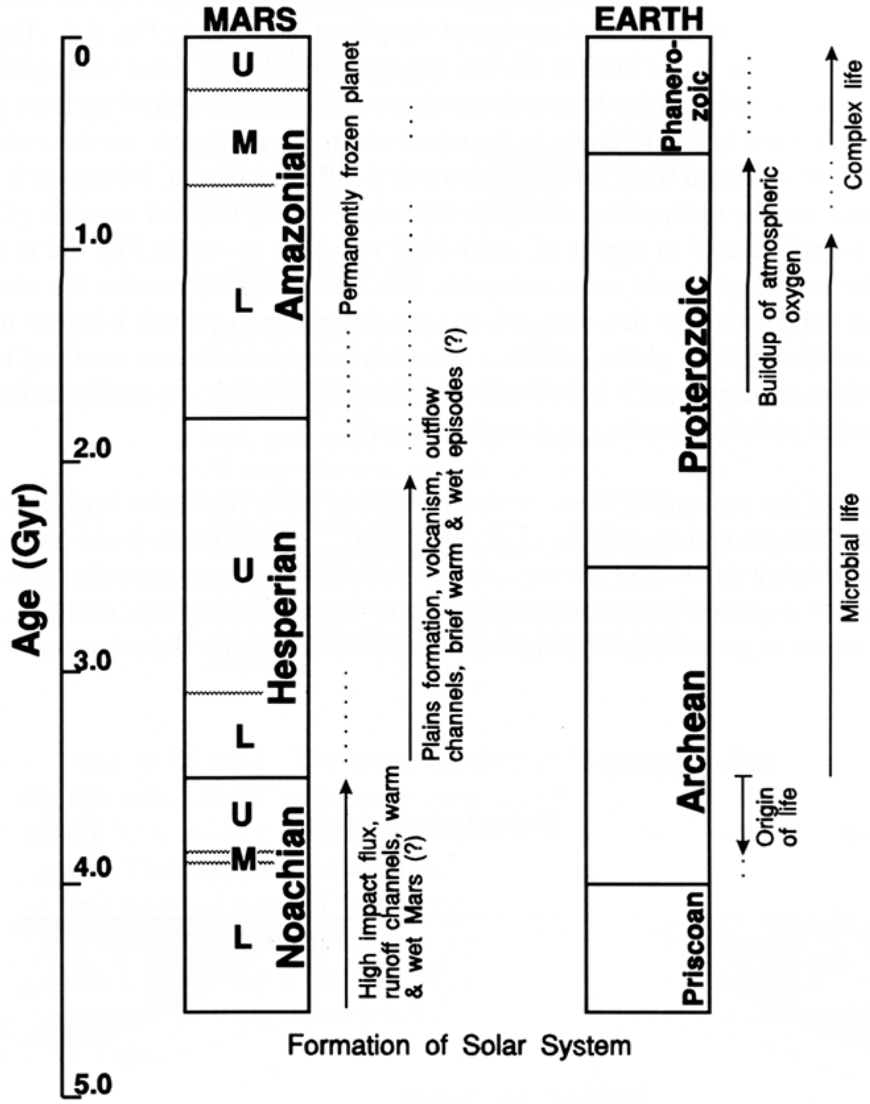

Figure 5.2 *Geological time scale of Mars compared with the Earth. L=Lower, M=Middle, and U=Upper. Dates of the Martian boundaries are very uncertain and taken from Ref. [40]. Other time scales substantially reduce the length of the Hesperian Epoch. The Martian and terrestrial environments start to diverge after ~3.5 billion years ago. Brief warm/wet interludes may have continued for a billion years or so afterwards.*

An estimate of the capacity of Mars' various proposed water reservoirs is given in Table 5.5, along with the assumptions behind each calculation [12]. The figures given are expressed as globally equivalent depths and are very crude. Nonetheless they suggest that Mars does have the capacity to sequester several hundred metres worth of water in its regolith, mostly as ground ice overlying liquid at greater depth. Geomorphological evidence for the existence of this water-rich permafrost may be at hand. The great majority of Martian impact craters, especially those situated poleward of 20 - 30^{o} latitude are surrounded by ejecta deposits that seem to have been emplaced not by a ballistic trajectory, as is seen on the Moon, but by *horizontal flow* along the surface [12]. Their appearance is similar to that produced by throwing an object into mud and hence their informal name of "'splosh craters" (see Plate 5.6). In fact, the ejecta may well be solidified mud deposits, resulting from the liquefaction of permafrost by the sudden energy of the impact, producing a rock and water slurry that is propelled outwards. If this interpretation is correct, then the regolith of the temperate and polar latitudes of Mars may contain abundant water.

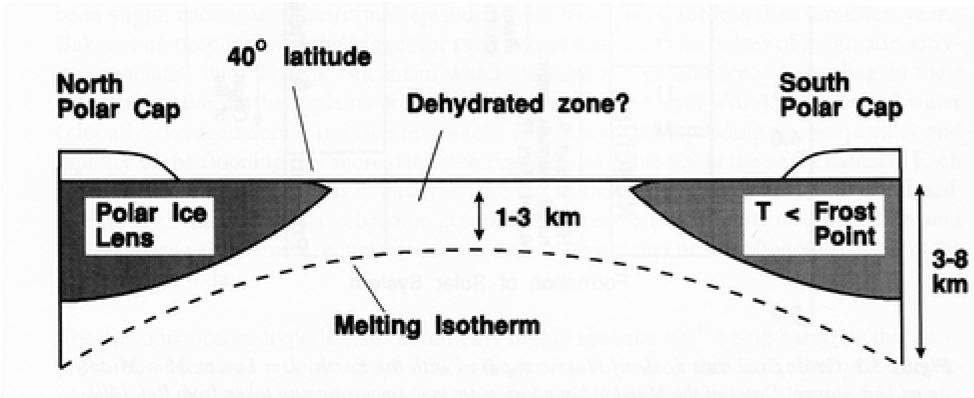

Figure 5.3 *Simplified cross-section of the Martian regolith from the north to south pole. Ground ice is stable poleward of about 40° latitude where the temperature is permanently below the frost point. Ice at lower latitudes must be isolated from the atmosphere by a diffusive barrier.*

TABLE 5.5 PRESENT LOCATION OF WATER ON MARS

Reservoir	Estimated global equivalent depth
Permanent caps[1]	~ 1 m
Layered terrain[2]	~ 3 m
Polar ice lenses[3]	~ 23 m
Clay minerals[4]	~ 3 m
Megaregolith[5]	~ 10 m
Ground-ice[6]	< several hundred
Groundwater[7]	< 450 m

Data taken from Ref [12].

1. 100 m thickness of ice to 80° latitude.
2. 2 km thickness to 80° latitude, 10% ice.
3. 1 km depth below poles, zero thickness at 40° latitude, 10% ice.
4. 100 m thick, clay-rich regolith, 3% water.
5. 1% water adsorbed on basalt, 1 km deep.
6. Separated from atmosphere at latitudes < 40° by diffusive barrier, possibly at depths > 1 km. Quantity may be large but no realistic estimates possible.
7. Situated deeper than 273 K isotherm, porosity 10% at 1 km → zero at 10 km. Aquifer may not be fully charged.

Our account of Martian history remains short of much needed detail from which to draw concrete conclusions. However, the evidence that we do have seems to at least point to a pattern of evolution that is comprehensible — a planet where habitability, and the geochemical cycles that such a state depends on, declined in concert with the waning of its geothermally driven processes [16]. If one looks far enough back into Martian history — to the Noachian epoch — Mars appears to have been not unlike the contemporaneous Earth, drier and colder perhaps, but with the aqueous environments thought to be suitable for the origin of life. However, if Genesis also took place on Mars, then its progeny are probably long extinct. The surface appears lifeless and the atmosphere exhibits none of the chemical disequilibrium character that is the stamp of life on Earth. We can be certain therefore that there exists no Martian biosphere — at least not in the integrated, global, sense that we are familiar with. Life deep underground, in so-called "cryptic niches" (where liquid water is present and reduced compounds from volcanic gases are available as a basis for a food chain) is feasible [42], but is it heard to envisage such isolated and disconnected habitats remaining continuously viable for billions of years.

Plate 5.6 *One of the most well known of "splosh craters," the 18 km diameter crater Yuty (22°N, 34°W). The ejecta looks like a muddy slurry that has flowed into position, as opposed to ballistically deposited rocky fragments. Such craters have been cited as evidence for the existence of sub-surface ice deposits. (Photo courtesy of NASA.)*

The search for life on Mars — one of the oldest of scientific preoccupations — is thus evolving into the search for past life on Mars. In a real sense too, it is becoming the search for *future* life also, as our emerging understanding of its history has fundamental implications for how the planet might be terraformed. The Mars of the past, with its rivers and lakes, its warm, moist atmosphere, and maybe its Boreal Ocean too, gives hope for the Mars of the future. It holds out the possibility that we might be able to *restore* the Red Planet to its previous habitable climate (suitable at least for primitive organisms) rather than having to create such a condition on worlds unsuited to it. If it is feasible to rearrange Martian parameters such that the planet becomes attracted towards its past quasi-stable state, terraforming may be less like resuscitating a planetary corpse — rather, it would be more akin to awakening Mars from a long and icy slumber.

5.3 Approaches to Terraforming Mars

Terrestrial biology is unsuited to conditions on Mars as we presently understand them. Thus, to render Mars suitable for life, on a planetary scale at least, inevitably involves bringing about large changes in its environmental parameters. The principal modifications required in order to create two variants of a habitable environment are shown in Table 5.6. The column under the title *Minimal Ecopoiesis* shows those changes needed for anaerobic life to be established, whilst that under *Terraforming* displays the necessities of an environment habitable for man.

It is evident that five main alterations to Mars will be essential:

1) the surface temperature must be raised;
2) the atmospheric pressure must be increased;
3) the chemical composition of the atmosphere must be changed;
4) the surface must be made wet and
5) the surface flux of UV radiation must be reduced.

These requirements are of a far lesser magnitude for ecopoiesis than for full terraforming and, as was discussed in Section 3.4.1, the requisites of an environment suitable for the widespread growth of higher plants may be intermediate between the two. Mars will also need the kind of biospheric matter cycles characteristic of those on the Earth that were outlined in Chapter 2. To a large extent, these may occur spontaneously once the planet is unfrozen — the unrestricted nature of a planetary biosphere and its continuous dissipation of huge amounts of solar energy automatically generates, on all scales, cycling systems in the atmosphere and hydrosphere in which ecosystems can participate. The effectiveness of Martian biogeochemical cycles however cannot be taken for granted and are discussed later in Sections 5.6.4 and 6.3.3. They will though be a secondary concern at the beginning. The initial job of planetary engineers will be to bring about those first-order changes listed in Table 5.6 that will allow cycles compatible with life to be set in motion.

The unknowns inherent in Martian planetology allow for a flexible approach to the question of terraforming. No optimum or preferred methods of terraforming Mars yet exist. Models that are proposed therefore are inevitably coloured by one's philosophical views and one's assumptions of what the future has in store. A more rigorous analysis and a convergence of opinion awaits better knowledge of parameters and processes that will constrict the control space in which the mind is free to speculate.

Philosophical approaches to terraforming were discussed in Section 3.3 and were characterised as lying in a continuum of opinion between extremes of ecocentrism and technocentrism [43]. These labels are, to an extent, caricatures and not exact representations of real viewpoints. Nonetheless, they are descriptions of two broad intellectual trends that are discernible in the literature on terraforming Mars. Ecocentrists basically favour “doing it with biology,” whilst technocentrists are attracted to technological solutions.

TABLE 5.6 MARS - TERRAFORMING REQUIREMENTS

Parameter	Present value	Modification required for: Minimal ecopoiesis	Terraforming
Surface Gravity:	0.38g	Not possible	
Rotation Period:	24.6 h	Unnecessary	
Axial Inclination:	25°12'	Unnecessary	
Insolation:	589 W/m^2	Increase up to 1370 W/m^2	
Albedo:	0.25	Low as possible	
Mean Surface Temperature:	217 K	~60 K Increase	
Surface atmospheric pressure:	~ 7 mbar	> 10 mbar	380 - 3700 mbar
CO_2 Partial Pressure:	~ 7 mbar	> 0.1 mbar	< 10 mbar
O_2 Partial Pressure:	~ 0.008 mbar	Unnecessary	95 - 500 mbar
N_2 Partial Pressure:	~ 0.2 mbar	> 1 - 10 mbar	> 285 mbar
Hydrosphere:	0%	> 0%	>> 0%
UV Flux 0.2-0.3 μm:	~ 6 W/m^2	Reduction	Zero

The former viewpoint regards Mars from the broad perspective of the totality of life and is mainly concerned with using the minimum possible technological input consistent with the creation of an environment that can support some form of biology — however primitive. Ecopoiesis is therefore regarded as being a worthy end in itself, rather than as one step in an ongoing terraforming process leading to a human-habitable environment. In the words of Robert Haynes [44], *"The objective of ecopoiesis need not be to achieve climatic and biological conditions as they now exist on the Earth. If the present Martian environment could be altered to support the growth of any biota, however exotic, then the more modest goal of ecopoiesis would be attained."* Ecocentric scenarios usually reduce human control of the engineering process to a minimum and invoke a purely biological, Gaian, mechanism for subsequent stabilisation of the global environment. Full terraforming is not ruled out but is thought of as such a remote possibility that it is considered only in the vaguest of terms. The aims of planetary engineering therefore become diverted to other ends as eloquently summed up by Penelope Boston of Complex Systems Research in Colorado.

Quoted in Oberg's book, she stated [45], *"Mars can never be made a facsimile of Earth, but in a significant sense can be made habitable....on Mars we have the option of introducing life at the optimal level of adaptive organization to meet prevailing conditions."*

The ecocentric position therefore holds that ecopoiesis may be attainable on Mars, but that terraforming will be extremely difficult. Technocentrists, who are less inhibited about proposing much more radical and speculative planetary engineering solutions, see less of a difference between the two and therefore always have some variant of a human-habitable environment specifically in mind. Both approaches do share some important assumptions though, such as: Mars is lifeless; long-term biological adaptation to 0.38 g is possible; and that mankind has attained a permanent presence in space. They differ as far as the latter is concerned in the level of industrialization on Mars itself, and elsewhere in the Solar System, deemed necessary for effective planetary engineering.

A first step to terraforming Mars is commonly considered to be to thicken the atmosphere and to use its increased greenhouse effect to warm the planet's surface. Speculations on how this might be done require an assumption as to which Martian climate model is valid — i.e. the quantities of volatiles available, their physical and chemical state, location, and how easy they are to mobilise. The nature of this assumption explains a lot about the bifurcation between ecocentric and technocentric approaches and is summed up on the catastrophe graph in Fig. 5.4.

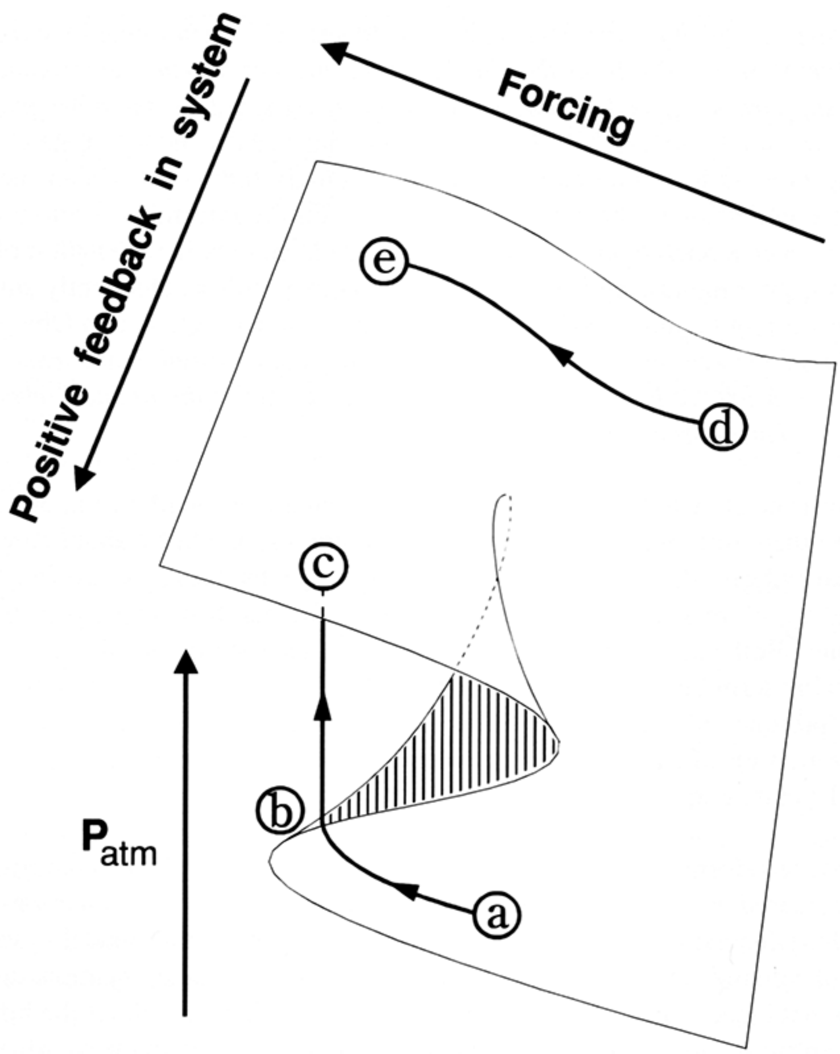

Figure 5.4 *The creation of a dense Martian atmosphere. Environmental trajectories are plotted on a cusp catastrophe surface with arbitrarily scaled axes. Two cases are shown where climate change is governed by either high or low positive feedback. Trajectories **a→c** intersects the cusp at **b**, whereupon a runaway outgassing occurs to a new high-pressure state. Exploitation of this instability by planetary engineers would mean that much less climate forcing is required to bring about major changes. In contrast, trajectory **d→e** does not intersect any discontinuity and all the pressure change has to be directly manufactured.*

Ecocentric scenarios are able to minimise the planetary engineering involved, (the degree to which the environment must be artificially forced into a biocompatible state,) by postulating a Martian climate that is *highly unstable*. Positive feedback between surface temperature and atmospheric pressure is assumed to be very strong — large excursions being possible as a result of a minor initial perturbation. This is represented on Fig. 5.4 by the trajectory **a→c**. The Mars of today is at the location **a**, and planetary engineering takes it to point **b**, whereupon the climate becomes unstable and rapidly undergoes a spontaneous transition to a new high-pressure state at **c**. *Most of the work therefore to manufacture a dense Martian atmosphere comes from the innate amplification within the system and only a modest amount of planetary engineering is needed to set the process going.* (The technique has a large *leverage*, as defined in Section 3.5). This notion of "tweaking" Mars to life lends natural support to approaches that are philosophically averse to what might be called a "technical fix." The opposite assumption, that the climate of Mars is now grounded in a highly stable equilibrium state, requires terraforming to follow the route **d→e**. This time there is little positive feedback assisting the production of an atmosphere and all of it must be *directly manufactured*. In such a situation, which obviously calls for a much greater degree of planetary engineering, it is more difficult to foresee terraforming getting underway, but once it does, it is easier to imagine it being done with a long-term commitment to go the whole way, creating a fully earth-like environment.

We consider technocentric approaches to terraforming Mars in the next Chapter; here, we focus more on what might loosely be categorized as ecocentric designs for ecopoiesis. All of these rely on a modest initial warming of part or the whole of the planet in order to force it to the instability point **b** whereupon runaway production of atmosphere occurs. Planetary engineering techniques within the context of such scenarios are therefore almost entirely applied to raise the surface temperature of Mars. These techniques include modifications to all three free parameters in Equation 3.4 — the insolation, albedo and greenhouse effect and are summarized in Table 5.7. They are covered in the context of the scenarios in which they are used in the following Sections.

TABLE 5.7 PROPOSED TECHNIQUES FOR TRIGGERING CLIMATIC INSTABILITY ON MARS IN ECOCENTRIC SCENARIOS

Application	Technique	Tools	Authors
Intrinsic terraforming			
Increase surface temperature of polar caps → evaporates CO_2.	Reduce albedo of CO_2 ice by applying a thin dark layer.	Dark dust, distribution mechanisms; genetically engineered vegetation (?)	Sagan [49]. Averner & MacElroy [50].
Increase global surface temperature → releases CO_2 from both caps and regolith.	Inject trace greenhouse gases into the atmosphere.	Halocarbon gases, production facilities.	Lovelock & Allaby [54]. McKay *et al.* [55].
Extrinsic terraforming			
Increase global or local surface temperature → releases CO_2 from both caps and regolith.	Augment insolation with reflected sunlight.	Space mirrors, station keeping mechanisms and ancillary infrastructure.	Mentioned in passing in many texts, but see Zubrin and McKay [60].
Increase seasonal low temperatures of polar caps → evaporates CO_2.	Optimise orientation of Martian rotation axis with its orbit's perihelion by applying a torque to Mars with orbiting masses	~ Ten asteroids, propulsion systems, processing machinery.	Burns and Harwit [48].

5.4 Early Ecopoiesis Models

The first flyby space probes to return photographs of the Martian surface, Mariner 4 in 1965 and Mariners 6 and 7 in 1969, seemed to have shattered any remaining Lowellian illusions of Mars. If anything, the planet appeared to resemble the Moon, more than any world that might have been habitable. However, Mariner 9, an orbiter probe that arrived in late 1971, was able to map the entire surface and image the younger areas of the planet for the first time, including those possible fluvial features described above. This new evidence for a past salubrious climate on Mars had to be taken into account in new models of the planet and it was from this work that there emerged the first scientifically-based suggestions of terraforming strategies.

An early model of the dynamics of the Martian environment, that provoked wide interest and immediately post-dated Mariner 9, was the so-called “Long Winter Model” (LWM) proposed by Carl Sagan and colleagues [46,47]. Since little work had been done on Martian chronology up to that time, it seemed reasonable that the channels visible in the Mariner photographs might be quite recent. Sagan therefore proposed a model of a Martian climate cycling between two quasi-stable states — one with the bulk of the volatiles frozen onto a cold surface and the other where the volatiles are gaseous, blanketing a warm and wet surface. He suggested that Mars' missing atmosphere (up to a pressure equivalent of ~ 1 bar) might be frozen out and deposited in the North polar cap since presently the North pole points away from the Sun at perihelion (see Plate 5.7). However, Sagan pointed out that since the equinoctial precession period of Mars is ~ 50,000 years, a similar — but opposite — configuration would occur in ~ 25,000 years time, except that these volatiles would have been circulated and stored in the South polar cap. In intermediate epochs however, where the line of equinoxes is roughly along the line of apsides of the Martian orbit, both poles would be heated equally at perihelion, resulting in vaporisation of much of the cap material and an enormous excursion in atmospheric pressure and climate.

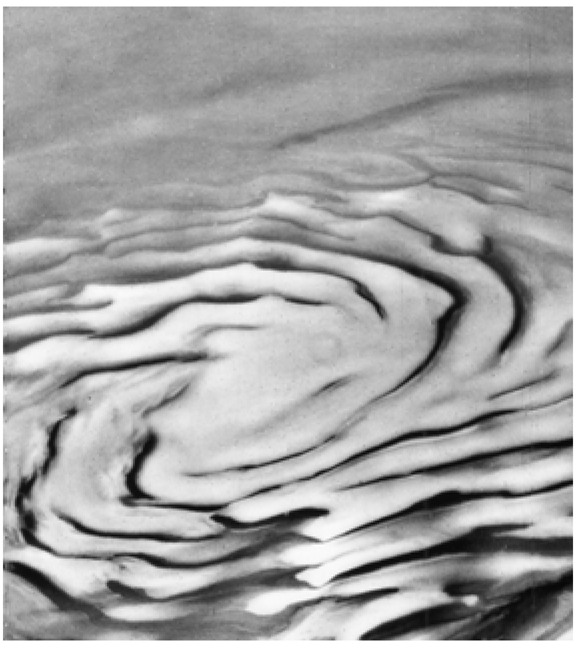

Plate 5.7 *The residual North polar cap of Mars, now thought to consist mainly of water ice. Its swirl texture is generated by winds. (Photo courtesy of NASA).*

According to the Long Winter Model therefore, Mars has super-long seasons brought about by an extreme climate instability driven by the equinoctial precession cycle. The alternation between “Winter” and “Summer” would occur every ~ 12,000 years, but in addition to this cyclic instability, further work on the LWM [47] which included calculations of the effectiveness of atmospheric advective heat transfer from the tropics to the poles, also predicted that the Martian climate would be sensitive to changes in both solar luminosity and the albedo of the polar caps. The implication for terraforming Mars of this inherently unstable situation was obvious. It seemed possible that with just a small “push”, the Martian environment might be induced to undergo a rapid, runaway, change into the warmer of its two climatic regimes.

5.4.1 The Burns-Harwit Maneuver

The first suggestion for exploiting the Long Winter Model for the purposes of planetary engineering (assuming it to be true) — and the very first academic paper [48] to be published on Martian terraforming — came from Joseph Burns and Martin Harwit of Cornell University in 1973. They were not concerned with accelerating the onset of Martian “spring,” but proposed a method of maintaining the planet in a configuration that would prolong habitable conditions indefinitely. This emerged from the fact that the equinoctial precession period (P) of Mars results as the sum of two effects:

1) the prograde precession of the planet's orbit ($P_1 \approx 72{,}000$ years) and
2) the retrograde precession of its spin-axis ($P_2 \approx 173{,}000$ years)

where $P_1^{-1} + P_2^{-1} = P^{-1}$, giving $P \approx 50{,}800$ years. Thus, when a suitable angular orientation occurs between the Martian spin-axis and its orbit's perihelion (in ~ 10,000 years time), this could be retained if the precession period of the spin-axis of Mars was synchronized with the orbital precession period. In other words, at a configuration that the LWM predicts as suitable for biology we must alter the axial precession of the planet from $P_2 \approx 173{,}000$ years retrograde to $P_2 \approx 72{,}000$ years prograde. This might be done by applying a gravitational torque to the oblate figure of Mars that is not merely strong enough to counteract that due to the Sun, but which can induce the prograde precession required. Burns and Harwit calculated how this might be achieved by shifting Phobos, Mars' innermost satellite, to an orbit only 210 km above the planet's surface and tilted at 45° to the equator. However, they found that this arrangement would be unstable because of the torque applied to Phobos' orbit plane by the equatorial bulge of Mars. The mass of Phobos is just too small to do the job. As an alternative therefore, they examined how material removed from the asteroid belt and placed in Martian orbit might serve instead. Their equations defining the problem turned out to be satisfied by an infinite number of solutions that suggested that the desired torque could be provided by a retrograde revolving mass, or ring of material. An example of a workable solution that they cited was 1.34×10^{19} kg of material orbiting 31,600 km from the centre of Mars and inclined at 45°. This is about 1000 times the mass of Phobos and is roughly equivalent to ten ~ 100 km diameter asteroids (< 1% of the mass of the asteroid belt). The physical form of the mass does not matter and it could either be spread out in a ring, or consist of discrete masses, or a single artificially assembled moon ~ 200 km across.

Although this scheme is actually extrinsic planetary engineering, it is included in this review of ecocentric ideas since it exploits the climatic instability inherent in the LWM. Burns and Harwit emphasized their paper as being more a speculative thought experiment in orbital mechanics, rather than an immediately practicable proposal. The requirement to move so much matter through millions of kilometres of space renders the technique into an option for the more distant future. As far as the authors were concerned though, time was clearly on their side: *"The proposal is, perhaps, a fantastic one to contemporary minds. However, it seems to us that the required technology will not be wanting if man is alive 10,000 years from now."*

5.4.2. Sagan's Runaway Greenhouse

Carl Sagan himself entered into the arena of printed debate with a short paper later the same year [49]. He rightly pointed out that a 10,000 year wait for habitability to come about naturally might be pre-empted by alternative planetary engineering techniques. Since an alteration in the polar cap albedo would be the easiest to bring about artificially, he suggested that it might be possible to trigger a Martian "Spring" prematurely by darkening the surface of the polar ice with a layer of black dust or plant growth. This would cause the caps to absorb more solar radiation, heat up and to release some CO_2 into the atmosphere. This thicker atmosphere would have a greater greenhouse effect and would be more efficient at transporting heat poleward from the equatorial regions. The result would be an amplification of the original warming increment producing, if the initial perturbation was strong enough, a runaway growth of the Martian atmosphere in a timescale as short as ~ 100 years. The planet would not be fully habitable at the end of this process, but would have an atmosphere of carbon dioxide similar in density to that of the Earth, a greatly boosted greenhouse effect and a warm, moist, surface — most of the conditions required for ecopoiesis (see Table 5.6).

This concept is illustrated in Fig. 5.5 and is *particularly important* as it has become the basis for a number of variant runaway greenhouse terraforming models that have come since. The outgassing produced by the initial engineered warming, in turn generates a further warming, which causes more outgassing and so on... The implication is that the hypothesized inherent instability of the Martian climate might hand planetary engineers a particularly powerful lever with which to effect wholesale changes to Mars with comparatively little effort. After instability is artificially induced, the process runs away to completion using nothing more than the planet's natural endowment of solar energy (**b→c** in Fig. 5.4). *The changes in temperature and pressure required to permit ecopoiesis might therefore be relatively easy.*

The planetary engineering effort required to bring about this transition in Sagan's scenario did not seem all that great. He estimated that a reduction in the net albedo of the polar caps by a few percent might suffice and that this could be achieved by depositing a 1 mm layer of material with the albedo of carbon black over 6% of the cap area (see Plate 5.8). The total mass of material would amount to ~ 100 million tonnes, too much to transport from the Earth but easily obtainable on Mars itself where rocks with albedos < 0.09 in the Syrtis Major region have been seen. However, as Sagan recognised, the dark dust scenario has the problem that the layer could be prone to dispersal by the wind. To produce a dark layer permanent enough to make the instability run away he estimated that 10 - 100 times as much material might be needed. This increases the magnitude of the undertaking, but does not seem an implausible requirement for a future Martian civilisation wishing to terraform their planet. (It is several orders of magnitude less than the annual mobilization of rock by civilization on Earth — see Section 4.1.1). His alternate suggestion of using vegetation to darken the Martian poles seems superficially to be an even more attractive option, having the advantage that the low albedo layer would be self replicating and anchored to the surface. Very little transport or maintenance of material would be needed. However, since no terrestrial organisms can grow under the conditions prevailing in the polar regions of Mars, the use of biology would have to await substantial progress in genetic engineering or the ecopoiesis of Mars by other means.

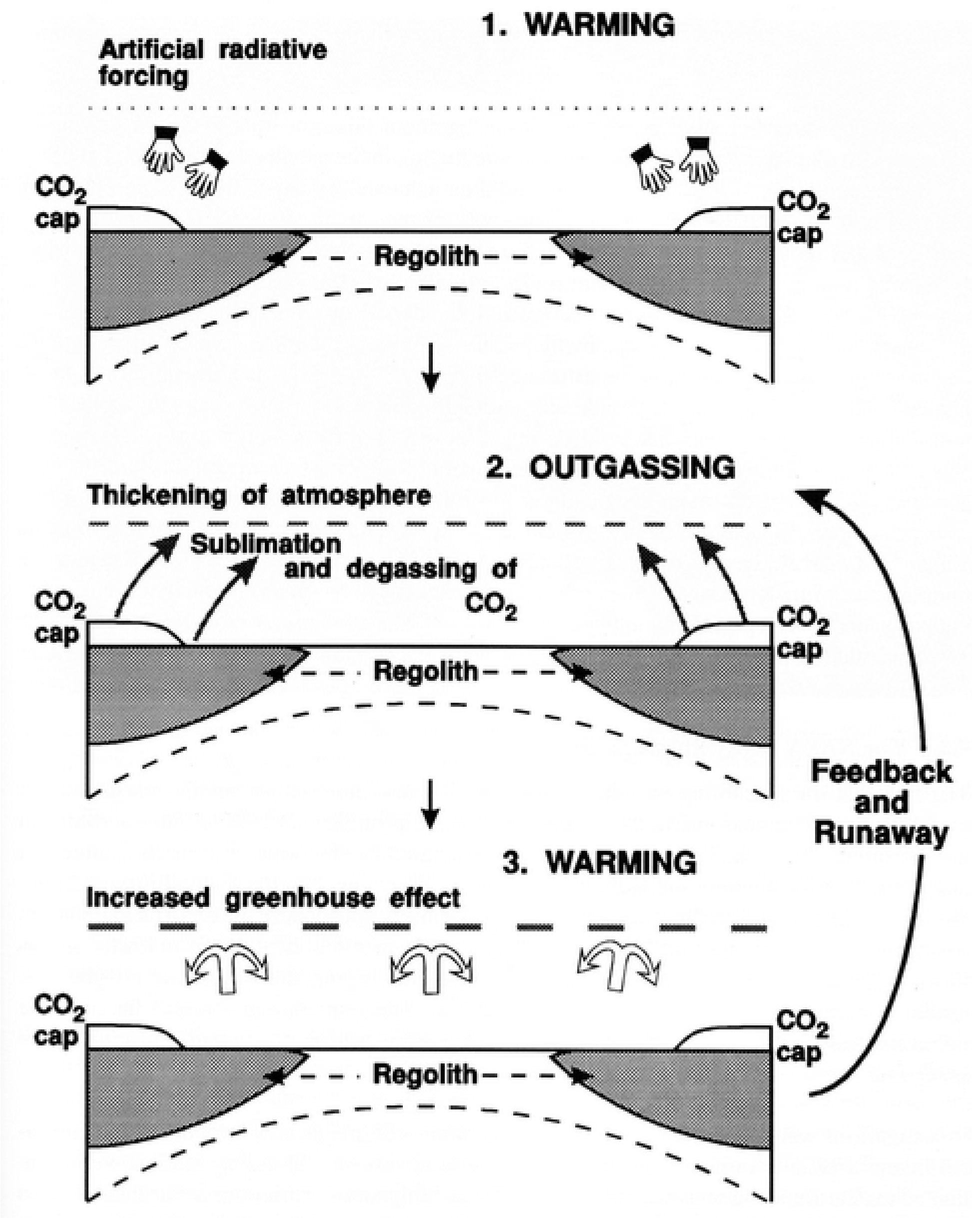

Figure 5.5 *Schematic of Sagan's runaway greenhouse scenario[49]: (1) Various planetary engineering techniques are used to warm volatile-rich regions of Mars; (2) Carbon dioxide in the polar caps and the Regolith starts to vaporize; (3) The thicker atmosphere warms the surface and hence causes a further release of gasses. If positive feedback is strong enough, self-sustaining outgassing may occur as a result of a comparatively trivial forcing.*

5.4.3 The NASA Ecosynthesis Study

The fact that the possibility of bringing life to Mars was now being openly discussed, and could be based on reasonable data for the first time, prompted NASA to fund a study on terraforming. It resulted in a 105-page report [50], prepared by the Ames Research Centre, and edited by Melvin Averner and Robert MacElroy. The title, On the Habitability of Mars: An Approach to Planetary Ecosynthesis was particularly apt, because the report's main thrust was to assess the suitability of Mars, as revealed by Mariner 9, to host life from Earth. It was this emplaced biota that would take on the task of modifying the Martian atmosphere to render it suitable for a wider range of living forms. The principal question of the exercise therefore was, in the words of the authors, *"Can terrestrial photosynthetic organisms be seeded on Mars, survive, grow and generate oxygen?"*

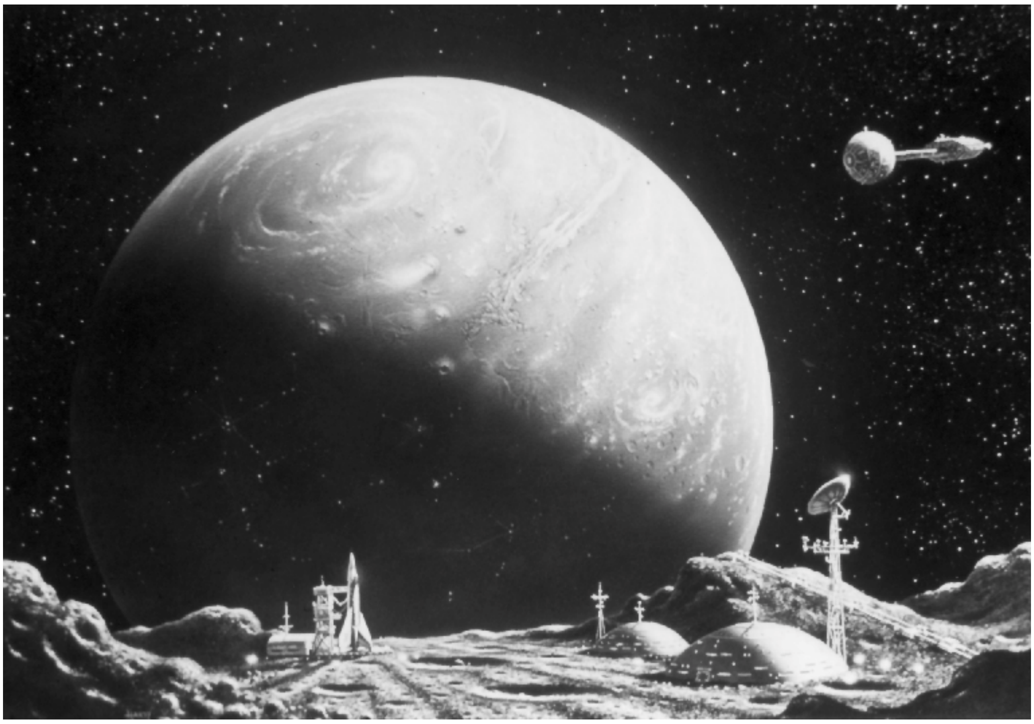

Plate 5.8 *Artist's impression of the Sagan scenario for Martian terraforming. Sagan also mentioned the possibility of pulverizing a small asteroid to obtain the dust to be scattered on the polar caps [49]: so we see here the Martian satellite Phobos being mined for the purpose. It turns out that this would not be necessary as there are abundant dark rocks present on Mars itself. (Artist: David hardy.).*

Investigations were done to estimate reasonable bounds of the physical properties and chemical inventories determining conditions at the Martian surface. Modeling studies were conducted to determine the seasonal and diurnal surface temperature variations at various latitudes and the intensity of the surface ultraviolet flux. The authors estimated that the surface from the equatorial regions down to 45^{o}S would be seasonally warmed above -3 ^{o}C for a total of ~ 2000 hours every Martian year. In high Summer therefore, ~ 7 hours per day would be warm enough for growth of cold-adapted ecosystems, assuming enough moisture was available and other essential nutrients, such as nitrogen and phosphorous. Their results for ultraviolet irradiation were less hopeful. Absorption by atmospheric CO_2 is capable of preventing ultraviolet radiation of wavelength < 190 nm from reaching the surface, but does not significantly attenuate wavelengths between 190 - 300 nm. This UV flux of ~ 6 W/m^2 would be lethal to most, if not all, unprotected organisms.

Having defined their model of the planet's environment, the authors then proceeded to speculate over those terrestrial organisms that might be suitable for transplantation on Mars. Ecosystems existing in the dry valleys of Antarctica survive in conditions closest to those they were proposing for Mars and so they concentrated primarily on assessing the survival of lichens and cyanobacteria. Both of these are resistant to desiccation and some lichens are also resistant to large doses of UV light. It was suggested that cyanobacteria might obtain protection from ultraviolet by surviving under a thin layer of soil or translucent rock or by growing in a microbial mat, protected by a dead surface layer of cells. Their mathematical models of lichen growths and cyanobacterial mats led them to conclude that, *"... there is a definite possibility for growth of certain anaerobic, cold-adapted terrestrial bacteria on Mars."* Although they were careful to add the cautionary note, *"Even a most optimistic appraisal suggests that the kinds of terrestrial organisms able to survive in the present Martian environment are quite limited and the growth of these forms would be restricted in vigour and extent."*

They resolved therefore that planetary engineering, primarily to increase the stability and abundance of liquid water, would be desirable for extensive growth of terrestrial organisms. In order to speculate over how this might be possible, they adopted a climate model similar to the LWM, assuming up to ~ 0.75 bar of CO_2 being present in the polar caps and ~ 2.5 bars adsorbed in the regolith. According to their calculations, a climatic runaway to a stable warm, high pressure state could be triggered by increasing the amount of solar energy absorbed by the polar caps by 20% for ~ 100 years.

They suggested four planetary engineering techniques that might have the desired effect:

1) Altering Mars' distance from the Sun from 1.5 AU to 1.4 AU;
2) Changing its orbital eccentricity from 0.09 to 0.49;
3) Tilting the planet from an obliquity of 25^{o} to 31^{o} or
4) Darkening the albedo of the polar cap from 0.77 to 0.73.

Not surprisingly, the authors identified the latter choice as being the only practical one and so their proposal for terraforming's first step was essentially identical to Sagan's runaway greenhouse model [49]. The study then went further and looked at what kind of ecosystems might function in this modified, but still quite hostile, Martian environment. (Pioneering Martian organisms and ecosystems are considered in greater depth in Section 5.6). Since no further planetary engineering was considered, it was calculated that photosynthetic production of oxygen by this sparse Martian biosphere would take ~ 140,000 years to generate a partial pressure suitable for human beings. This six figure timescale for *full* terraforming has remained an accepted ballpark figure ever since and has only been challenged recently (see Chapter 6).

The NASA study summed up its findings by stating that no fundamental, insuperable limitation of the ability of Mars to support a terrestrial ecology had been identified. However, the habitation of Mars by higher organisms, and ultimately humans, was felt to be a very remote prospect and perhaps impossible without extensive planetary engineering possibly involving the use of genetically engineered organisms specialized for conditions on Mars.

The same year the report was published (1976), the Viking probes arrived at Mars, each a two component vehicle with both an orbiter and lander. Both Vikings functioned perfectly, sending new and better quality data back to Earth, information that answered some of the questions left open by Mariner 9. In 1979 Averner and MacElroy reassessed the habitability of Mars in the light of what had been learned from the Viking project in a privately circulated manuscript [51]. Their conclusions were decidedly more downbeat, particularly concerning the instability of liquid water anywhere on the Martian surface and the low partial pressure of nitrogen. This seems to rule out any chance of a purely biological route to ecopoiesis without substantial planetary engineering first. Even this they seemed to doubt, stating in their penultimate paragraph, *"It is not a* *strong possibility that even a massive engineering project could trigger the conversion of all of Mars into a more hospitable environmental state."*

Many workers in the field now would contend that the above statement is probably too pessimistic — as it does not define and probably understates what could potentially be involved in a "massive planetary engineering project". However, evidence returned from the Viking missions did destroy the basis of the Long Winter Model — as the Martian channels were found to have been dry for far longer than ~ 10,000 years and the North polar cap was shown to consist predominantly of water ice and not frozen carbon dioxide [12]. What CO_2 does exist in the Southern cap may not be sufficient to double the atmospheric pressure, let alone increase it by 2-3 orders of magnitude [52]. It seems likely therefore that the runaway greenhouse scenario, as originally conceived, is unrealistic.

5.5 Modern Ecopoiesis Models

As described by Oberg, the early period of interest in terraforming reached a peak of intellectual excitement at the First Terraforming Colloquium in 1979 (see also Chapter 1). Serious investigation of the subject then largely returned to the scientific back-burner. Christopher McKay was one of the few remaining workers who continued a discreet, but unbroken, commitment to the idea and published his first paper [53] on terraforming Mars in 1982. This can perhaps be regarded as the last serious work to emerge from the period of terraforming's birth as a legitimate subject for study, and the first in which recognisably 'modern' ideas began to crystallize. It was the first paper to adopt the word "terraforming" in its title and outlined a planetary engineering model and an ecocentric philosophy that remain the most influential context in which to study the subject.

Whilst the LWM was dead, the runaway greenhouse terraforming concept derived from it has remained very much a front runner. The revision necessary for this continued state of health has been a relocation of its putative reservoir of non-chemically bound CO_2, from the polar caps, to gas adsorbed on mineral grains within the regolith. It is thought that this sub-surface stockpile of carbon dioxide can be mobilized and driven into the atmosphere by an increase in temperature, much as warming damp blotting paper releases water vapour. The crucial question is how much CO_2 is available in this labile form: if it is ~ 1 bar or more, then ecopoiesis may still be possible with a single act of planetary engineering. McKay therefore envisaged terraforming as a two stage process. The first would be a short phase of ~ 100 years, warming the surface, releasing volatiles and creating a microbial biosphere. Conscious planetary engineering would then cease, ushering in a second ~ 100,000 year stage in which a breathable atmosphere is gradually produced by autonomous biological methods alone. Whilst this scheme was similar to those of the seventies, it was McKay who associated it so strongly with the geophysiological ideas of James Lovelock, a crucial part of his vision involving independent planetary evolution and homoeostasis by a Martian version of Earth's hypothetical Gaia.

McKay did not specify a particular planetary engineering technique in his 1982 paper but felt that, *"A terraformed Mars need not duplicate the Earth in every respect..,"* and thus argued for a "passive" approach using, *"... current or foreseeable engineering methods... allowing time to accurately observe and learn from the complex interactions and physical and biological factors resulting from the process."* He therefore divided planetary parameters into two categories (listed in Table 5.8), *physical* and *environmental*, and envisages that only the latter can be subject to change by planetary engineering in any practical fashion. His personal preference remains for biological methods if at all possible.

For this philosophy to be workable however, he still needed an acceptable method of bringing about the initial warming of the planet. This was provided by Lovelock himself in his novel The Greening of Mars in 1984 (reviewed in Section 1.2.2) in which he described a scenario where the planet is heated by adding chlorofluorocarbon gases (CFCs) into its atmosphere [54]. These compounds are thought to be a positive nuisance on Earth, not just because of their erosion of the ozone layer, but also because of their enormous greenhouse effect — thousands of times the strength of CO_2 (see Table 4.4). However, on Mars this latter disadvantage offers the beneficial prospect of creating a powerful anthropogenic radiative forcing with a manageable quantity of material. Whilst it would be far too expensive to ship the necessary mass of CFCs from Earth, as is depicted in the novel, nothing appears to rule out their industrial, and possibly biological, manufacture on Mars.

TABLE 5.8 MCKAY'S CATEGORISATION OF PLANETARY PARAMETERS

Physical	Environmental
Sun-planet distance	Surface temperature
Rotation rate	Pressure
Obliquity	Humidity/precipitation
Eccentricity	Atmospheric composition
Radius	Albedo
Mass	Atmospheric transmissivity
Orbital perturbations	Volatile distribution
Volatile budget	

Quiet research behind the scenes continued between 1982 and 1987 when the subject started to re-emerge from obscurity, mainly due to the efforts of McKay and Haynes in North America and Martyn Fogg in the UK. The most significant recent paper on terraforming Mars was written by McKay and two co-authors, Owen Toon (an original collaborator with Sagan) and James Kasting [55]. It was a work of considerable importance, not least because of the prestigious and widely-read forum where it was published in 1991 — the journal *Nature*. Although it was billed as a "Review Paper," its scrutiny of research into the range of habitable conditions and the various estimates of the Martian volatile inventory was secondary to its main purpose of presenting new, quantitative, modelling. Years of reflection on the story the Viking data was telling about Mars' early history had gradually given birth to a new paradigm — terraforming as a *restoration project*, rather than the works of humanity writ large on a planet-sized blank slate. As expressed by the authors, *"If Mars did have an early clement, possibly life-supporting, environment, then it is important to our understanding of planetary evolution to develop models for the fate of the early atmosphere and to consider under what conditions, artificial or natural, this environment could return."*

In order to better define the scale of the problem of warming Mars, McKay *et al.* used a one dimensional radiative-convective model of an Earth-like planetary atmosphere in equilibrium with liquid water. The model planet was placed the same distance from the Sun as Mars, carbon dioxide was included at a partial pressure of 10 mbar (the toxic limit for humans), and the surface temperature (T_{surf}) was set at 15°C. The results of the model, in terms of infrared radiation escaping from the planet, are plotted as the solid line in Fig. 5.6. The upper dotted line is the blackbody curve for the *surface* temperature and the lower dotted line is the blackbody curve for the *effective* temperature of the planet (T_{eff} — that at which it radiates into space), which is mainly controlled by the insolation, and hence the distance of the body from the Sun (see Equations 2.15 and 2.16). For the system to be in equilibrium the area under the solid curve must equal the area under the lower curve. This is clearly not the case and it can be seen that far to much infrared is being radiated into space, especially from the "window region," between wave numbers of ~ 800 - 1200 cm^{-1} (wavelengths of 8.3 - 12.5 μm). Running the model to allow T_{surf} to adjust to a state of radiative equilibrium (incoming sunlight = outgoing heat) gave a surface temperature of -55°C, scarcely warmer than Mars is now. The reason for this is the positive feedback relationship between water vapour and surface temperature. On the Earth, water vapour is the main greenhouse gas ($\Delta T_{green} \approx 30^{o}C$); but in this model of an Earth-like atmosphere on Mars, water vapour freezes out of the atmosphere as the surface cools to adjust to radiative equilibrium, reducing the greenhouse effect and accentuating the cooling.

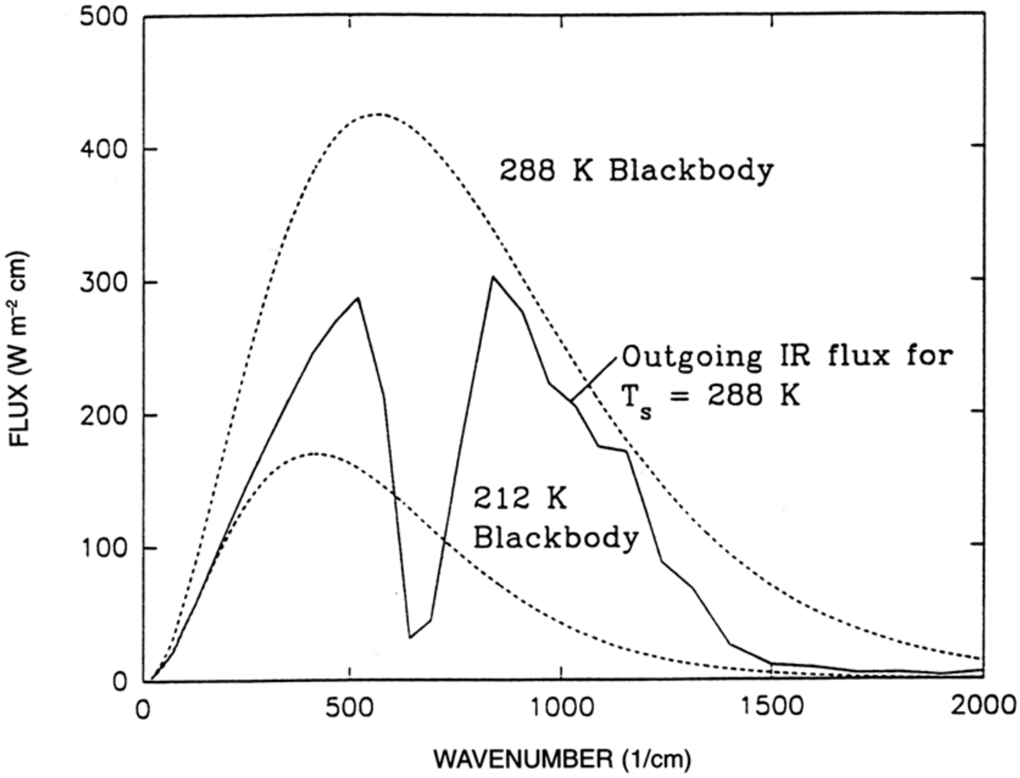

Figure 5.6 *Thermal balance of a model 1-bar Earth-like atmosphere on Mars with 10 mbar of CO_2 in equilibrium with water. The surface temperature is set at 15° C and is shown as the upper dotted curve; the temperature at which the planet should radiate to space is shown as the lower dotted curve. The solid line is the actual infrared radiation emitted at the top of the atmosphere showing that the surface is far too hot to be in equilibrium. (Reproduced with permission from Ref. [55].)*

McKay *et al.* [55] therefore had demonstrated a need for an atmosphere of radically different composition than the Earth's, with a much stronger greenhouse effect, in order to adequately warm Mars. The most significant sections of the *Nature* paper therefore were those presenting new, and more detailed models of both the anthropogenic and runaway greenhouse scenarios.

5.5.1 The Trace Gas Greenhouse

Following Lovelock's lead, McKay *et al.* tried to assess the likely effectiveness of adding large quantities of CFCs into the Martian atmosphere.

As outlined in Section 4.1.3, the efficiency of CFCs as greenhouse gases results from their absorption of outgoing infrared radiation in the atmospheric "window region" in which water vapour and carbon dioxide have little activity. Models of their radiative forcing in the Earth's atmosphere suggest that a concentration of just 1 part per billion of such gases in the atmosphere can cause a ~ 0.1°C rise in surface temperature and that this warming would extend over several hundred years due to their long persistence in the environment. From this one might suppose that in order to provide a $\Delta T_{surf} = 60°C$ for Mars, one might therefore require concentrations of CFCs in the parts per million range. McKay *et al.* identified a cocktail of C_2F_6, CF_3Cl, CF_2Cl_2 and CF_3Br being of particular interest since they are non-toxic, have absorption bands throughout the infrared window, and long atmospheric lifetimes (see Fig. 5.7 and Table 4.4). For the purposes of illustration they assumed that 10 ppm (~ 0.01 mbar) of these gases would need to be introduced into the Martian atmosphere — a mass of 40 billion tonnes. Should the average lifetime of the cocktail be ~ 400 years, this would entail the manufacture of ~ 100 million tonnes per year, ~ 100 times the present demand on Earth but not beyond present day chemical manufacturing capacity.

Models of greenhouse warming on Earth due to CFCs cannot however be used with confidence to predict an outcome on Mars since concentrations typically 1000 times greater are involved. Because of this, McKay *et al.* modified their atmosphere model by specifying two hypothetical cocktails of trace greenhouse gases. The first was where the gases were active in the infrared window region only (see Fig. 5.7); the second was a "uniform grey absorber" — one that covers the entire infrared spectrum with the same opacity at all wavelengths.

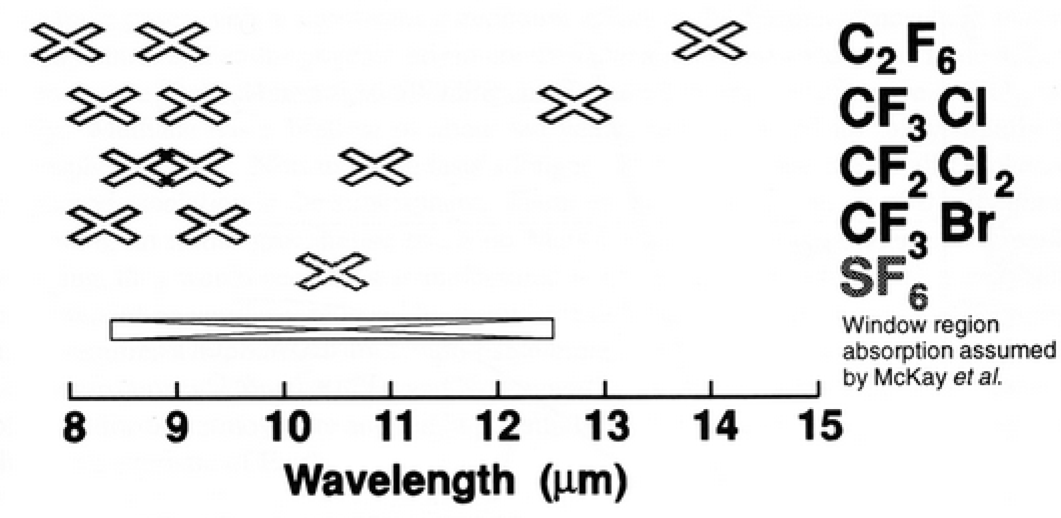

Figure 5.7 *The mixture of trace gases identified to be of particular interest by McKay et al.[55] and the positions of their absorption band centers in the infrared window. The crosses are not representative of bandwidths. Also shown are data for sulfur hexafluoride (which was mentioned in passing) and the hypothetical window region absorption assumed for their simulation of greenhouse warming.*

The results of this modeling are shown in Fig. 5.8 and it is interesting to note that where absorption is confined to the window region the average temperature of Mars remains below freezing. Temperature increases of $\Delta T_{surf} \approx 30$ °C seem possible for the present atmosphere of Mars and $\Delta T_{surf} \approx 40$ °C for an Earth-like atmosphere, before the effect saturates, due to the loss of infrared radiation from other spectral regions. Only a uniform grey absorber can raise the temperature above 0°C, since it prevents leakage of heat over the entire infrared spectrum. One can perhaps infer from these results that, if trace greenhouse gases are to take on the entire task of warming Mars, a realistic cocktail of chemicals might only give planetary engineers about half of the temperature increment they need.

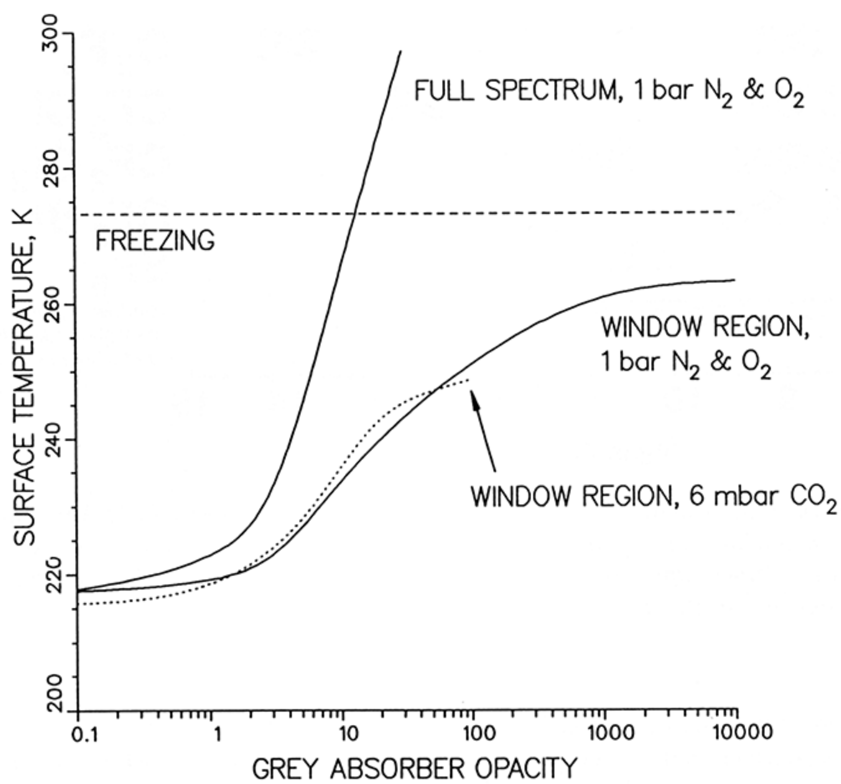

Figure 5.8 *The effect of adding trace gases to the Earth-like Martian atmosphere shown in figure 5.6 (solid lines) and to the present-day atmosphere of Mars (dotted line). Trace gas absorption in the window region gives maximum warming increments of ~40°C and ~30°C, respectively. A uniform gray absorber, however, a hypothetical mixture of gases that is active over the entire infrared spectrum, can warm Mars above freezing. (Reproduced with permission from Ref. [55].)*

There are specific problems with CFC gases that will limit their use as terraforming tools and these include their vulnerability to photodissociation by UV light in the 200 - 300 nm range, and the fact that the active chlorine released by this process would destroy a crucial feature of a habitable planet — its ozone layer (as described in Section 4.1.2). The reason for the long survival of CFCs in the Earth's environment is because the lower atmosphere is screened from this radiation by the ozone layer in the overlying stratosphere. It can take many years for CFC gases to be transported from the troposphere into the stratosphere where they can be broken down. On Mars, the atmosphere is transparent to this radiation and thus CFCs would be destroyed at a much faster rate — expected lifetimes falling from centuries to days. McKay *et al.* calculated that with such loss rates, CFCs would have to be manufactured at a rate of 3 trillion tonnes/year — an impractical proposition. Chlorofluorocarbon gases can therefore only survive for long timescales if protected by an ozone layer, but themselves contribute to the destruction of that ozone layer — a classic Catch-22 situation!

There are of course other candidate gases with powerful greenhouse effects in trace concentrations that might be used instead of CFCs. Some of them might be manufactured biologically, which might have the advantage of linking the regulation of surface temperature with biogeochemical cycles in a more autonomous and Earth-like way. Pollack and Sagan [56] have considered using ammonia to boost the Martian greenhouse effect, having estimated that a partial pressure of ~ 0.1 mbar of NH_3 could raise the mean global surface temperature above freezing. However production of this amount of ammonia would require virtually all the nitrogen in the atmosphere and relies on the dubious prospect of genetically engineered organisms surviving in the pre-terraformed environment. An even greater difficulty is rapid photodissociation by UV radiation which they estimate would totally break down 0.1 mbar of ammonia in 30 years, a loss rate that would probably outstrip any feasible rate of production. A substantial ammonia partial pressure within a fully terraformed atmosphere is even more problematic. the amount of NH_3 in the Earth's atmosphere is < 1 ppb and its great affinity for dissolving in water limits its lifetime to a few days. In addition, a partial pressure of 0.1 mbar of this gas is close to the limit of human tolerance.

Two trace gases with a significant greenhouse effect in the Earth's atmosphere that are of mixed natural and anthropogenic origin are methane and nitrous oxide (see Table 4.2). On a per molecule basis, their radiative forcings are 21 and 206 times as effective as CO_2 respectively. Methane has a lifetime of about ten years, being mopped up fairly rapidly in the troposphere by OH. Nitrous oxide lasts a longer ~ 150 years, since it is finally broken down by photodissociation in the stratosphere. These gases are unlikely to be of significant use in producing an initial greenhouse effect on Mars because, to produce a similar greenhouse warming, they would need to be manufactured in greater quantities than CFCs and their lifetimes would be similarly reduced by ultraviolet radiation. Moreover, biological production again requires a hypothetical, and improbable, biota capable of flourishing in the present Martian environment. However, CH_4 and N_2O would be useful additions to the greenhouse effect of a terraformed atmosphere and might potentially be manufactured to greater concentrations than characteristic of Earth.

The modeling of the anthropogenic greenhouse in the *Nature* paper did show that there is nothing *fundamental* that rules it out as a possible terraforming technique. The authors concluded, *"Therefore it seems possible, in principle, to produce a warm oxygen-rich atmosphere given an adequate supply of N_2, O_2 and the appropriate trace greenhouse gases."* However, no such cocktail with uniform grey absorption is yet known and so there remains a large gulf between principle and practicality. The properties of the ideal greenhouse gas mixture have been listed by Fogg [57]:

1) uniform grey absorption
2) strong radiative forcing at low concentrations
3) non-destructive of ozone
4) long atmospheric lifetime
5) resistance to photodissociation
6) non-toxic in ppm concentrations
7) manufacturable from elements likely to be abundant on Mars

Properties 3 - 5 are interrelated in the sense that the gases must be chemically and photochemically inert.

Possible candidates for this hypothetical cocktail are beginning to emerge and these are fully fluorinated compounds, such as the perfluorocarbons, and sulphur hexafluoride. Recent work [58] has shown that their persistence in the Earth's environment is much longer than previously thought since the major loss process is photodissociation in the mesosphere by Lyman-a radiation at 121.6 nm (or in the case of SF_6, by reaction with free electrons). On Mars, Lyman-a is screened by carbon dioxide — the principal component of the atmosphere — and so the lifetimes of *thousands of years* predicted for these compounds on Earth might similarly apply (see Table 5.9). Another advantage of these compounds is that when they do finally break down, no chlorine-containing fragments are released, and since fluorine does not catalyse ozone destruction, any Martian ozone layer should be unaffected.

TABLE 5.9 PERFLUORO GASES AS TERRAFORMING TOOLS: AN UNKNOWN POTENTIAL

Species	Infrared Band Centres (mm)	Lifetime (years)†
CF_4	7.78, 7.93, 15.8	> 50000
C_2F_6	8.00, 8.96, 14.00	>10000
C_3F_8	?	?
C_4F_{10}	?	>2600‡
C_5F_{12}	?	4100
C_6F_{14}	?	3100
c-C_4F_8	?	3200
$(CF_3)_2$c-C_4F_6	?	2900
? #	?	?
? #	?	?
...#	...	...
SF_6	~ 10.5 & ?	3200

Data taken from Refs [58,59].
† Lifetimes appropriate for Earth, where significant loss occurs by the passage of air through high temperature combustors. In the absence of this process lifetimes of CF_4 and C_2F_6 could be ~ 10 times longer.
‡ Lower limit estimate.
# Many other possible perfluorocarbons.

Only the absorption bands of CF_4 and C_2F_6 are available and these are situated on the edges of the infrared window; data on one band for SF_6 has been published and is usefully located in the middle at ~ 10.5 µm [59]. Whilst there are no data on the absorption bands of the higher perfluorocarbons, it seems likely that at least some of them will exhibit absorption bands that will plug other holes in the window. Whether though it will ever be possible to concoct a mixture of fluorinated compounds that will absorb efficiently over the entire infrared is another matter entirely. Thus, property (1) of the above list may be an uncertain expectation, but we can be reasonably optimistic about properties (2-7).

At the present time therefore, the prospect of an trace gas greenhouse delivering all of the 60°C warming required on Mars looks doubtful. However, as a method of warming Mars that might operate in concert with other techniques, it has considerable promise. This is especially in view of the fact that research into designer greenhouse gases for use in terraforming has hardly begun; as is shown in Table 5.9, gaps in our knowledge of the properties of perfluoro compounds mean that their potential is uncertain.

5.5.2 The Runaway Carbon Dioxide Greenhouse

Might a lesser anthropogenic warming by trace greenhouse gases (or other candidate tools from Table 5.7) be used to vaporize CO_2 and trigger Sagan's runaway greenhouse? Quantitative modeling of this process was done by the *Nature* authors [55] and more recently by Robert Zubrin, an engineer at Martin Marrietta Astronautics, working in concert with McKay [60].

5.5.2.1 The poles again

Techniques for vaporizing the South polar cap are still worth studying even though optimistic assumptions place an upper limit to its storage capacity of < 100 mb of carbon dioxide. This is because CO_2 ice directly exposed at the surface will be the most accessible to planetary engineers. The $\Delta T_{surf} \approx 10$ °C increase that would result from an increased greenhouse effect, if all this inventory were to be vaporized, is only a sixth of that required for terraforming but might possibly be of use in concert with other processes, such as triggering a larger outgassing of the regolith.

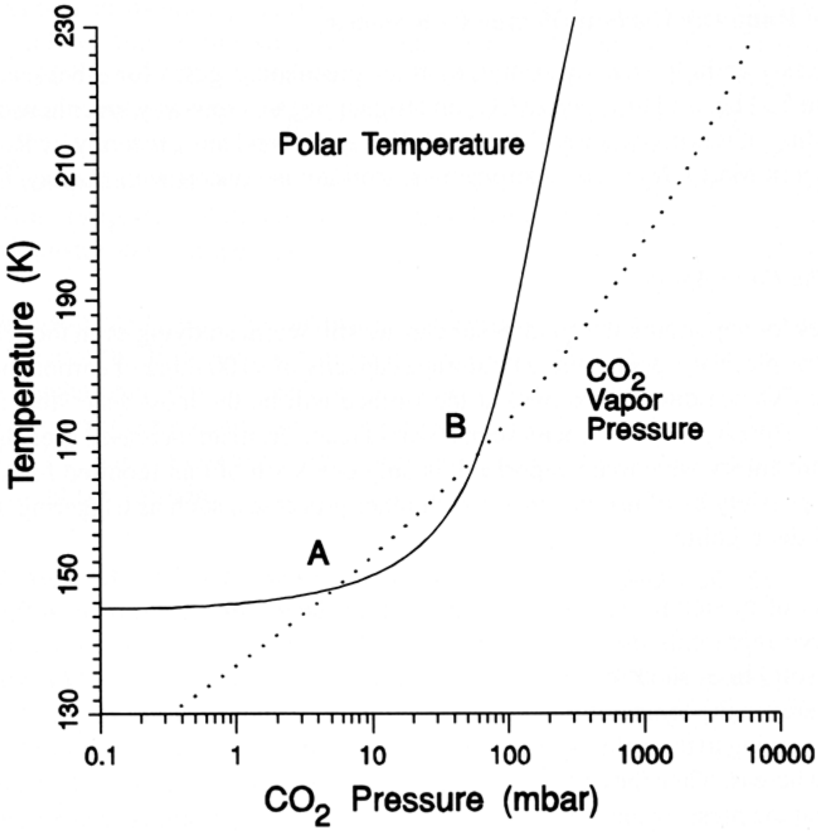

Figure 5.9 *Evaporation of carbon dioxide from a Martian Polar cap. The dotted line represents the vapor pressure of CO_2 with respect to temperature. The solid line is a climate model prediction of the polar cap temperature as a function of atmospheric pressure. The intersection point **A** is stable and represents the present condition. The point **B** is an unstable equilibrium and to the right of this the temperature curve is above the vapor pressure curve. Forcing the system a little beyond **B** will result in a runaway evaporation of the cap. (Reproduced with permission from Ref. [55].)*

The results of modelling the vaporization of Mars' polar caps are shown in Fig. 5.9. The dotted curve represents the vapour pressure of CO_2, as a function of the polar temperature; whilst the solid lines show the polar temperature as a function of the CO_2 atmospheric pressure. Wherever the temperature curve lies above the vapour pressure curve, the system responds by moving to the right — the cap sublimes and the temperature and atmospheric pressure increase; whereas, when the opposite is true, the system moves to the left — CO_2 condenses on the caps and the pressure and temperature falls. The polar temperature curve crosses the vapour pressure curve at points **A** and **B**. **A** is a stable equilibrium and represents the current state of Mars — a polar temperature of ~ -126 °C and an atmospheric pressure of ~ 6 mbar. **B** is an unstable equilibrium and at pressures in between **A** and **B**, the system is drawn towards **A**; however a tenfold increase in atmospheric pressure above ~ 60 mbar causes a runaway vaporization, to a new stable state where all the cap inventory is in the atmosphere.

Zubrin [60] has pointed out that an artificial warming of the cap would be represented by shifting the solid polar temperature curves upwards. Points **A** and **B** would converge and eventually, the temperature curve would be above the vapour pressure curve everywhere and the cap would sublime. So long as > 60 mbar of CO_2 is released by the process, the artificial warming could be switched off after the job is done without fear of a recondensation of the atmosphere back onto the poles. It seems that as little as a 5°C increase in polar temperature might suffice to trigger the process, something that might be achievable by the albedo reduction or anthropogenic greenhouse scenarios previously discussed. Zubrin however has raised another possibility — the use of a space-based mirror with which to enhance the South pole's insolation.

One can estimate the size of mirror needed to raise the surface temperature of the required area of Mars by treating the illuminated surface area to be a black body. The total surface area South of 70° latitude is ~ 4.34×10^{12} m^2 and, assuming its temperature is at equilibrium, then input of energy = output. At a temperature of 150 K, the polar region will therefore be receiving $4.34\times10^{12}\ \sigma \times 150^4 \approx 1.25\times10^{14}$ W (where σ is the Stefan Boltzmann constant). At 155 K (ΔT = 5°C) energy input must rise by $(155/150)^4$ to 1.42×10^{14} W and it is the difference between these two values, 1.7×10^{13} W, that must be provided by the mirror. Given a Martian insolation of 589 W/m^2, the requirement can be met by a plane mirror ~ 100 km in radius. In fact, since the mirror will have to be tilted to the solar beam, its size will be greater — Zubrin's estimate being a radius of 125 km, made of solar sail material with an areal density of 4 tonnes/km^2 (4g/m^2) and massing 200,000 tonnes. It is interesting to note that this is similar in scale to some of the larger soletta systems envisaged by Ehrike to be used around the Earth but is over an order of magnitude smaller than the large parasol systems designed to offset global warming (see Section 4.2.6). The Earth's current aluminium production is ~ 15 million tonnes per year and so the level of space manufacturing capacity needed to produce the material for the mirror is not unfeasible, especially if spread out over a decade or so.

The configuration of mirror proposed by Zubrin is derived from a concept of a levitated satellite invented by Robert Forward [61], the well-known aerospace engineer (and lately, science fiction author). The "statite," as Forward has named it, does not orbit a planet, but maintains itself in a static equilibrium position by balancing light pressure force against gravitational force. Its principal component is therefore a light sail from which a payload can be suspended and a schematic of the concept, positioned above the Earth, is shown in Fig. 5.10a. Zubrin envisages his Martian mirror operating as a statite positioned 214,000 km behind the planet where its power output can be trained permanently on the South pole (Fig. 5.10b). Whether or not the total mirror area should be assembled in one piece, or consist of a fleet of smaller statites, is not clear. However, the techniques of stabilization of space reflectors discussed in Section 4.2.6 would similarly apply.

Since space reflectors are extrinsic terraforming tools, they are not favourably regarded from the ecocentric stand-point, especially if they would need to be positioned and maintained permanently. Zubrin's mirror is only intended to be utilized for as long as it takes to release polar volatiles, however if the mass of CO_2 sequestered on the South pole is much smaller than 100 mbar, its usefulness will be very limited in any case.

Whilst Mars would certainly benefit from a substantial increase in its overall insolation, much more ambitious mirror designs would be required and are therefore reserved for discussion in Chapter 6.

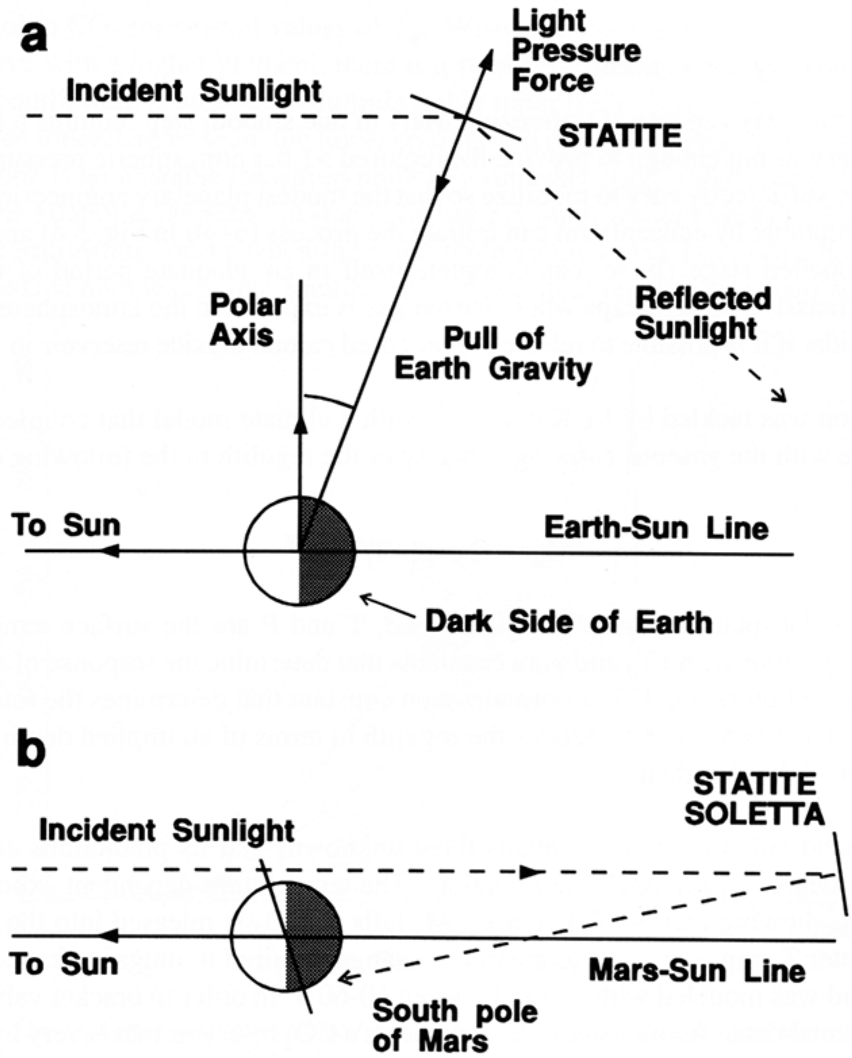

Figure 5.10 a. *The "Statite" concept of Robert Forward, A satellite that can hover by balancing a planet's gravitational force against light pressure on a solar sail. (Adapted with permission from Ref. [6].)* ***Figure 5.10 b.*** *The use of Forward's statite by Zubrin and McKay[60] for heating the south pole of Mars. The mirror is not shown to scale and, for the sail density assumed, would operate at a distance of 214,000 km behind the planet.*

5.5.2.2 Degassing the Regolith

A climatic runaway capable of unfreezing Mars in one smooth step requires a labile carbon dioxide reservoir big enough to provide the required > 1 bar atmospheric pressure. This CO_2 must also be sufficiently easy to mobilize that the modest planetary engineering techniques thought acceptable by ecocentrism can initiate the process (**a→b** in Fig. 5.4) and the following "self-propelled" stage (**b→c**) can complete itself in an adequate period of time. In the absence of massive enough caps where frozen gas is exposed to the atmosphere, it is important to consider if it is possible to release the proposed carbon dioxide reservoir in the regolith.

This question was tackled by the authors of the *Nature* paper [55] with a climate model that coupled the surface temperature with the gaseous carrying capacity of the regolith in the following expression:

$$M_a = C \exp(-T/T_d)P^{\gamma} \qquad (5.1)$$

where M_a is the total amount of CO_2 adsorbed, T and P are the surface temperature and pressure respectively and T_d and γ are constants that determine the response of adsorption to temperature and pressure. C is a normalization constant that determines the total amount of adsorbed gas and hence parameterizes the regolith in terms of an implied depth and specific surface area of the absorbent.

The right hand side of equation 5.1 contains three unknowns and thus its predictions are inevitably subject to a degree of personal interpretation. The temperature-dependent exponential term is dominant, showing that, as T increases, M_a falls as CO_2 is released into the atmosphere. The parameter T_d therefore represents the temperature change required to outgas a fraction 1/e of the reservoir and was modelled with values between T_d = 10 - 60 °C in order to bracket values provided by experimental data. A low value of T_d therefore represents a CO_2 reservoir that is very loosely bound and a high value one that is very tightly bound. The pressure term, which tends to increase adsorption with pressure, was considered to have a secondary influence and the parameter γ was set at a value of 0.275, again on the basis of experimental data. In the modeling presented in the *Nature* paper, C was set so as to simulate a 1 bar total CO_2 atmosphere-regolith reservoir.

McKay *et al.* ran their model for two limiting cases. The first is where carbon dioxide is adsorbed uniformly within a global regolith which is thus treated as being at the average planetary temperature; the second is where the CO_2 is concentrated in the two polar regoliths and is therefore subject to the polar temperature. The latter case may be more realistic since the poles act as natural volatile traps due to their low temperature. Modeling of the former suggested that there is no high-pressure/high-temperature stable state on Mars unless T_d = 10 °C which is not very plausible. However, the polar regolith simulation proved to be more labile and prone to runaway to a warmer, potentially habitable, climate.

The results for the polar regolith are shown in Fig. 5.11. The dotted line represents the polar temperature as a function of atmospheric pressure and the solid lines are the desorption pressures of regolith CO_2 for several values of T_d. Where the desorption curve crosses the temperature curve with a higher gradient, there is a stable equilibrium point; when the opposite obtains, the equilibrium is unstable. Multiple stable states for T_d = 10 - 40 °C, where the curves intersect three times, can therefore be seen: the lower equilibrium being characteristic of the Mars of today, the middle one being an unstable transition point to a runaway state and the upper equilibrium representing the goal of ecopoiesis — a stable, higher pressure, warmer climate. Favourable dynamics for terraforming occur when the polar temperature curve lies above the desorption curve, beyond the middle unstable equilibrium. In this situation, the system shifts to the right — gas leaves the regolith for the atmosphere, its greenhouse effect heating the surface and desorbing more gas until either the upper equilibrium point is reached or the reservoir is exhausted. When the polar temperature curve is below the desorption curve, the system moves to the left — returning Mars to its present frozen condition. The distance between the lower equilibrium point and the middle instability point therefore can be looked upon as the "resistance" within the system (**a→b** in Fig. 5.4) — a measure of the "inertia" that planetary engineers must overcome, before Mars starts to move freely down its imposed environmental trajectory (**b→c**).

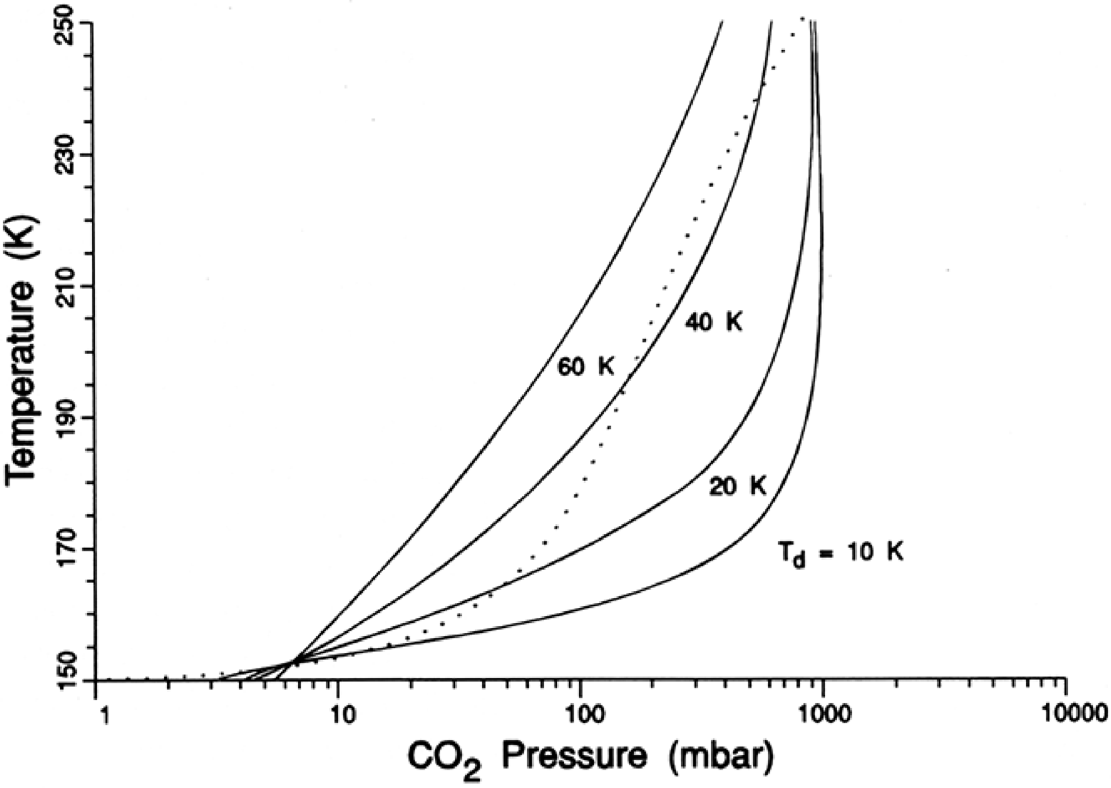

Figure 5.11 *Desorption of carbon dioxide from a polar regolith for an assumed inventory of 1 bar. The dotted line is the polar Regolith temperature as a function of atmospheric pressure, as determined by climate model calculations. The solid lines are the desorption pressure of regolith gas as a function of temperature for four different values of T_d. Where the dotted curve lies above the solid curve the system moves spontaneously to higher temperatures and pressures. Either until regolith is exhausted , or the two curves intersect. Stable warm climates are predicted for all cases except T_d=60°C. (Reproduced with permission from Ref. [55].)*

Fig. 5.11 shows that hopeful results are predicted for values of T_d between 10 - 40 °C. For example, if T_d = 20 °C, then when the atmospheric pressure rises to ~ 40 mbar, outgassing becomes dominated by positive feedback and a climatic runaway occurs, mobilizing essentially all of the 1 bar adsorbed reservoir into the atmosphere. At these pressures, the tropical regions of Mars would be above freezing for an appreciable fraction of the year. The desorption of a ~ 2 bar reservoir, should it exist, would produce a Mars with its mean global temperature > 0 °C. It is unlikely however that regolith CO_2 is as loosely bound as T_d = 20 °C implies. A more realistic value of 40 °C pushes the instability point to a pressure of > 100 mbar. However, the picture can be improved with artificial warming which will have the effect of lifting the polar temperature curve so that the instability points slide down the desorption curves to lower pressures. Instability thus becomes easier to trigger and, except for T_d = 60 °C where no high temperature stable state exists, the artificial warming could be stopped once the runaway was complete. This applies also to the less tractable global regolith and it seems that if planetary engineers can provide 5 - 30 °C of artificial warming, then most of the cases studied can be made to respond with drastic increases in both atmospheric pressure and surface temperature.

The work of McKay *et al.* [55] has therefore shown that a more sophisticated appraisal of the runaway CO_2 greenhouse on Mars lends credence to the validity of its basic physical mechanisms. It is possible therefore that minor modifications to the Martian insolation, albedo or greenhouse effect can result in great improvements in the planet's habitability; large feedback factors of $f \approx \Delta T_{surf}/\Delta T \approx 60^oC/5^oC \approx 12$ seem possible in optimistic scenarios (see Equation 3.5). This does not mean however that the idea is necessarily realistic, only that it is reasonable given the magnitude of uncertainty inherent in Martian planetology. There are particular doubts (outlined in Section 6.1) over the mass of the regolith reservoir and whether, without a much greater level of technological intervention, outgassing can actually occur in as short a time as ~ 100 years. However, too little is known about the absolute and relative masses of volatile reservoirs for the concept to be disproved on these grounds. Should these doubts become serious objections however, then more techno-centric approaches to terraforming Mars may be in order (Chapter 6).

Having considered how the Mars' volatile inventory might be rearranged, only rough estimates of the energy requirements for terraforming Mars can be made. Basic calculations of the energy needed to mobilize enough Martian volatiles for ecopoiesis (~ 2 bar CO_2, ~ 10 m water, plus water vapour and soil) by warming them from -123 ^oC to 15^oC are given in Table 5.10. Since most of the warming in the runaway scenario comes from the energy of sunlight, especially in the "self-propelled" stage (**b→c** in Fig. 5.4), then the requirements are stated in terms of Mars' annual insolation, as well as in Joules. The greatest requirement is to create the atmosphere which needs ~ 8 years of Martian sunlight. If 10% of sunlight can be used to drive the process, then we arrive at the ~ 100 year timescale mentioned above. Much more energy would be needed to create a more Earthlike environment (~ 500 m of water and ~ 200 mbar of oxygen) and sunlight could only be coupled to melting deep permafrost and to photosynthetic processes at very low efficiencies.

TABLE 5.10 ENERGY REQUIRMENTS FOR TERRAFORMING MARS

Initial State	Final State	Amount (kg/m^2)	Energy (GJ/m^2)	Energy/Solar (years)†
CO_2(s) at -123 ^oC	CO_2 at 15 ^oC	2 bars; 54,000 kg/m^2	37	7.9
Dirt at -123 ^oC	Dirt at 15 ^oC	~ 10 m; 20,000 kg/m^2	1.2	0.3
H_2O(s) at -123 ^oC	H_2O(l) at 15 ^oC	10 m; 10,000 kg/m^2	5.5	1.2
H_2O(s) at -123 ^oC	H_2O(g) at 15 ^oC	20 mbar; 540 kg/m^2	1.6	0.33
H_2O(s) at -123 ^oC	H_2O(l) at 15 ^oC	500 m; 500,000 kg/m^2	280	56
CO_2(g) + H_2O	(CH_2O) + O_2(g)	200 mbar; 5400 kg/m^2	80	17

† The annual global averaged solar energy on Mars is 4.68 GJ/m^2.
(Table reproduced with permission from Ref [55].)

The establishment of a global environment on Mars suitable for anaerobic bacteria will undoubtedly be much simpler than creating an environment suitable for man. Thus, compared with the ease of ecopoiesis as depicted by the runaway greenhouse scenario, the daunting task of full terraforming makes it tempting for eco-centrists to speak of the cessation of planetary engineering once a stable bacterial biosphere is in place. The notion of accelerating further developments in Martian habitability with more or greater technological intervention, which may have to be sustained for a long period of time, is not favourably regarded. The restoration of the past biocompatible climate of Mars is viewed as possibly achievement enough — whereupon humanity takes a back seat and the primitive Martian biosphere is left to unconstrained evolution. Whether this evolution will eventually produce a planet with a breathable atmosphere, depends on whether a biosphere can be designed which will naturally follow a similar environmental trajectory to that of the Earth.

5.6 Organisms for Pioneering Mars

5.6.1 The Earliest Habitable Environment

The aftermath of the CO_2 greenhouse, augmented if necessary by trace greenhouse gases, is considered to be an environment similar to a chilly and arid version of the Precambrian Earth. Large areas of Mars are predicted to be at or above freezing, either permanently, or on a seasonal basis. Permafrost will start to melt, releasing moisture into the soil which, because the atmospheric pressure has been raised by a factor of ~ 100, can be stable as liquid — the essential pre-requisite for biological processes. As heat from the warmed surface penetrates underground, groundwater will start to flow, percolating to lower elevations and perhaps seeping out to the surface in springs where the water table intersects with topographic contours. The ancient runoff channels might gather some of this discharge carrying it into natural depressions, feeding pools and lakes that might be open to the air or, if the environment is still too harsh, could be protected from evaporation or freezing by an insulating cover of ice. Once sufficient water becomes available, then there is the possibility of large-scale atmospheric and surface transport, cyclic phase changes — evaporation and precipitation. The development of a massive global hydrological cycle like Earth's however, assuming enough ice is present, will take a long time (as hinted at in the calculations in Table 5.10).

If the continued thawing of Mars is left to passive processes, the moist oases where water has begun to collect will only gradually expand in number and extent. Most of the surface will remain a chilly desert. The thicker atmosphere will dramatically reduce the amount of cosmic radiation that reaches the ground, but the lack of an ozone layer means that UV radiation of wavelengths 190 - 300 nm will still be a serious biological hazard. Since the mixing ratio of oxygen in the Martian atmosphere (~ 0.13%) is determined by photochemical processes, it is possible that the outgassing of large quantities of CO_2 might result in the photochemical production of a corresponding quantity of oxygen [55]: a pCO_2 of ~ 2 bars might generate a pO_2 of ~ 2.5 mbar. Whilst this oxygen partial pressure is well below the critical oxygen pressure for higher plants, it may well be sufficient to provide for the respiratory needs of microscopic plants, such as green algae. In addition, since this oxygen corresponds to a column mass of ~ 3% that on Earth, it is possible that sufficient ozone might be generated to provide some screening from ultraviolet between 220-300 nm [62] (see Section 3.4.1). Nitrogen is a more difficult problem over which to speculate, except for saying that it is likely to be the nutrient that is most severely limiting life on Mars. The present pN_2 of 0.2 mbar may tax the nitrogen fixing abilities of microorganisms to their limit and is only enough to supply the needs of a quite modest biosphere. Hypothesized nitrate deposits must therefore be invoked, both to supply the first ecosystems and for eventual inclusion in a nitrogen cycle that includes the atmosphere.

The closest modern terrestrial analogues to this vision of Mars on the threshold of ecopoiesis are the dry valleys of Antarctica, in an area that has become known as the Ross Desert [63]. The crucial differences for life are that the atmosphere on the new Mars will be anoxic and direct sunlight dangerous. Nonetheless the improvements over the previous environment are substantial. For instance, although people will still have to live inside enclosed biospheres, they will no longer need pressure suits to venture outside; the alternative of donning cold weather clothing, sunglasses and breathing apparatus will be much more convenient. Whilst additional planetary engineering could improve the habitability of this environment for a wider range of forms, microbial life of an Antarctic type could be introduced at this stage. Mars might be pioneered by a limited set of organisms as soon as niches on the planet are fit to receive them. If the engineering timescale for further amelioration of the environment is less than the time that such organisms would take to effect those changes autonomously, then this initial seeding of the planet is more of a symbolic, rather than practical importance. However, since strict ecocentrism dictates a cessation of technological intervention in terraforming once ecopoiesis becomes possible, then pioneering organisms and ecosystems take on a supreme position of importance — indeed, they are the *raison d'être* for the entire enterprise, for it is through their agency that the future evolution of Mars will be directed.

5.6.2 Ecopoiesis out of Antacrtica

Organisms on which to base the first Martian ecosystems can therefore be sought among the land-based primary producers of the Antarctic, particularly in that small fraction of the continent not covered by ice sheets. Precipitation in the dry valley regions is very low and so they are arid as well as cold, having an average annual temperature of ~ -20 ^{o}C. Conditions are thus extremely hostile to life and only the hardiest forms can survive [64]. On the valley floors, temperatures can rise above freezing in the Summer, providing, from what sparse snowfall there has been, meltwater which moistens the soil and feeds ice-covered lakes. The major primary producers in these niches are mats of green algae and cyanobacteria which, in the lacustrine case, can grow on the sunlight that penetrates the overlying ice. The activity of life in the soil is episodic depending on temperature and moisture; organisms are therefore adapted to withstand both freezing and desiccation. The environment within the lakes is much better buffered and, so long as there is a fresh supply of meltwater each Summer, liquid water persists under the ice throughout the year [65], even though exterior temperatures average well below freezing. In the more clement regions, such as the Antarctic peninsula, where temperatures and precipitation are slightly higher, lichens and mosses are the dominant producers. However, few or no animals thrive in any of these ecosystems — consumers consisting of heterotrophic bacteria, actinomycetes, fungi and protozoa.

At heights of ~ 1500 m in the mountains surrounding the dry valleys, average annual temperatures are ~ 10^{o}C lower than on the valley floors and the maximum seasonal air temperatures remain below freezing. Conditions are unsuited even for the soil and aquatic ecosystems outlined above. However, Summer sunlight is capable of heating favourably positioned rocks up to 15^{o}C above ambient temperature which allows liquid water to form and percolate between mineral grains. Porous rocks, such as sandstones, can therefore become a refuge for microorganisms [66] — these *cryptoendolithic* habitats being perhaps the last retreat in the face of cold where terrestrial life can maintain a precarious existence. Not surprisingly analogous niches have been proposed on Mars, as life's last stand before extinction [67] or, much more improbably, where life may persist at the present day [68]. As terraforming replays the tape of Martian environmental degradation — backwards and at much greater speed — the cryptoendolithic niche on Mars may therefore become the first that is hospitable to a biota from Earth.

Antarctic cryptoendolithic ecosystems consist of algae, cyanobacteria and fungi — often in lichen associations — yeasts and heterotrophic bacteria. They survive under 1 - 3 mm of rock and inhabit a zone parallel with the surface, several mm thick, where sufficient sunlight penetrates to permit photosynthesis. Because both the standing crop and metabolic rate of the communities are very low, mineral nutrient requirements are also small and are provided either by leaching from the rock or, in the case of nitrate, by atmospheric deposition. Not only do the rocks provide a warm substrate for growth, but they also afford protection from both ultraviolet radiation (which penetrates rock less efficiently than visible light), and the bitter and desiccating winds of the exterior environment. Nonetheless, numerous dead colonies have been found [69] where presumably conditions fell below even the tolerance threshold of these most psychrotolerant of life forms. These minimum biocompatible prerequisites are thought to be ~ 500 hours/year of metabolic activity determined by [70]: a flux of photosynthetically active radiation at the rock surfaces of > 100 μmol photons/m^2/s; a subsurface temperature of > -10 °C and a relative humidity in the pore spaces of > 75%.

One of the functions of pioneering Martian ecosystems will be to generate atmospheric oxygen. The productivity of these ecosystems is therefore very important as it is one factor determining the timescale for the oxygenation of the Martian biosphere. Friedmann *et al.* [70] have studied the long-term dynamics of lichen-dominated cryptoendolithic communities and calculate the annual gross primary productivity (GPP) for horizontal rock to be ~ 1.2 g C/m^2/yr, equivalent to ~ 3 g dry biomass/m^2/yr. To precisely compare this value with the others quoted in this book, we need to know the net primary productivity (NPP), which is the biomass remaining after accounting for plant respiration. However Friedmann *et al.* were unable to disentangle autotrophic and heterotrophic respiration in their study and so they calculated a value of ~ 1.5 g dry biomass/m^2/yr for what they termed the *net photosynthetic gain* (the GPP minus the respiration of the total colony). Now this is similar to what was defined as the net community production (NCP) in Section 4.2.1 where it was shown that, for maximum carbon fixation and oxygen production it is best that NCP→NPP, whereas for a climax ecosystem NCP→0. Although the net photosynthetic gain for the cryptoendolithic community is low, it is very high, as a proportion of GPP, for a climax ecosystem. However, the annual net increase in actual biomass was calculated to be a minute ~ 7.5 mg dry biomass/m^2/yr which does tend to zero and so it appears that the standing crop of organisms (~ 30 g/m^2) is being maintained in a near steady state by non-heterotrophic losses. These losses are thought to result from the large metabolic costs of surviving the extreme freeze/thaw and desiccation/wetting cycles of the environment and results in almost all of the net photosynthetic gain being lost as non-vital organic matter that leaches into the surrounding rocks.

On Mars, it will be the net photosynthetic gain (or NCP) that will determine the amount of oxygen released and it is interesting to estimate the efficiency at which cryptoendolithic ecosystems might utilize Martian sunlight. If we assume a NCP of 1.5 g dry biomass/m^2/yr, then this is equivalent to 0.05 moles of oxygen released /m^2/yr. The globally averaged intensity of sunlight is a quarter of the top-of-atmosphere insolation = 147.5 W/m^2 ≡ 4.65×10^9 J/m^2/yr. Photosynthesis requires 4.77×10^5 J to produce 1 mole of oxygen and so at 100% efficiency we would generate $4.65\times10^9/4.77\times10^5 \approx 9748$ mol O_2/m^2/yr. Thus the photosynthetic efficiency of utilization of top-of-atmosphere sunlight is 0.05/9748 ≈ 0.0005%. Since about half of the GPP is not instantly consumed in respiration and hence reconverted to CO_2, one can roughly compare the net photosynthetic gain of cryptoendolithic ecosystems with the data for NPP for various terrestrial ecosystems shown in Table 2.10, (the Friedmann *et al.* data actually fits well into "extreme desert" category). The efficiency of our hypothetical Martian cryptoendolithic biosphere turns out to be only ~ 1% of that of the terrestrial biosphere (~ 0.05%); such a rate of oxygen production, assuming the whole planet is colonized and no fixed carbon is re-oxidised, would take ~ 340,000 years to produce the ~ 20 mbar O_2 required by higher plants and ~ 1.7 million years to generate the ~ 95 mbar of oxygen needed for marginal human habitability.

The authors of the NASA ecosynthesis study were the first to look at the inhabitants of the Antarctic dry valleys with a view to assessing their suitability for transplantation on Mars [50,71]. Their categorisation of the relative merits of the four major photosynthetic groups, compared to an ideal Martian pioneer are shown in Table 5.11. They suggested that cyanobacteria and lichens are best suited to Mars — the former because of their general hardiness, ability to grow without oxygen and to fix nitrogen, and the latter because of good resistance to desiccation and UV light. Their computer models of the growth of these two forms (the cyanobacteria in a microbial mat) led them to conclude [50]:

> *1. The organism's temperature would be closely coupled to the surface temperature, rather than the atmospheric temperature.*
> *2. The organism's temperature would decrease with increasing wind speed because of convective heat loss.*
> *3. A layer of desiccated cells on the upper surface of the algal mat would control water loss.* [They also noted that such a layer could also help screen the vital layer of the mat below from ultraviolet radiation.] *The lack of such a layer would permit large water losses from the lichen. The losses would, in turn, be affected by such factors as lichen thickness and wind speed.*
> *4. Temperature and water loss would limit photosynthesis to only 3 to 5 hours/day. Allowing a 25% coverage of the surface of Mars, blue-green algae* [cyanobacteria] *could generate an amount of oxygen equivalent to the present amount of carbon dioxide in the Martian atmosphere (approximately 5 mbar) in 7000 years. To produce an amount equivalent to the minimum necessary for human breathing (approximately 100 mbar) would take 140,000 years. The lichens would take approximately 10 times longer.*

The NASA authors arrived at their figures for oxygen production because their models predicted that the cyanobacterial mat could evolve ~ 10^{-6} mol O_2/cm^2/day and the lichens ~ 10^{-7} mol O_2/cm^2/day. The former of these two figures is about as efficient as an average cm^2 of terrestrial biota, but since they assumed 25% coverage of Mars and photosynthesis during only half the year, their overall biospheric efficiency is ~ 1/8 that of Earth. These conclusions turned out to be erroneous for the present day Mars, since moisture was assumed to be available. However, they remain relevant for a planet after the first stage of planetary engineering.

TABLE 5.11 CHARACTERISTICS OF SOME TERRESTRIAL ORGANISMS AND AN IDEAL MARTIAN ORGANISM

Organism	Requires oxygen	Extreme Resistance to UV radiation	Extreme Resistance to drying	Growth rate	Growth habitat
Green algae	Yes	No	No	Fast (hr)	Soil (surface and sub-surface)
Lichen	Yes	Yes	Yes	Yery slow (yr)	Surfaces (rock, tree)
Moss	Yes	No	No	Slow (wk)	Moist surfaces
Cyanobacteria	No	No	Yes	Fast (hr)	Soil (surface and sub-surface), water
Ideal Martian organism	No	Yes	Yes	Very fast (min)	Soil (surface and sub-surface), water

(Table reproduced from Ref [50].)

5.6.3 Two Nominated Pioneers

Imre Friedmann and co-workers however have pointed out that the water requirements of microbial mats nonetheless rule them out as initial growth forms (see Plate 5.9). They have focussed instead on cyanobacteria adapted to living in deserts and have actually nominated two species as potential Martian pioneers. The first [72] is *Chroococcidiopsis sp.*, a primitive type of cyanobacterium and one of the most extraordinary environmental generalists known (see Plate 5.10). It is found living in a large variety of extreme conditions: exceptional aridity, salinity, nitrate concentration, high temperature and low temperature. In the most hostile of these environments, *Chroococcidiopsis* can be the dominant, or the sole surviving organism. This is particularly the case in arid habitats and Friedmann *et al.* have described it as, *"...probably the most desiccation-resistant cyanobacterium."* In milder situations however, it is usually rare or absent, as it lacks the ability to compete with more sophisticated, or specialised, organisms.

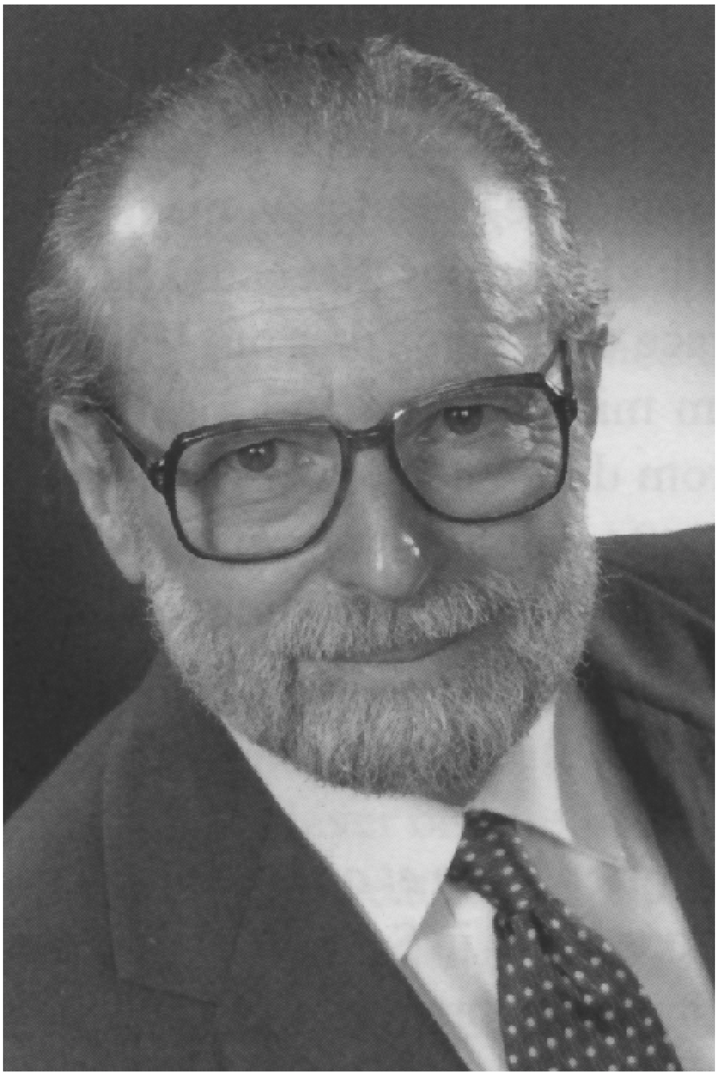

Plate 5.9 *E. Imre Friedmann: Professor and Director of the Polar Desert Research Center of the Florida State University; a distinguished researcher in the field of microbial ecology in extreme cold and dry environments — an interest that he is now applying to the question of ecopoiesis on Mars.*

Whilst *Chroococcidiopsis* can inhabit the cryptoendolithic niche, Friedmann *et al.* have proposed exploiting a different habitat that is particularly common in regions with desert pavement geomorphology, such as the Gobi desert. Here, the organism lives under pebbles, half-embedded in the desert floor, which are sufficiently translucent to transmit light. These stones play and important double role of both reducing the intensity of sunlight and acting as a moisture trap. This latter function is particularly crucial as moisture can persist in the rock-soil interface for weeks after the surrounding ground has dried up.

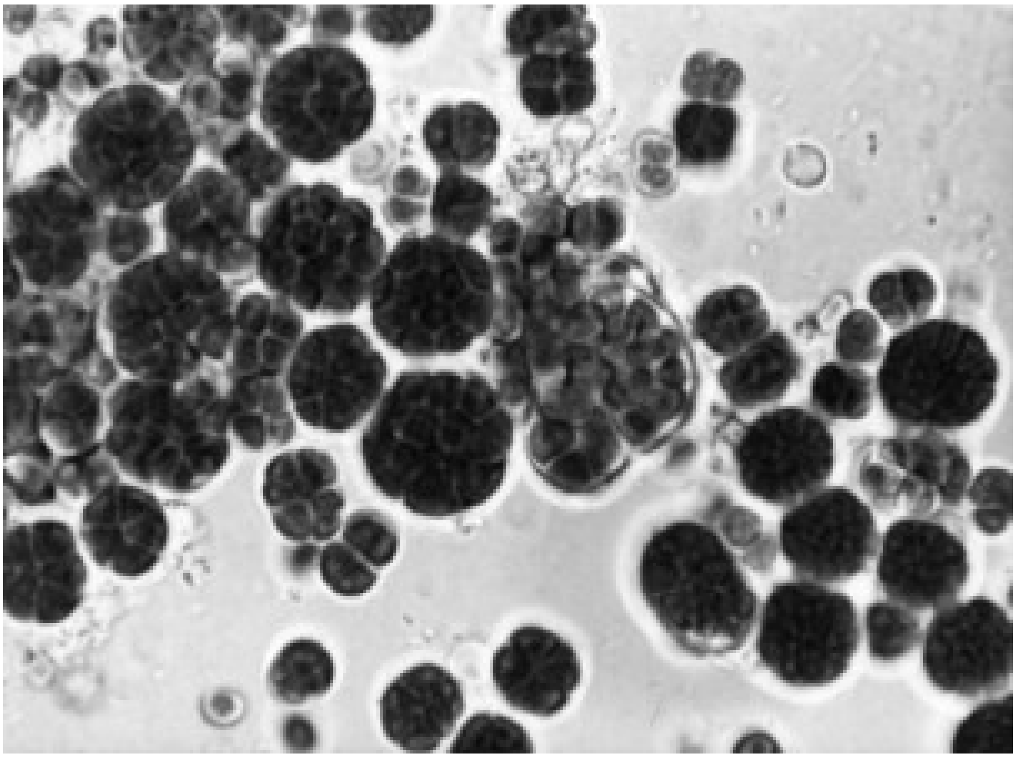

Plate 5.10 *Chroococcidiopsis sp.: mag: 1200 ×. A primitive and extremely hardy cyanobacterium, proposed as a pioneer for Mars as it can sometimes be found on Earth as the sole-surviving organism in desert locations. This specimen was gathered from the Sonoran Desert, Mexico. (Photo courtesy of E. Imre Friedmann.)*

This *sublithic* habitat could have ready analogues on Mars. The two Viking lander sites were strewn with rocky debris and it is possible that, not long after terraforming is underway, condensed water might collect preferentially under such rocks long before the general area receives its first rainfall. Where suitable desert pavement is not available, Friedmann *et al.* suggest scattering the surface with glass strips that could be manufactured from local materials and perhaps treated with a trace of iron to filter out UV light. These would serve as dew traps and would provide a warm microclimate and a solid substrate for microbial growth. Since they are both sheltered from direct contact with the air, the minimum environmental conditions mentioned for the cryptoendolithic communities above might apply also to the sublithic habitat. *Chroococcidiopsis* is by nature a pioneer of extreme habitats — several wetting events per year and > 500 hours above freezing and Friedmann's inoculated glass strips would start to turn green.

The second species nominated by Friedmann *et al.* [73] is one specifically proposed to counter the "carbonate problem" (covered in more detail in Section 6.2). Since Mars lacks plate tectonics and may lack active volcanism, the return branch of the geochemical carbon cycle (carbonate to CO_2) may not operate. Some method may be needed to liberate CO_2 from carbonates, either for terraforming, or for maintenance of the desired pCO_2 after terraforming is complete. A variety of lime boring organisms are known on Earth that can mobilize carbonate but the Friedmann group's recent discovery in the Negev desert, *Matteia sp.*, is unique in belonging to the ecological group of desiccation-resistant cyanobacteria (see Plate 5.11). It is a more advanced genus than *Chroococcidiopsis*, being filamentous in shape and having the ability to fix atmospheric nitrogen when nitrogen compounds are unavailable from the surrounding medium. It is found 1 - 2 mm beneath the surface of carbonate rocks and actively bores in the substrate. This is apparently done, not by secreting acids, but by incorporating the carbonate anion in an organic complex. The exact process is not fully understood and the fate of the calcium cation and the provenance of the replacement anion, with which it must combine, are obscure. However it is not difficult to envisage how, once the carbonate becomes incorporated in biochemical processes, it could end up as CO_2.

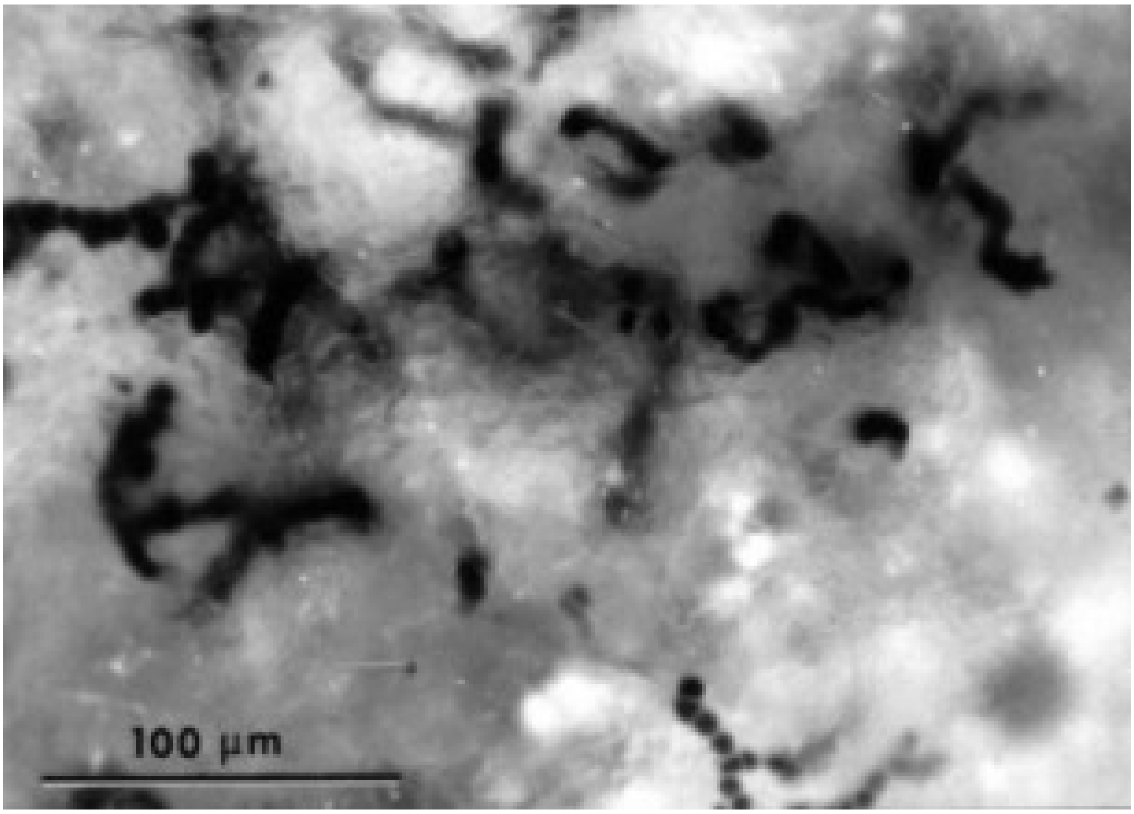

Plate 5.11 *Filaments of Matteia sp., a desiccation-resistant, carbonate-dissolving, cyanobacterium, seen here boring in limestone rock. Also proposed by Friedmann et al. as a Martian pioneer, with possible uses in "designer" biogeochemical carbon cycling, this specimen was collected from the Negev Desert, Israel. (Photo courtesy of E. Imre Friedmann.)*

Friedmann et al. have suggested inoculating broken-up carbonate beds on Mars with a liquid culture of *Matteia*. As with *Chroococcidiopsis*, several wetting events per year would be sufficient to maintain active life. The idea however that *Matteia* — or some organism like it — might be able to release enough CO_2 to significantly contribute to terraforming seems far fetched, as they would need to process a planet-wide layer of pure limestone several metres thick. However, the fluxes required to offset chemical weathering and to sustain a long-term geochemical carbon cycle (see Section 6.3.3) are much lower and *Matteia* deserves further study on this account. Even if its putative CO_2 releasing ability turns out to be ineffective, its other attributes still recommend it as an early Martian pioneer.

5.6.4. Anaerobic Biogeochemical Cycles

To function as an adequate life-support system, Mars will require the kind of biogeochemical matter cycling that operates on Earth. In the final terraformed state, this must be balanced to maintain the supply of essential biogenic materials in order to sustain a stable environment. However, if it is desired to oxygenate Mars, then *the matter cycling set up after ecopoiesis must be unbalanced*, so that photosynthetically produced oxygen can accumulate in the atmosphere.

For every one mole of glucose fixed in photosynthesis, six moles of oxygen are released:

$$6\,CO_2 + 6\,H_2O \rightarrow C_6H_{12}O_6 + 6\,O_2 \qquad (5.2)$$

and, as well as the fixation of carbohydrate, various other macro and micro-nutrient elements are incorporated into biomass (note that this an alternate version of Equation 2.1).

The simplest way therefore to oxygenate Mars might be to seed the planet entirely with photosynthetic, autotrophic, life and to exclude heterotrophs altogether. If this were to happen, one could imagine a progressive build-up of atmospheric oxygen concomitant with an accumulation of unconsumed biomass on the planet's surface. There is in fact a precedent for this sort of process in certain areas of the Antarctic peninsula where cold limits the abundance and activity of heterotrophs [64]. Mosses, lichens and algae can produce patches several hundred metres wide, under which a large quantity of organic matter accumulates. This material decomposes very slowly and leads to the build up of a bed of peat that is permanently frozen and is up to several metres thick.

Whilst the idea of accumulating large standing stocks of dead and undecomposed biomass is attractively simple, metre-thick peat beds on a global-scale are required to produce significant quantities of oxygen. Antarctic peat takes thousands of years to accumulate and it is unrealistic to expect it to remain completely inert and for Mars to remain forever, or even for a short time, uncontaminated by heterotrophic organisms. In any case, heterotrophs are essential components of virtually all terrestrial ecosystems, recycling organic matter back into inorganic compounds that can be re-utilized by autotrophs. After the runaway greenhouse on Mars, there will be an over-abundance of CO_2 — in fact the job of the autotrophs will be to get rid of some of it and replace it with oxygen. However, without heterotrophic recycling of nutrient elements, the one-way matter flows of producer-only ecosystems would be a recipe for a moribund biosphere.

The accumulation of oxygen in the Earth's atmosphere has occurred gradually over billions of years though the natural burial of organic matter, usually within water-deposited sediments. This stores reduced carbon away from the surface for a long time, protecting it from oxidation and thus leading to a permanent gaseous oxygen excess (see Section 2.7.3). Thus, the challenge for back seat ecocentric terraformers is to create Martian ecosystems with viable biogeochemical matter flow/cycling, which can bring about as rapid an oxygenation of the planet as possible — all on a world with very little water. According to their ethos, this must be done both autonomously and without massive technological assistance, and must therefore be an ability built into the design of the initial biosphere.

Before oxygenation has begun, Martian heterotrophs must extract energy from their food anaerobically. An important mechanism for doing this is fermentation — a progressive breakdown of organic molecules, by a large variety of microorganisms, into simpler fragments and hydrogen. Methanogenic bacteria can acquire energy by oxidising this material with carbonate and so the ultimate products of fermentation and methanogenesis are given by:

$$C_6H_{12}O_6 \rightarrow 3\ CO_2 + 3\ CH_4 \tag{5.3}$$

Traces of methane in the atmosphere may be a useful addition to the greenhouse effect, but the concentration will be kept low by photooxidation. The eventual fate of the methane will therefore be:

$$3\ CH_4 + 6\ O_2 \rightarrow 3\ CO_2 + 6\ H_2O \tag{5.4}$$

These are the basic equations that would have governed the terrestrial carbon cycle prior to ~ 1.8 billion years ago when the Earth was an anaerobic planet. Addition of (5.2), (5.3) and (5.4) results in balance. Only the sequestration of some of the biomass that feeds consumption in Equation (5.3), by burial in sediments, permitted a net oxygen accumulation.

An alternative notion was suggested by the authors of the NASA ecosynthesis study [50] who designed a scheme for biogeochemical recycling on Mars based on the ability of many anaerobic microorganisms to use mineral oxidants for respiration, such as nitrate, sulphate, carbonate and ferrous iron. In the case of nitrate respiration, carbohydrate is oxidised to CO_2 by nitrate, not oxygen:

$$5\ C_6H_{12}O_6 + 24\ NO_3^- \rightarrow 30\ CO_2 + 18\ H_2O + 24\ OH^- + 12\ N_2 \tag{5.5}$$

and nitrogen gas is released as a by-product. Since this is the denitrifying part of the nitrogen cycle, it is a particularly desirable process, *especially on Mars*, as nitrogen is released into the atmosphere where it is made available to the entire biosphere. The NASA study team therefore concentrated on nitrate respiration as it enabled them to couple their Martian carbon and nitrogen cycles. They briefly considered sulphate respiration and might also have chosen to mention the possibilities of iron respiration — SO_4^{2-} and Fe^{3+} are now thought to be common in Martian soils.

Their biogeochemical cycle is illustrated in the energy/matter flow diagram in Fig. 5.12 and exhibits some interesting properties. Since no biomass is accumulating (it is all being consumed), then the biota is at ecological climax. Oxygen however is building up in the atmosphere *without* the need to sequester organic carbon. The problem is that it originates, after one circuit of the loop, from nitrate, which is effectively a finite resource. The mass flow of the nitrogen cycle is much less than the carbon cycle and so nitrogen fixation and nitrification could not replace the nitrate fast enough — and if it did, it would remove the free oxygen released in the first place. What is effectively happening is that the surface is being reduced at the expense of oxidising the atmosphere. Whilst an interesting proposal that merits further study, it seems unlikely that such a process could succeed at generating a breathable partial pressure of oxygen. Bacteria would have to process substantial volumes of regolith in order to obtain the appropriate oxidants, and as pO_2 increases, the reduced products of sulphate and iron respiration would be prone to re-oxidation. Much worse is that the biota would come under selective pressure to switch to the much more efficient aerobic respiration and so the NASA authors proposed that all their heterotrophs should consist of obligate anaerobes, incapable of using oxygen. Even so, the origin of a strain capable of aerobic respiration, either by natural mutation or accidental contamination, would prove ruinous to the whole scheme — net oxygen production would cease and the system would tend to ecological climax, probably at a pO_2 too low for advanced organisms.

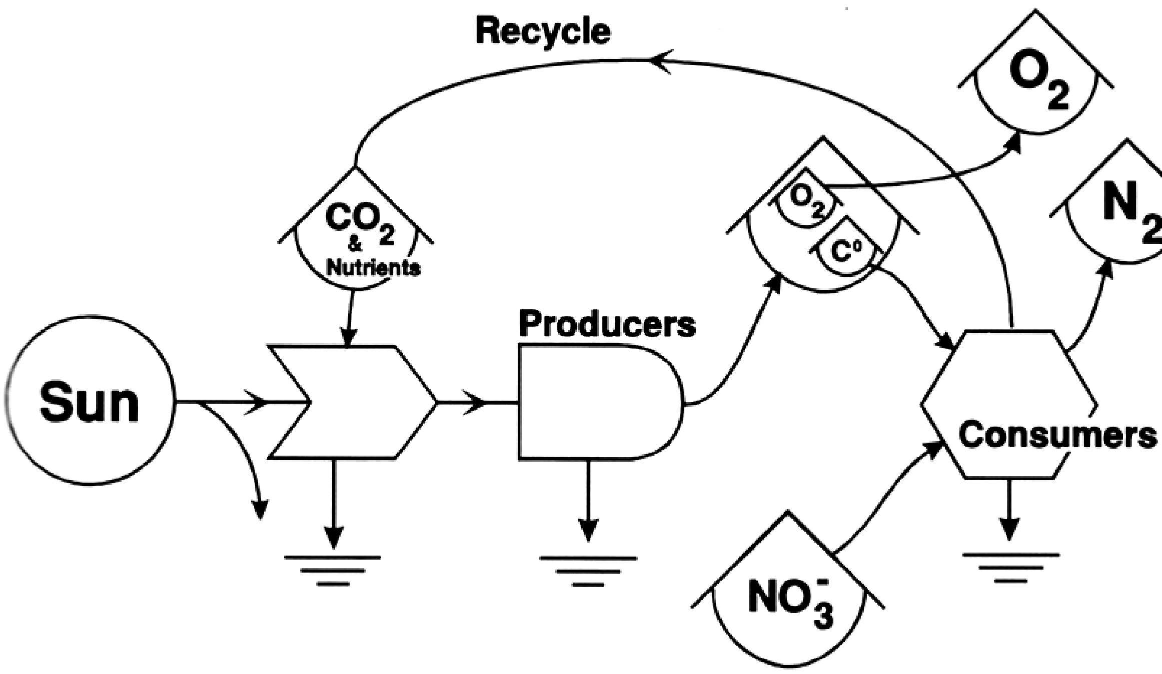

Figure 5.12 *Concept of a Martian biogeochemical cycle that does not use oxygen. Biomass (C^0) is consumed and CO_2 and mineral nutrients are returned to Autotrophs (producers) by using nitrate respiration. Photosynthetic oxygen accumulates in the atmosphere, but its ultimate source is nitrate. (Energy/matter flows are shown undifferentiated.)*

Another problem with the NASA scheme is that, since no organic carbon is being removed from the system, no CO_2 is being removed from the atmosphere — oxygen is mixing with carbon dioxide and not replacing it. (*Some*, but not all CO_2 might in fact be absorbed by OH^- anions to form carbonate: see Equation 5.5.) The process therefore cannot render the Martian atmosphere breathable to organisms intolerant of high pCO_2. *Sequestration of biomass will therefore be essential to ensuring that the composition of the atmosphere of Mars moves towards that of the Earth.* The ~ 100,000 to 1 million year timescales mentioned above for photosynthesis to generate a breathable pO_2 depend on an assumption that *all* the biomass fixed is sequestered and not re-oxidised. This is usually admitted to be extremely optimistic since isolation is always assumed to occur via the natural geological processes of sediment deposition and burial. On the Earth, this is much less than 100% efficient — the estimated fluxes on Fig. 2.11 showing that only ~ 1 part in 3000 of NPP might escape near-immediate re-oxidation. If we apply this to Mars, which may still be optimistic since the planet will be drier, then the timescale for a breathable pO_2 jumps to ~ 300 million to 3 billion years! Even this may be too short, as we have not taken into account the possibility of some buried carbon being returned to the system by erosion and re-exposure at the surface.

One way to mitigate these difficulties is to postulate that we simply have not found the right organisms for terraforming Mars yet. This line goes that if we look hard enough, candidates will be found from which ecosystems optimised for Mars can be created. This is not an unreasonable argument — after all, the search for Martian organisms amongst life on Earth has hardly begun. The metabolic versatility of the microbial world is truly extraordinary and it might be that a biochemical process that is insignificant in the larger scheme of things on Earth might be exploited on a vastly greater scale on Mars. Biological terraforming arguments are often further bolstered by invoking the power of genetic engineering [50], *"...to construct organisms far better adapted to grow on Mars than any present terrestrial organisms."* If it ever becomes possible to freely swap various specialized abilities between organisms, then one can certainly imagine creating new, specifically Martian, species. Desirable attributes might be rapid growth, UV resistance, ability to thrive at high pCO_2, ability to fix nitrogen at low pN_2, tolerance of cold, high salinity, desiccation, low nutrient concentration etc. In addition, other genetically engineered modifications can be proposed that are specifically designed to facilitate new oxygen production. Perhaps autotrophs might be caused to divert some of their productivity into manufacturing non-biodegradable substances. These might be chemicals such as aliphatic and aromatic hydrocarbons, steroids, carotenoids, terpenes, saturated fatty acids and porphyrins, which are not broken down in the absence of oxygen [74]. A strategy such as this might therefore result in a larger fraction of organic matter remaining unconsumed, at least in the early stages of oxygenation. Other tricks like this can be readily imagined and it is an undoubted fact that, if terraforming is ever attempted, genetically engineered organisms will be part of the planetary engineer's toolkit. Their full potential however is completely unknown and it may be far from realistic to invoke genetic engineering to solve every difficulty.

With present day, purely biological techniques, ecocentrists are therefore faced with the prospect of waiting a similar time to produce a breathable atmosphere on Mars as it took to form on the Earth. This is hardly surprising, since the mechanisms being considered are identical. Their reluctance to seriously consider the terraforming of Mars beyond the much easier stage of ecopoiesis is therefore understandable. One can only conceive of the terraforming of Mars, in any timescale relevant to the human species, by adopting a different philosophical approach to the problem. This we turn to in the following Chapter.

5.7 Summary

- The Martian environment is presently hostile to life, but of all the planets in the solar system it appears to be the one most suitable for colonisation. All the elements required by life and technology are almost certainly present in considerable abundance.
- Preliminary study of Martian geomorphology suggests that the planet had a warmer and wetter climate during the first billion years of its history. This implies the presence of an early, dense, atmosphere with sufficient pressure and greenhouse effect to stabilize liquid water. Mars would have frozen when its waning volcanic activity was no longer capable of recycling volatile minerals; weathering eventually dominated outgassing and the atmosphere accumulated in surface reservoirs. Occasional warm interludes in the subsequent permanent ice age may have occurred following outburst flooding events, possibly triggered by pulses of Tharsis volcanism. The present day Mars however is thought to be largely quiescent.
- The implication for terraforming of Mars' history are profound. If its palaeo-atmosphere and hydrosphere are still present in surface reservoirs, then it may be possible to restore the planet to its past habitable condition. If no indigenous Martian organisms emerge from cryptic niches, then ecopoiesis could proceed with microorganisms exported from Earth.
- There are models of the Martian climate that suggest the existence of quasi-stable states, similar to those describing Mars' early history. Furthermore the models suggest that these states can be approached by forcing the climate to a cusp catastrophe point, whereupon a runaway occurs to higher temperatures and pressures. Planetary engineers may therefore be able to exploit generous positive feedback inherent in the Martian climate, greatly reducing technological input into terraforming.

- Runaway terraforming on Mars may be possible by vaporization of CO_2 in the polar caps or regolith. This will add to the greenhouse effect of the atmosphere, warming the surface and causing increased outgassing. Recent modelling suggests — if the carbon dioxide exists in the requisite quantity — that an artificial temperature increase of 5 - 30 ^{o}C might suffice to trigger the transition to a warmer climate.
- Planetary engineering techniques suggested to achieve this initial warming include scattering dust on the polar caps to reduce the albedo; warming volatile-rich areas with space-based mirrors and creating an artificial greenhouse effect with trace gases.
- The new Martian environment created by the runaway greenhouse process would resemble a dry and chilly Precambrian Earth — an atmosphere rich in CO_2, poor in O_2 and a surface unprotected from ultraviolet radiation. Land-based Antarctic ecosystems seem best suited for transferral to Mars at this stage. Cyanobacteria and lichens have been considered as ecopoiesis pioneers.
- The unproductive nature of pioneering ecosystems, and the difficulty of creating natural biogeochemical cycles that bury most organic carbon, suggest that further transformation of Mars, such as the oxygenation of its atmosphere, will be an extremely slow process. Additional improvements to its environment to render the planet habitable to a more diverse biota, in any timescale relevant to the human species, will require continuing planetary engineering.
- The use of genetically engineered organisms, designed to thrive in conditions where terrestrial life cannot, are sometimes invoked to overcome those obstacles in terraforming that would otherwise require a non-biological solution. However, it its presently unknown just how much the already great flexibility of terrestrial life can be improved upon.
- Ecocentrism — a philosophy of terraforming that maximises the role of biology and restrains that of technology, gives us a vision of a Martian future where ecopoiesis is a comparatively easy and passive awakening — a world being gently stirred, rather than violently shaken to life. The goal of ecocentric ecopoiesis, is not embodied in the individual microorganisms and primitive plants that are seeded on Mars — but in the *biosphere* that they comprise. It is this creation of a global entity — that is alive in the hypothetical Gaian sense — that is paramount. Human life is a possible ingredient of this vision, but since full terraforming is regarded as being near impracticable, not a necessary one.

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