

# Part 1

## INTRODUCTION

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# Terraforming and Colonizing Mars

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## **Abstract**

Humankind is on the verge of becoming a multiplanet species, but the main obstacle it has to face in this endeavour is that the environment of all celestial bodies in the solar system is very harsh, completely unsuitable for terrestrial-type (and hence, human) life. To colonize the planets, moons and asteroids of the solar system we must create artificial and enclosed environments, where we can live in shirt sleeves conditions. If on one side we are used to live in artificial environments since the neolithic revolution, in particular in some particularly harsh parts of our own planet, it is true that the colonization of the solar system could be made easier only if we start terraforming the places we aim to live in.

For many reasons, the first candidate of this terraforming effort is Mars, since the closest places (the Moon and Venus) are even worse. Terraforming Mars is a huge enterprise, which will take possibly hundreds years and very high costs. The essential aspects of this endeavour, scientific-technological, economical and ethical, are here discussed. In particular, an ethical problem is related to the possibility of existence of indigenous life: if on Mars there are indigenous living beings, most likely at the bacterial level, any effort aimed to terraform the planet likely would cause their extinction. Before any terraforming endeavour is started, a deep study aimed to exclude their existence must be undertaken.

**Keywords:** Mars terraforming, Mars colonization, greenhouse gases, multiplanet species, extraterrestrial life, planetary contamination, planetary atmospheres

## **1.1 Introduction**

The human species has always experienced an urge to explore and to settle new territories. On Earth, it evolved in a small area in East Africa and from that beginning it expanded on much of the planet, at least in regions which could be easily reached just by walking on land.

It is likely that most of the individuals who participated in this process were completely unaware of it: a band of humans moving its camp by just 10 m each year (always in the same direction) would find itself 10,000 km from its original place in one million years.

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However, things were not as easy as this: in many regions the climate was too harsh for humans to survive, and above all the climate in the various regions of our planet was changing continuously, with terribly cold ice ages and hot interglacial periods, and a continuous alternance of dry and wet periods.

To go through all this humans had to develop specific technologies, and also to adapt themselves with continuous evolutionary changes [1.11]. While the first process was quick enough to allow survival in a continuously changing environment, the latter were too slow and likely played a small role, to the point that in the last few hundred thousands years a single species, *Homo Sapiens*, emerged.

*Homo Sapiens* developed technologies which allowed to survive in the most harsh climates, particularly in cold climates, which are most difficult for a species developed in the hot African plains. It was observed that the wooden goggles that Inuit wear since the palaeolithic to prevent snow blindness and the multilayer skin garments they use in the open, and without which life would be impossible in these conditions, are as complex as the visor of a space helmet or the space suit we have to wear to explore space.

Apart from the technologies humans had to develop to survive in environments which were very different from those to which they were naturally adapted, later on in their expansion on the planet they had to develop transportation means which were essential for reaching, exploring and colonizing new lands. The most impressive examples are the boats and the navigation techniques developed in Neolithic times by Polynesians, which allowed them to settle practically all the islands of the Pacific Ocean, and the ships that at the turn between the Middle Ages and the Modern Age allowed the era of the geographic discoveries [1.4], [1.5].

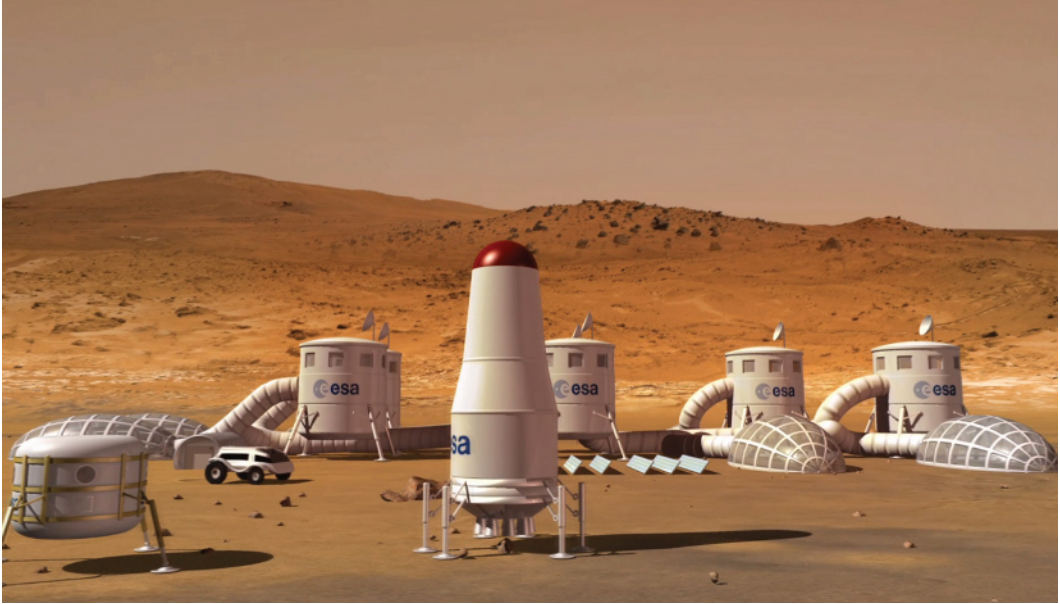
Today humankind is at the beginning of a new era of exploration and colonization, and again it must develop enabling technologies to pursue its goals. From one side, the complexity of this new endeavour is unheard of, since, at least in the solar system, the environments in which the new human settlements will be located are much harsher than any environment of our planet, but from the other modern scientific technology, as opposed to the ancient technology based on trial-and-error attempts, is such a powerful tool that we can be reasonably sure that we have all the required means to succeed [1.11].

The point is thus not whether the human species, which developed on Earth, will be able to explore and colonize the nearby celestial bodies, transforming itself into a spacefaring, or multiplanet, species, but when this process will start (Figure 1.1).

## 1.2 Earth: A Terraformed Planet

Before starting considering these topics, particularly in the view of speaking of terraforming, i.e. modifying the surface and the atmosphere of a planet to make it suitable to human life, we must however go back in time to make some considerations about our own planet.

Our planet is roughly 4.5 billion years old. In the first half a billion years, the whole solar system was undergoing its process of formation, with continuous collisions of planetesimals and red-hot nuclei of planets which were forming. Then everything slowly settled out and our Earth cooled down, developing a solid surface, covered (completely or partially) by an ocean filled with the water carried here by innumerable comets. If we could land on our



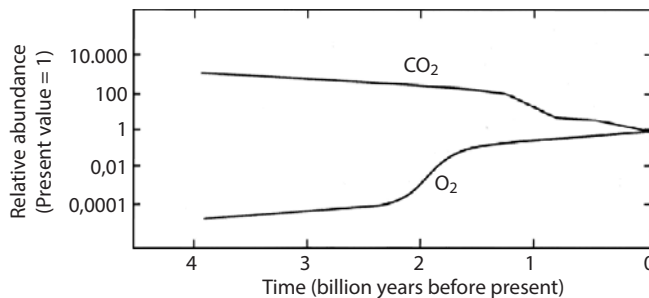
**Figure 1.1** Mars Base. Design by Martin Kornmesser and image courtesy of ESA.

planet at that time we would find a planet completely unsuitable for human (and in general animal) life [1.9], [1.18].

The atmosphere of our planet would have been unbreathable, being composed by nitrogen and carbon dioxide, with no oxygen at all.

It was at that time, roughly 3.7 billion years ago, that the first life appeared, most likely in the oceans. And life started evolving in those conditions. The archeobacteria, and the other forms of life which followed, started using the huge amounts of carbon dioxide present in the atmosphere, producing oxygen. This slowly changed the composition of the planetary atmosphere making it suitable for supporting forms of life breathing oxygen, including human beings (Figure 1.2).

We can thus say that the first planet to be terraformed was Earth itself, and the actors of this transformation were the primitive forms of life like unicellular algae, which started the



**Figure 1.2** Relative abundance of CO<sub>2</sub> and O<sub>2</sub> (relative to the present one) as a function of time. Note the logarithmic scale [1.12], [1.13].

process, and then, in half a billion years, the plants which developed in the ocean to migrate later on dry land, which gave the finishing touch.

During most of this process, the planet had the aspect of a lifeless world – all life was concentrated in the oceans – and the only sign that Earth was a living planet was the presence of oxygen in its atmosphere.

This consideration, developed for Earth, holds for any planet and bears three important consequences.

- The only planets having an atmosphere which is breathable for humans and other animals are planets on which life – or better, Earth-like life – developed to become a very widespread phenomenon, so widespread that it changed completely the initial characteristics of the planet. Moreover, to have a breathable atmosphere, a planet must still have life: if for any reason life disappears from the planet, owing to the high reactivity of oxygen, sooner or later the atmosphere would revert to its pristine conditions.
- The presence of oxygen in the atmosphere of a planet is a marker for the presence of (Earth-like) life.
- During the process of formation of a breathable atmosphere the anaerobic lifeforms of a planet are substituted by aerobic lifeforms, i.e., the living beings which are the actors of this change are very likely to get extinct, or at least to become a marginal part of the biosphere of the planet.

### 1.3 Planetary Environments

The idea that the planets of the solar system – and also what now we call extrasolar planets, as soon as it was realized that the stars are other suns and likely they have planets – host forms of life is very old, dating back to Greek natural philosophy. Most seventeenth century scientists were of this opinion, even if Galileo Galilei warned that if extraterrestrial bodies are inhabited, the beings living there must be not only different from those we meet on Earth, but even different from what our wildest imagination can predict [1.7], [1.9].

Following this line of thought it was a common opinion that the environments we could find, once we will be able to reach the planets, would be more or less comfortable, but at any rate would allow us to live there.

In the solar system the two closest planets, Mars and Venus, were thought to be habitable. Mars was assumed to be a cold desert, owing to the fact that it is more far from the Sun than Earth, while Venus was thought to be covered by hot and wet jungles, with huge insects, owing to its proximity to the Sun.

In the second half of the 19th century three great astronomers – the Italian Giovanni Schiaparelli, the French Camille Flammarion, and the American Percival Lowell – contributed much to the scientific knowledge of Mars and to its myth. The former drew a number of maps, which remained the best maps of Mars until the first pictures of the planet were taken by space probes. In a number of popular science articles he set his imagination

free, proposing that the dark lines, they thought to identify on the surface of the planet, were in fact areas dense with vegetation that flanked artificial waterways, presumably built by an ancient civilization in an attempt to survive the desertification of the planet by bringing water from the melting polar caps to the more temperate and equatorial zones. Consequently, the idea that intelligent beings, or at least complex living beings (similar to Earth's plants and animals) lived on Mars came to be generally accepted, not only in science fiction but also in serious astronomical studies and in the early plans for human missions to the planet [1.10], [1.17].

Even if in the first half of the 20th century some of the classic misunderstandings on Mars were clarified—there was neither oxygen nor water vapor in Mars' atmosphere, very little liquid water, if any, could exist on the surface, the canals were an optical illusion (artifacts of the low-resolution telescopes), and so forth — the general picture outlined by Schiaparelli and Lowell persisted. In the general understanding of the time, Mars was a barren world with a very thin atmosphere, but it was nonetheless habitable, at least by primitive forms of life. If intelligent beings were living there, they would have had to seek refuge underground, perhaps aided by those fanciful atmospheric machines that were depicted in the many fictional descriptions of the time.

In 1960, only three years after the launch of Sputnik 1, Russia (then Soviet Union) launched the first two probes to Mars. Both failed, however, as did the three subsequent attempts launched in 1962 and another in 1964. In 1964, the Americans tried their hand at a Martian probe, launching Mariner 3 and Mariner 4, also intended to do flybys of the planet. The first failed, but Mariner 4 reached Mars on January 14, 1965, and sent back 22 photos. Even if they depicted only 1% of the surface of the planet, these images forever changed mankind's conceptions of the Red Planet. It turned out that the surface of Mars was very similar to that of the moon: it was covered with craters and utterly dry, with no vegetation, no rivers, no lakes. Some of the craters seemed to have some traces of ice, but nothing else. The instruments also revealed that Mars had no magnetic field, meaning there was nothing standing between its surface and the bombardment of cosmic radiation. In addition, the atmosphere, composed of carbon dioxide, had a much lower pressure than previously thought. Not only people could not breathe the Martian air, just going outdoors would require a full spacesuit, only slightly less demanding than that required in interplanetary space. The following probes substantially confirmed these conditions. Even if Mars proved to be much more complex than shown by the first pictures and was not a dead world like the Moon, it was certainly not the planet of Schiaparelli's and Lowell's imaginations.

The Mars of the nineteenth century astronomers was substituted by the Mars of the probes.

A similar fate awaited Venus: the probes which reached the planet and then the few which landed on it showed that the situation on its surface was even worse: it was a hot hell, with a very high atmospheric pressure (almost 100 times that on Earth). Venus air was made mostly by carbon dioxide (96%) and the rest nitrogen and trace gases.

While the probes sent to Venus and Mars sent back these discouraging results, the first human missions to another world, the *Apollo* missions to the Moon, showed that exploration of an airless world with low gravity was possible and humans could walk wearing a space suit and even travel on the surface using a fairly conventional car.

At this point it was clear that the colonization of any world in the solar system involved creating artificial environments completely separated from the planetary environment and using space suits when outdoors.

Thinking about it, this is not a very severe limitation: even on Earth humans do something similar in many instances. All modern commercial airliners have a pressurized fuselage to protect the passengers from the low pressure and temperature of the air outside, which are not much better than those we must endure on the Mars surface. People going around, eating and enjoying themselves in an air conditioned shopping center located in any city in very hot or cold countries, do not live in a less artificial environment than future Mars colonists living in their pressurized dwellings. These buildings can be transported to the Moon or Mars, just by reinforcing their structures to withstand the pressure difference between the inside and the outside and adding airlocks and other devices. But these are just technicalities, the feeling of living in an environment separated from the outside is similar.

Both on the Moon and on Mars another problem adds to that of the lack of an atmosphere (or to the very thin atmosphere): the lack of a magnetosphere which protects the surface from radiation, both Galactic Cosmic Radiation (GCR) and the radiation from the Sun. This may be even more severe than the lack of atmosphere, since radiation is quite harmful to all forms of terrestrial life, including human life.

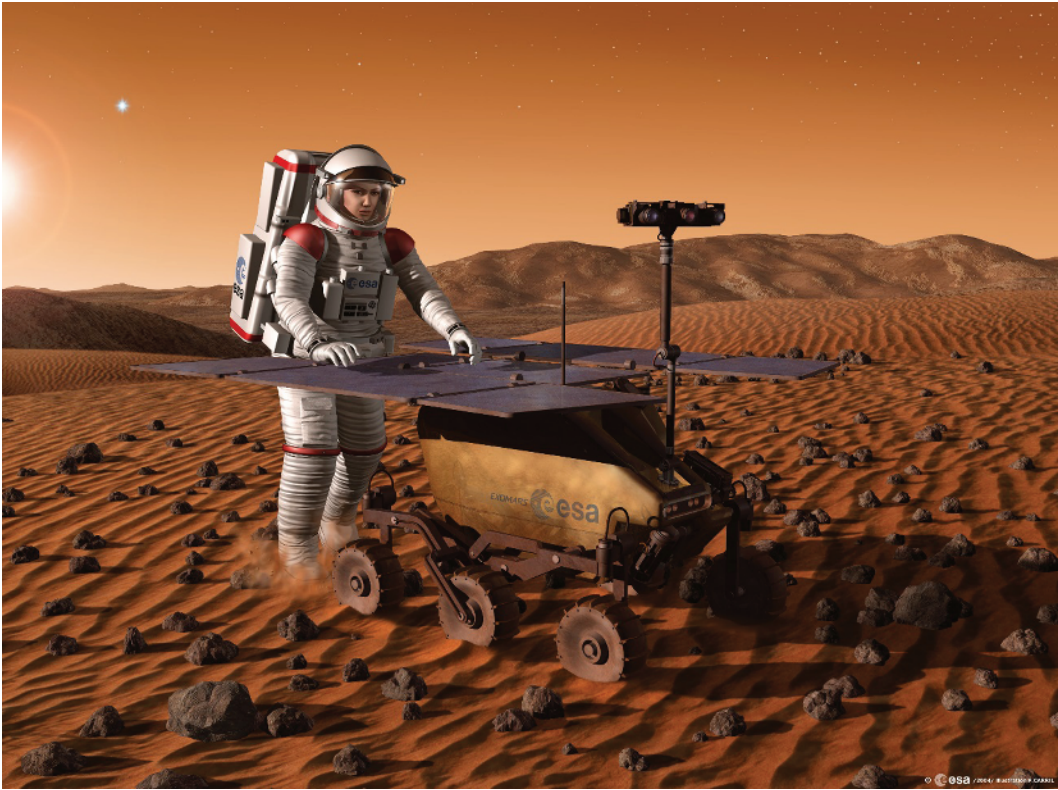
One of the most effective measures to protect colonists from radiation of all kind is building the habitat underground, and the two bodies we are speaking about offer an excellent opportunity: they seem to be both rich of lava tubes, long – and particularly large, owing to the low gravity – caves existing in many locations. Since in several points the ceiling of these caves has collapsed, mostly due to meteorite and asteroid impacts, the access to these caves is easy.

Living in lava tubes allows to enjoy an almost radiation-free environment and it is even possible to directly pressurize parts of a lava tube to obtain a pressurized habitat.

However, while on the Moon this is a viable approach to build habitats, on Mars it is questionable. Since there is the possibility that the surface, and above all the underground, of the planet hosts fossil or even existing life, a very reasonable strategy to human exploration is subdividing the surface, and the underground, of the planet in zones of two kinds: *normal zones*, where we are sure that no Martian life exists, and *special zones*, where it may be present. In the zones of the former type human exploration is possible with no particular problems of contamination (forward and backward). The zones of the second type are completely forbidden to humans and may be explored only using robotic devices, complying with strict anti-contamination rules.

This strategy can develop in this way: at the beginning, that is now, all the planet is considered as a *special zone*. Then a sample return mission brings back samples from a certain zone, which are accurately examined in search for life. If no life is found, that zone becomes a *normal zone* and humans can land in that place.

Humans supervise the robotic exploration of the surrounding special zones (Figure 1.3), which are de-rated to *normal zones* as soon as it is proven that they contain no life. Operating in this way, the first places where it will be possible to build habitats will be on the planetary surface, while lava tubes will remain *special zones* for as long as they are demonstrated to be otherwise.



**Figure 1.3** Human-robotic exploration of Mars. Image courtesy of ESA.

This difficulty may be circumvented by present additive manufacturing technologies, since it is possible to build a thick walled habitat using the planetary regolith on the surface, without the need of entering into special zones located underground.

Both lava tubes and thick walled surface habitats cause some problems, mainly psychological, linked with living in a closed environment without windows. Another problem is the need of using artificial light for growing plants, but today this is no more a problem owing to the high efficiency artificial lighting: today it is more efficient using the solar light to produce electricity through photovoltaic panels and using the electricity so produced to supply light to the plants through LEDs than to use directly the solar light for the plants.

Using nuclear power to produce electricity, particularly on Mars where the solar light is much weaker than on Earth, allows to grow plants of all kind in places protected from cosmic radiation.

A solution for the psychological problems may be the use of virtual windows: large screens, perhaps thin-film screens, attached to the inside of the walls, showing the image taken by a video camera located on the outer side of the same wall. Such a virtual window may be sufficient for solving the psychological problems of those who live in the habitat, but if it is realized using a normal 2D screen, it may impair the ability of the inhabitants to feel a 3-D vision, which may be dangerous when the colonists go outside performing activities like driving rovers or operating machinery. The use of true 3-D screens, like the

one at present under study which do not require to wear glasses or VR devices, could solve completely this problem.

The alternative to thick walled habitats with little or no windows is using an active radiation screening, either electrostatic or electromagnetic [1.2].

## 1.4 Terraforming Mars

The idea of terraforming was likely used, for the first time, in 1930 by Olaf Stapledon in his novel *Last and First Men*, where he describes human beings terraforming Venus. It is common opinion that the term terraforming was introduced about 10 years later by Jack Williamson (under the pseudonym Will Stewart) in his science-fiction short story *Collision Orbit*, published in *Astounding Science Fiction* in 1942. Note that the first speaks about terraforming Venus and the second one a small asteroid.

Little was said at that time about terraforming Mars, since most astronomers and other people interested in space traveling thought that Mars had no need of being terraformed: if something was needed, the use of one of the many atmospheric machines described in many science fiction novels would have been sufficient.

To pass from fiction to reality, implementing terraforming has three main aspects:

- Scientific-technological aspects. Terraforming is a highly interdisciplinary effort, based on physics, chemistry, biology, but also electronics, material science, nanotechnology, etc. General progress in astronautics is considered a pre-requisite: to operate on a planet, we must be able to reach that planet safely, consistently and at a reasonable cost. Generally speaking, all the related technologies still need to be developed and may require a very long R&D effort.
- Ethical aspects. All technologies have a deep impact on the environment and the way of life of people as side effects, while for terraforming this impact is the primary goal.
- Financial aspects. The cost of operating at planetary level is huge, so these operations must be properly planned also from this viewpoint. As an additional point, terraforming is an operation which may last decades, or better, centuries. The plan must be sustainable and adequate guaranties must be stated that, once started, the operation will be completed. A most dreadful outcome would be a half-terraformed planet resulting from the change of strategy of a public enterprise or the bankrupt of a private 'terraforming company'.

While terraforming is generally considered a very complex enterprise, which will start only in the far future, recently some claims have been heard stating that terraforming a planet may be easier than had been thought. And so the word terraforming has gained a place in our technical vocabulary, just as have many other words invented by science fiction writers: robot being one of the better known. The following description of a possible terraforming of Mars is derived from [1.8].

Even before starting the actual terraforming process, we could try to seed the surface of the planet with some life forms that can endure the very harsh Martian conditions. After the first human landing (or even before), the first attempts to grow plants in protected environments on Mars can be made.

Terrestrial plants might thrive in a pressurized greenhouse (Figure 8.4). As far as we know, the regolith contains absolutely no organic matter. It must be enriched with fertilizer and with the organic substances that plants require. It is likely there will be oxidizing agents that are harmful to plants, so these will first have to be removed. If water obtained by melting Martian ice is used, that might have to be purified.

Genetic engineering might be used to adapt plants to accept a lower pressure in the greenhouse or a soil which has not been so heavily modified. But, sooner or later, an attempt to farm outside of a greenhouse will have to be made.

The ethical issues raised by that step will be considered below. Some very primitive terrestrial bacteria can survive in extreme environmental conditions, but it is unknown whether, if transferred to Mars, they could withstand the very cold night-time temperatures, radiation, and the ultraviolet light flux caused by there being no ozone layer in that planet's atmosphere. Research to identify the best bacteria has begun at the NASA Ames Research Centre in California.

If none is identified, perhaps it will be possible to genetically engineer the best candidate. There is no doubt that the terraforming process could be greatly accelerated if the conversion of regolith into soil could be initiated prior to the environment changing much.

Bacteria have been found living inside nuclear plants, even on the fuel rods. *Micrococcus Radiodurans* can survive radiation doses 10,000 times that which can be withstood by a human being. It may be possible to genetically engineer this micro-organism to obtain many products, particularly medicines, that will be important to the first Martian colonists.



**Figure 1.4** Martian greenhouse design concept. Image courtesy of NASA.

Owing to the characteristics of the planet, the work of terraforming can be divided into two phases: first increasing the atmospheric pressure, perhaps by heating the surface; then making it breathable.

The first step seems to be easier than the second. There is evidence that the atmosphere of Mars was much thicker in the very remote past. It has even been suggested that the surface pressure was twice the present atmospheric pressure on Earth.

As a result, the planet might have been a lot warmer. We must remember that at that time the Sun issued much less energy, so the opposite opinion, that Mars was much colder at that time, is also reasonable. The first phase would be a sort of planetary restoration project aimed at giving back to Mars the atmosphere which it possessed some four billion years ago. A way of doing this is to use the greenhouse effect, which means capturing some of the heat that is otherwise radiated by the planet to space, thereby increasing the temperature at its surface.

Some gases (collectively known as greenhouse gases) are very efficient in this regard, particularly carbon dioxide and water vapor, and even more so methane and ammonia. Mars' atmosphere is mostly composed of carbon dioxide, plus traces of water vapor, but its density is insufficient to produce the desired effect.

However, heating the surface could liberate some of the carbon dioxide locked away as carbonates, and this would start to increase the atmospheric pressure. In turn, the greenhouse effect would further increase the temperature. Numerous ideas have been put forward, ranging from using large orbiting mirrors to scattering a dark dust on the polar caps, and from exploding thermonuclear bombs underground to sending an asteroid crashing onto the planet, or even digging very deep wells to extract heat from the inner part of the crust of the planet. But these methods are probably insufficient. By releasing chlorofluorocarbons (CFCs) into the atmosphere it may be possible to raise the temperature at its surface. Since the molecules of these gases aren't entirely inert and are decomposed by sunlight on a time scale of about 200 years, a continuous production of CFCs would be required in order to maintain a temperature higher than the present one. It has been estimated that an annual release of about 100,000 t would be needed in order to maintain the equatorial zone of Mars at a temperature similar to that in a temperate zone on Earth [1.20].

This is only a fraction of the amount that was being produced annually on Earth in the 1970s and led to the creation of the Antarctic ozone hole that caused so much concern world-wide. To create the required concentration of CFCs within 40 years would need an initial production ten times greater than that, plus 5,000 MW of electrical power, equivalent to the output of five medium-sized terrestrial power stations. It therefore appears feasible that we could heat the surface of Mars in this manner or, if a longer time is acceptable (namely 80 years) this could be done by running three medium-sized power stations and a plant whose output was the same as overall production of CFCs on Earth in the 1970s.

This is clearly possible, because the actual energy which heats Mars comes from the Sun, and the role of humankind is that of tampering with the thermal regulation system of the planet. This effect could be achieved using perfluorocarbons (PFCs), which have the advantage of not dissociating ozone. Hence, as soon as oxygen began to form in the Martian atmosphere, ozone would also start to form, which in turn would begin to attenuate the ionizing ultraviolet light that reaches the surface.

A number of changes would be triggered by warming Mars. The dry ice (i.e. solid carbon dioxide) in the polar caps would sublime into the atmosphere. In about 40 years the

surface of the planet would have a pressure of about one third of that on Earth. This would allow colonial astronauts to dispense with their space suits and move around on the surface with just a mask and a bottle of oxygen, as scuba divers do. The ice in the permafrost would slowly melt, and water would flow across the surface and down the beds of the ancient rivers to form lakes. Evaporation would start a fresh water cycle, with the formation of rain and snow. In winter, snow would add to the water ice at the poles. However, it is not known how long all this would take, because it depends mainly on how far the permafrost is below the surface.

The increase of carbon dioxide and water vapor in the air would both aid the greenhouse effect and hence reduce the rate at which CFCs would need to be produced. By this point the restoration would be complete, and the planet would have regained its ancient aspect. Although history shows that warm and wet conditions on Mars are unstable, it took a very long time for the planet to lose its atmosphere and cool down. The colonists would be able to maintain stability by periodically boosting the atmosphere with a small quantity of CFCs.

It is not known whether life developed when Mars was a warm planet rich in water, nor indeed whether any hardy life forms are still present in well-protected niches. But when Mars has been restored to its former glory (or possibly before that, as pointed out above), humans will attempt to grow terrestrial plants outdoors. In an atmosphere containing so much carbon dioxide, vegetation will thrive, even more so if humans select, or genetically modify, certain species to make them more suitable to the Martian environment.

It is likely that many plants and trees could be introduced early in the process, when the temperature and the pressure are only slightly above their present values. Agriculture will thrive on the vast open plains and the rougher regions could be forested. But plants have another important function – they produce oxygen. As already stated, originally there was no oxygen in Earth's atmosphere: it contained only carbon dioxide and nitrogen. Oxygen was introduced by micro-organisms and later greatly increased by vegetation. This could also occur on Mars. It has been computed that the process would require only several centuries. This is nothing in terms of the geological history of a planet, and is not long for a civilization. To obtain a Martian atmosphere which humans could breathe freely would be a wonderful audacious achievement.

This is, however, a controversial issue. In order to render the atmosphere breathable by humans, the concentration of carbon dioxide must be reduced drastically, and that would in turn reduce the greenhouse effect. Some people argue that the choice will be between a warmer planet, with an atmosphere that requires humans to carry oxygen bottles and masks, and a very cold atmosphere at a low pressure that has a higher concentration of oxygen. If these issues can be resolved satisfactorily, then Mars could one day have a breathable atmosphere and a flora and a fauna similar to Earth's, albeit adapted to the local environment.

The planet could support a population of several million humans within a time similar to that which separates us from the arrival of Christopher Columbus in America. Mars would then be the first planet to be terraformed by colonizers from planet Earth. An interesting (and epic) fictional account of an endeavours to tailor Mars to human requirements has been told by Kim Stanley Robinson [1.15].

A hypothetical map of a fully terraformed Mars, with a large ocean covering the whole of *Vastitas Borealis*, is shown in Figure 1.5.



**Figure 1.5** A hypothetical map of a fully terraformed Mars, with a large ocean covering the whole of Vastitas Borealis [1.22].

It would probably be impossible to obtain enough water to create such a large ocean from Martian resources, so this situation would be possible only if some comets were made to impact in order to obtain their water. The scenario described above seems to be feasible.

But there are other options that would reduce the power needed to produce the CFCs. First, large mirrors could be put in orbit around Mars to heat the surface using reflected sunlight. This can be done at almost no cost if solar sails are employed to reach the planet, because when these are no longer needed as propulsion devices they can be left in orbit and oriented in such a way as to melt the polar caps, liberating carbon dioxide into the atmosphere.

The greenhouse effect would then amplify that heating. If only a few solar sails were available, then only a small effect would be attainable, and it would be necessary to use large mirrors to obtain the desired large scale. The mirrors could be built in space with aluminium mined from either the Moon or an asteroid and then propelled to Mars by the radiation pressure of sunlight [1.21].

Alternatively, it might be possible to change the orbits of small asteroids or comets and drop them onto Mars. This could be done by a combination of relatively low thrust electric thrusters and gravitational assists from a giant planet. The kinetic energy of the asteroid or comet would be converted entirely into thermal energy, causing localized heating around the point of impact and releasing the materials from which it was made.

A comet nucleus that is rich in ice could significantly increase the amount of water vapor in the planet's atmosphere, and an asteroid rich in ammonia (if one is found) would release this gas into the atmosphere, thereby increasing the greenhouse effect and creating a protective layer against ultraviolet light. It may appear to be a weird idea to crash asteroids and comets on a planet in order to terraform it, but this mimics the natural mechanism of

planetary formation. It is thought that, during its accretion, the Earth received water and carbon (the latter perhaps already having formed organic compounds) from falling cometary nuclei.

The techniques described here for terraforming Mars are perhaps too primitive to work precisely, but they are the result of just a few years of deliberation of a completely new theme. They are based on the greenhouse effect, and as such they are an application to Mars of what has recently been learned about the effects of human activity on the Earth's environment. When the time comes to progress from speculation to feasibility studies and then to actions, all these subjects will be known in much greater detail. And it is possible that simpler, more effective, and perhaps more economical methods will be found. For example, nanotechnologies offer a tantalizing promise in this field (as they do in many others) [1.3].

Molecular automata, with their incredible ability to replicate themselves and then operate on a very large scale with negligible costs, could change the chemical composition and the characteristics of a planet's atmosphere in times a fraction of those mentioned above. Here the aim is simply to show that it should be possible to terraform Mars, rather than to describe the detailed ways in which the many and varied technical issues could be solved.

## 1.5 The Role of Solar Wind

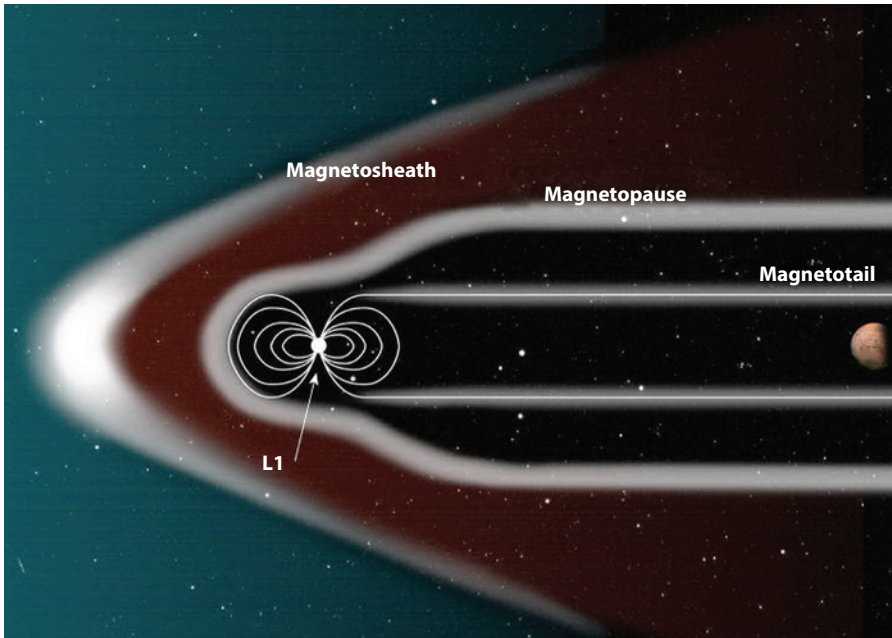
All what has been said above can however be countered by the observation that a planet with no magnetosphere like Mars, and above all a small planet, cannot retain a thick atmosphere because the solar wind will sweep away any atmosphere we may succeed to create around it.

This issue must be studied in detail, because we know well that it is not true for a planet of the size of Earth: Venus is much closer to the Sun than Mars, and maintains a very thick atmosphere without having a magnetic field. We know however that the lightest components of Venus atmosphere (like hydrogen) have been depleted and we are sure that the solar wind had at least some role in depleting the atmosphere on Mars.

This is a controversial aspect and needs to be clarified; above all we need to compute what is the rate at which the solar wind would reduce the atmosphere we try to build around Mars and what is the maximum rate that we can compensate for by simply replacing the gases that are swept away.

If these studies will prove that it is impossible to terraform Mars without screening it from solar wind, it could be possible to resort to active radiation screening techniques to protect the planet. It has been suggested that a spacecraft containing a large solar generator and a suitable coil, located in Lagrange point L1 of Mars (or, better, in a point close to L1, where the gravitational attractions and the thrust the sunlight exerts on the array are balanced) can completely screen Mars from the Solar wind [1.19], (Figure 1.6).

First studies have shown that this approach is feasible, although being a huge enterprise like all other ones linked with terraforming, and has also the advantage of reducing the amount of radiation the colonists on Mars will have to endure. Reducing, because it will be completely useless in protecting against Galactic Cosmic Radiation (GCR) which however will be much less a concern when Mars has a thick atmosphere.



**Figure 1.6** Screening Mars (by an artificial magnetosphere) from radiation from the Sun. Image courtesy of NASA/Jim Green.

It is clear that the complexity of this approach grows with the increase of the protection against solar wind we want to supply the planet and may be implemented in steps, starting with a partial protection and then proceeding to larger devices.

## 1.6 Ethical Aspects

To terraform Mars will be a huge undertaking, greater than some engineering feats of the past such as building the Great Wall of China or excavating the Suez Canal. And, apart from giving humanity a new planet on which to settle, it is bound to produce an invaluable body of scientific and technological knowledge. One important result will be a detailed insight into the mechanisms that regulate a planetary environment. In turn, this will assist humanity in cleansing the Earth of the effects of the industrial revolution. Moreover, this exercise will be invaluable in the future when other planets need to be terraformed, possibly under even more difficult circumstances.

One problem of a non-technical nature remains. Assuming that terraforming a planet is a feasible process, is doing so advisable or morally acceptable? The first concern relates to the massive production of greenhouse gases and particularly CFCs. The production of CFCs was banned on Earth because of the erosion of the ozone layer, but using CFCs elsewhere in the solar system could be beneficial. In a wonderful irony, chemicals that could irretrievably ruin the Earth's atmosphere, turning it into a hell resembling Venus, may be able to restore Mars to its ancient grandeur.

Is terraforming worthwhile? And acceptable? In his book, *The Search for Life on Other Planets*, Bruce Jakowsky lists the following points in connection with terraforming Mars and introducing an active biosphere there [1.12].

Seven arguments in favour are:

1. A thick atmosphere of carbon dioxide, even though it would be non-breathable, would greatly assist colonists by enabling them to explore the Red Planet equipped only with breathing apparatus rather than with full environmental space suits.
2. Locally generated biomass would be an important source of energy, food, and other useful materials for colonists.
3. Such an activity would provide a long term challenge on which humans could focus, with a goal that is both useful and desirable for humans.
4. Such a project would be an essential prerequisite to any future human colonization of Mars.
5. An active biosphere on Mars would provide a refuge for many forms of life on another planet in the solar system, safe against the event of war or a natural global catastrophe that might destroy life on Earth.
6. Much of the research would be highly relevant to addressing environmental problems at home and to understanding the intricacies of its biosphere.
7. Becoming a spacefaring civilization is less threatening than military developments or an arms race at home, and would provide a worthy outlet for international cooperation and competition and/or technology developments.

Seven arguments against are:

1. The time scale is so long that governmental institutions would not be able to maintain the necessary commitment to such a project.
2. It is not clear that there are significant economic benefits, especially in the short term, that would be commensurate with the cost and effort involved.
3. Scarce human and economic resources would be drawn from other worthwhile projects, such as addressing social and terrestrial environmental problems.
4. Something could go awry during the course of the project that could damage the new Martian biosphere beyond repair, leaving us in a worse situation than if we had never intervened.
5. Humans have made such a bad job of managing the Earth's environment that it would be presumptuous to imagine we are wise enough to succeed on another world.
6. If terraforming was successful, then Mars might become a tempting target for military and/or economic exploitation, thereby creating more sociopolitical problems than we have at present.
7. The evolution of a Martian biosphere could be inherently unpredictable, and might be detrimental to humans or (by back contamination) to Earth.

The present Author thinks that most of these arguments against can be easily dismissed. A rebuttal could follow these lines.

- Point 1. This is a very reasonable point and we cannot rely on governments to perform such a task. Terraforming a planet can be undertaken only in the context of a developed space economy, in which private enterprise has a large, or even the primary, role.
- Point 2. In the context of a space economy, are the market forces which will drive the process. Terraforming Mars needs to be seen in the context of the Martian economy, and its advantages are unquestionable.
- Point 3. This is the usual argument against space exploration in general, which has proven to be inconsistent. First the resources which will be attracted by terraforming (or exploring space in general) are largely insufficient to solve 'Earth' problems, but above all enterprises like exploring, colonizing and terraforming, a planet create resources and do not consume them. Technology is not a zero-sum game, and Earth's problems can be solved only if technology is free to progress [1.11].
- Point 4. If we stop for the fear of failure we will never progress. No early technology was as dangerous as fire, and if our ancestors used the principle of precaution would have refused to use it. We would still be at the palaeolithic.
- Points 5. This is just a revisited form of point 4.
- Point 6. Developing new resources will decrease the conflicts on our planet. It is the decrease of resources in a society which refuses to accept new challenges and to take new opportunities which will make more conflictual the relations on Earth.
- Point 7. Each biosphere evolves following its own lines and the laws along which this happens need to be studied, and will be studied as a part of the terraforming process. Strict anti-contamination procedures need to be a part of any terraforming process. To this we must add that all evolutionary processes are extremely slow, with all time to take the required counter-measures.

Actually the reasonable objection to terraforming Mars (or any planet) is that by doing so we could cause any local life form to get extinct. As stated by McKay and Haynes, "If, and only if, no potentially viable forms of life are found should we attempt to introduce immigrant species from Earth... What would be the greater good, Mars barren or Mars endowed with life? ... Should the Martian biosphere be tended to ensure at least early development in a manner agreeable to Homo Sapiens?" [1.14].

The terrestrial (and perhaps a Martian) ecosystem arose naturally by the actions of many factors which play different and contrasting roles. One of these factors is humankind. The fact that humans are intelligent does not deprive them of their right to play a part in the game, but it places upon our species the burden of behaving wisely by trying to predict the consequences of its actions. Yet, this responsibility must not paralyze us.

As already stated, the first planet of the solar system to be terraformed was Earth, long ago, by the primitive life that changed an atmosphere from one based on carbon dioxide to one rich in oxygen. In a sense, at that time the oxygen was a pollutant. To wonder whether they had a right to do that is clearly meaningless. If there is no life at present on Mars, all

the ethical problems may seem to stop with the question of whether humankind has the right to play some active role in shaping that infinitesimal part of the universe over which it exerts influence.

But if micro-organisms are found on Mars, the whole issue must be considered from two points of view. How might the terraforming operations affect them? And what would be the impact of their presence on the entire project? The changes might make them evolve, perhaps enabling them to complete the process that was halted in the distant past. But the changes imposed by humans are likely to be too sudden to allow life to adapt to the new conditions, and therefore the risk that it would not survive is great.

Consequently, it is important that any life present on Mars be studied in great detail before we start any work aimed at changing the environment. All the practical measures necessary to protect and preserve what can only be considered as an extreme and special case of biodiversity absolutely must be taken.

A radical point of view is based on the observation that, even if life still exists on Mars, we can be certain that it failed to produce an extensive biosphere. Therefore to supersede it with more successful life-forms, that could spread across the planet would be consistent with the basic logic of evolution whereby the fittest forms of life survive and propagate.

These are useful starting points for a debate. And since terraforming Mars is a distant prospect, there is plenty of time to acquire a deeper understanding of all the issues involved. Also in the light that it has recently been proposed that the Moon might be terraformed as well.

## 1.7 Venus, Moon, Titan...

We have spoken of terraforming, mostly in the context of terraforming Mars but, in principle, any rocky celestial body might be terraformed, and in the solar system there are plenty of such bodies.

As we have seen, the first time a terraforming operation has been described in science fiction was in the context of the colonization of Venus.

Outside science fiction, Carl Sagan in 1961 [1.16] proposed to terraform Venus by using genetically engineered bacteria to fix carbon from atmospheric carbon dioxide into organic compounds, although later this approach was shown to be impossible [1.1], [1.6]. The planet is too hot, and any organic compound would give way again to carbon dioxide when reaching the surface: the planet must be cooled before – and not after – the organic compounds are formed. Also, most of the hydrogen has been swept away from the atmosphere by the solar wind and too little is available to form the organic compounds.

Terraforming Venus would require:

1. Reducing Venus' surface temperature of 462°C,
2. Eliminating most of the planet's atmosphere, by converting its carbon and sulphur dioxides in some solid products (carbonates and sulphates) deposited on the surface,
3. Adding oxygen to the atmosphere.

However, today terraforming Venus is considered as a very difficult enterprise for a very distant future.

**Table 1.1** Characteristics of Moon, Mars and Venus which are important for terraforming.

	<b>Moon</b>	<b>Mars</b>	<b>Venus</b>
Gravity	Very low	Low	Earth-like
Atmosphere	None	Very thin	Very dense
Temperature	Correct	Low	Very high
Rotation	Way too low	Correct	Extremely low
Radiation	High	High	High
Life	None	Unlikely but possible	Very unlikely

A different thing could be terraforming the Moon. As a first point, the proximity of the Moon to the Earth would make any project regarding our satellite much easier than a similar project regarding any other body. Would terraforming the Moon be an important learning project on the way to terraforming Mars? The answer is likely to be negative for the reason that these two bodies are so different that whatever we learn from terraforming one will hardly apply to terraforming the other. Table 1.1 summarizes the main characteristics of the Moon, Mars and Venus from the point of view of terraforming.

The first difference between them is gravity. That of the Moon is too low to retain an atmosphere for long (at least in cosmic terms). If the Moon is terraformed, the atmosphere will have to be continuously replenished to compensate for the very slow (on a human scale) losses. The use of a heavy buffer gas (xenon, krypton) instead of nitrogen has been suggested because it would be less easily swept away by the solar wind, but it is difficult to imagine us obtaining such large quantities of these gases. And in any case, nitrogen is rare on the Moon. The Moon does not possess an atmosphere to initiate the terraforming process, and lunar volatiles are present in ppm quantities.

Water is present in the regolith in polar craters but we have yet to determine its locations and concentrations by direct sampling. One proposal is to augment the Moon with water and volatiles from comets, but in practice it would be difficult and could conflict with the early settlements that would surely exist when terraforming begins. Heating the surface of the Moon would not be required, in contrast to the situation for Mars. The rotation of the Moon is far too slow, with nights and days lasting two Earth weeks. This may cause large night-day temperature variations, with problems regarding atmospheric circulation. The possibility of crashing small asteroids on the Moon to increase its angular velocity has been proposed, but the proximity of the Earth would cause tidal effects which would act to slow the rotation again. The natural state for the Moon is synchronous rotation. No such problem exists for Mars.

Neither body possesses a magnetosphere, so, even after the terraforming was complete, the surface would be subjected to cosmic and solar radiation.

Also in the case of the Moon it is possible to put an electromagnetic screen against solar wind in space. In this case the screen must be put in a halo orbit about the L1 point of the Earth-Sun system. If this can be done, the conditions on the Moon may decidedly improve and terraforming the Moon might become possible.

The presence of oxygen in the enriched atmosphere would create an ozonosphere that could stop ultraviolet radiation, but achieving this would be more difficult for the Moon than for Mars.

The only advantage for the Moon is that we are certain there is no life, so there would be much less concern about ethical restraints than for terraforming Mars, where the situation is still ambiguous. As a conclusion, terraforming the Moon is more acceptable but much more difficult than terraforming Mars, and the difference between the two bodies means it is unlikely that from the Moon we could learn lessons applicable to Mars. Terraforming Mars is something that may, in the long term, be attempted. Terraforming the Moon may be a project for a much more distant and indeterminate future.

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