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Terraforming: The Creating of Habitable Worlds

Springer

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This book is dedicated to the past, present, and future peoples of Tikopia.

About the Author

Martin Beech teaches astronomy at Campion College, The University of Regina. His main research interests have focused on the smaller objects that reside in the solar system; asteroids, comets and meteorites. Asteroid 12343 martinbeech has been named for his research relating to the Leonid meteoroid stream, but he has published on topics as diverse as the works of graphic artist M. C. Escher, the folklore of mushrooms, the writer Thomas Hardy, and the formation of massive stars. In addition to interests in the history of science, scientific instruments and meteorite hunting, he is also actively concerned with the issues relating to global warming, global overpopulation and climate change. He lives in Regina, with his wife, Georgette, and a somewhat motley collection of three dogs and three cats.

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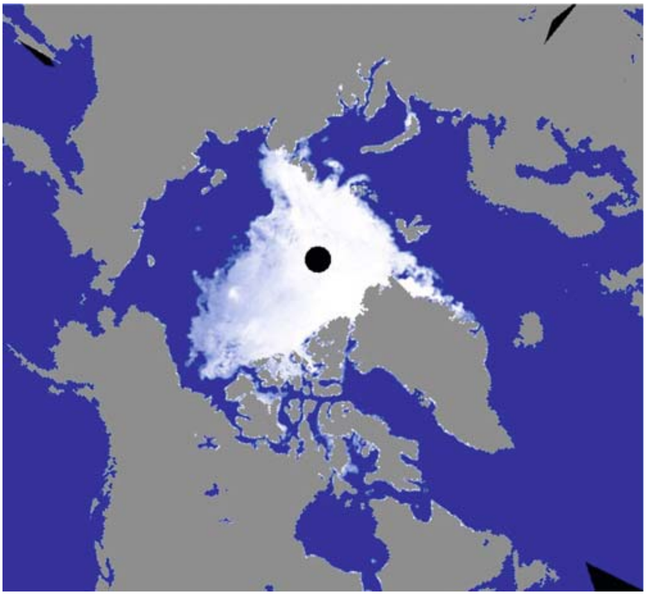

FIGURE 1.1. Satellite view of the Arctic ice coverage. On 15 August 2007, the area covered by the Arctic ice sheet reached its lowest ever recorded value of 5.31 million square kilometers. The thinning and reduction in size of the Arctic ice fields has been accelerating over recent decades as a consequence of global warming. It is predicted that by 2100 there may be no Arctic ice at all. Image courtesy of the Japanese Space Agency.

Summer, the Year 2100

It was decided. We would make a family holiday of it. All of us, even my sister, were going to see the big guns of Kugluktuk. I could hardly contain my excitement as the school holidays slowly approached. Each long day, sitting in class, I wiled away my time, fidgeting through math and sleeping through physics. I mean, what was a boy to do when the big guns beckoned.

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Time crawled by. It seemed an eternity, but the day eventually arrived when my father, after one final look around the house for any missed luggage, locked the front door and climbed into the family car. I had somehow managed to convince everyone that I should be the front-seat passenger (normally a much sought-after, and fought-over, seat), and even though we didn't need it I had the route map open in front of me. Head north and drive for 6 days straight; that was our route.

We crossed the prairies of Saskatchewan, through the boreal forest, and over the fly-blown taiga and muskeg. The northern highway was in excellent condition, and we made steady progress. There was so much to see, and I didn't even mind the stopovers at night or the quick museum and wildlife reserve visits during the day. The point was we were heading north, and our destination was getting closer.

The final few days of travel became long and hot, but as we neared the city of Kugluktuk my sense of anticipation became fever pitch. *We'll soon be there, we'll soon be there,* I kept repeating to myself, and there will be a whole day to spare before the shelling begins.

Kugluktuk is the Inuit name for the old town of Coppermine. Situated on the northern Canadian coast, it had become a much sought-out tourist destination. The region boasted of long, hot summers and endless beaches, rolling seas, and gentle ocean breeze. The prosperity of Nunavut, and Kugluktuk in particular, had come about because of global warming and the opening up, all year round, of the Northwest Passage to shipping. The Arctic ice had long ago vanished from the northern seas, and one can even take a boat trip to the North Pole these days. The whole area was undergoing an economic boom; vast oil and natural gas reserves had been discovered under the seafloor, and extraction platforms of one kind or another dotted the entire panorama.[1]

Although global warming had brought prosperity to northern Canada, the regions to the south were doing less well. The climate there had become so hot and fresh water so scarce that what used to be the breadbasket of the world was now mostly desert and useless scrubland. In an attempt to address the global warming problem and to cool the Earth down, the United Nations had begun to fund and organize a vast network of giant cannons, their purpose being to fire and then explode massive sulfur dioxide-bearing shells into Earth's upper stratosphere.[2]

"Welcome to the Baltimore Gun Club" read the sign above the big gun interpretive center. This was apparently a reference to a book written two and half centuries ago by an obscure French writer called Jules Verne. I made it my intention to find a copy of the book when I returned home. One of the introductory displays at the center explained that the idea of firing sulfur pellets into the stratosphere was to mimic the cooling effects caused by volcano plumes. This phenomenon was first noticed and investigated in the late twentieth century—the good old days. Nobel Prize-winning chemist Paul Crutzen made some of the first detailed model predictions in 2006 and found that a thin layer of stratospheric sulfur dioxide could counterbalance the warming trend due to the ever-increasing abundance of greenhouse gases.[3] The sulfur dioxide layer had the effect of increasing the Earth's albedo, thereby reflecting back into space more of the incoming sunlight.

Well, of course, the rest is history. Governments around the world bickered about greenhouse gas reduction quotas, and nothing useful was actually done to stop global warming. Apparently, and I thought this was well-worth knowing for *Trivial Pursuits* games, the derogatory expression "That's a load of Kyoto" was coined during the early 2020s. It was also at about this time that the science of geoengineering came into its own, and, of course, it is now one of the most profitable industries on the Earth. But enough history!

The guns were due to start firing at 13:00 hours, and I wanted a grandstand seat. Ever since I can remember, the Kugluktuk guns had been fired every 4 years, and this time I was going to see the show.

A total of 100,000 tons of sulfur was going to be placed into the stratosphere. The 200 mighty guns of the Kugluktuk range were going to fire, one after the other, again and again, a withering barrage of 50,000, two-metric ton sulfur-laden shells straight upward. Each cannon would fire 250 shells over a 48-hour period—about one shell per cannon every 12 min. It was going to be an incredible show. We were seated in the grandstand arena some 25 km away from the nearest vertical barrel. Each gun was spaced 2 km apart, and we were located opposite gun 100, half way down the chain. I could see the muzzle flashes long before the ground and grandstand began to shake to the thunderous timpani of the discharges. The sound was tumultuous; it blasted us mercilessly, and we loved it! The guns fired and fired. The flash from each barrel shot like a billowing flame, all yellow and gold into the sky. In clockwork fashion, one after the other, each cannon would discharge its massive shell that would sedately climb into the azure heavens. After each discharge, the muzzle plumes would darken into a mustard-brown cloud that twisted and gamboled like some demented *draco volans* as it drifted downrange.

Again and again the great guns fired. I sat there for hour after hour, the power of the percussion overwhelming my senses. My body shook, my ears felt as if they would burst, and my eyes began to hurt as they took in the shock of each new muzzle flash. The sensations were better than any carnival ride, and I had the time of my life: the scene was both terrifying and awe inspiring. The big guns of Kugluktuk were rocking the skies and cooling the planet Earth.

Notes and References

1. Global climate change has resulted in a drastic reduction in the Arctic ice cover, and in 2007 the ice sheet was reduced to the lowest level ever recorded. It has been suggested that a complete summer melt of the Arctic ice sheet could take place as early as 2030. With the potential opening up of the Arctic seafloor to oil and natural gas extraction, competing sovereignty land claims for the region have been launched by Canada, the United States, Russia, and Denmark.
2. Since the deposition height is about 20-km altitude, large ordnance shells rather than rockets are assumed to be more cost effective. More recently, it has been suggested that the sulfur dioxide might be pumped directly from the ground into the stratosphere through 20-km-long hoses attached to high-altitude blimps.
3. P. J. Crutzen: Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Climate Change*, **77**, 211–220 (2006). A recent publication in *Geophysical Research Letters*, **34**, L15702 (2007) by Kevin Trenberth and Aiguo Dai of the National Center for Atmospheric Research (Colorado) finds, however, that the "sulfur sunshade" might reduce global rainfall levels, and this could

have a devastating effect on the Earth's water cycle. A more recent study by Simone Tilmes, also of the National Center for Atmospheric Research in Colorado, finds that a sulfate sunshield might drastically reduce the size of the Earth's ozone layer. The devil, as always, is in the details, and the quest to understand the long-term effects of the sulfate seeding of the Earth's atmosphere continues.

2. Introduction

The word "terraforming" conjures up many exotic images and perhaps even wild emotions, but at its core it encapsulates the idea that worlds can be changed by direct human action. The ultimate aim of terraforming is to alter a hostile planetary environment into one that is Earth-like, and eventually upon the surface of the new and vibrant world that you or I could walk freely about and explore.

It is not entirely clear that this high goal of terraforming can ever be achieved, however, and consequently throughout much of this book the terraforming ideas that are discussed will apply to the goal of making just some fraction of a world habitable. In other cases, the terraforming described might be aimed at making a world habitable not for humans but for some potential food source that, of course, could be consumed by humans. The many icy moons that reside within the Solar System, for example, may never be ideal locations for human habitation, but they present the great potential for conversion into enormous hydroponic food-producing centers.

The idea of transforming alien worlds has long been a literary backdrop for science fiction writers, and many a make-believe planet has succumbed to the actions of direct manipulation and the indomitable grinding of colossal machines. Indeed, there is something both liberating and humbling about the notion of transforming another world; it is the quintessential eucatastrophy espoused by J. R. R. Tolkien, the catastrophe that ultimately brings about a better world. When oxygen was first copiously produced by cyanobacterial activity on the Earth some three billion years ago, it was an act of extreme chemical pollution and a eucatastrophy. The original life-nurturing atmosphere was (eventually) changed forever, but an atmosphere that could support advanced life forms came about.

Terraforming attempts to foster the growth of humanity and promises a better, less crowded, more fulfilled, more productive,

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and healthier future for billions of people. It provides humanity with the possibility of almost limitless expansion, and it ties us to our extended home, the Solar System. Indeed, the future for humanity holds immense promise and potential (although this is often difficult to see in the news events that we see on any given day), and perhaps just as importantly the resources and skills required to realize this wider (one might say utopian existence) are no longer the stock-in-trade of the science fiction writer. They are the *known,* and they are the *real* in the here and now. That humanity possess the rudiments of such technology and power is incredible, and it behooves us to use such skills wisely.

The desire to explore and the craving to understand have underpinned much of human history. Indeed, the thirst to appreciate what resides over the distant horizon, or to appreciate the workings of an atom, the properties of a distant star, or the minutia of, say, the life cycle of the Richardson ground squirrel have brought humanity to its present expansive viewpoint, and our collective horizon is now very, very broad. Between the quantum world of the atomic nucleus and the mapped-out realm of the cosmos, humanity's gaze encompasses an incredible 10^{61} orders of magnitude in scale.[1]

Certainly, there is much that we don't understand about the myriad objects within the observable universe, and no doubt many of our currently lauded and much cherished theories about the workings of the cosmos are wrong; the point is, however, we keep searching and we keep exploring, yearning to find out what resides over that far, distant horizon, beyond our present physical reach.

Not only do humans thirst for intellectual knowledge and understanding, but they also have an innate wanderlust for physical exploration. To climb, to crawl, to fly, to swim, to dive the oceans, all these adventures have preoccupied our ancestors. The distant horizon is not just the muse for our intellectual struggle; it is also the physical barrier beyond which we strive to move. Within this context, terraforming is a distant horizon that challenges both human intellect and the innate desire to explore and experience the cosmos. The exploration and colonization of other terrestrial planets and moons within our Solar System has not unreasonably been described as humanity's destiny. We seemingly have no choice; these other worlds will be our future homes, but before we can move in, a great amount of preparation will be required. This book is essentially about the pre-moving terraforming stage.

Perhaps every human generation has lived under the delusion that it exists at a special time. We are no exception, but it is probably fair to say that for the very first time we live with the danger of our outgrowing the planet Earth. As shall be seen in Chapter 4, the Earth might seem unimaginably large, but it is nonetheless a finite world, and it has a finite carrying capacity. Although it may seem that the Earth's distant horizon has begun to shrink in our ever-more connected, been there, done that society, our collective gaze is primed to explore the more distant and remote horizons that envelop other planets. The Earth is under stress; we pollute it, we ignore it, we abuse it, and yet it still sustains us. Humanity may never have the power to fully destroy the Earth itself, but we might destroy ourselves (time will tell), and we are rapidly approaching the limit beyond which the Earth can support us. We must either adapt ourselves to expect less, or we must adapt to other worlds, and here is humanity's first big break, for we live in a Solar System full of prime terraforming real estate.

What's in a Word?

A direct translation of the word *terraforming* is "Earth shaping," and this is further taken to mean the process by which a planet is made Earth-like, and by implication a world capable of supporting human life. Depending upon how literal one wants to be, there is really only one planet within our Solar System that might be made Earth-like, and that's the planet Venus.

The second planet out from the Sun, the mass, radius, and surface gravity of the Venus in Earth-units are 0.815, 0.949, and 0.90, respectively. In other words, it is already an Earth-like planet. The problem for humanity, however, is that Venus has a surrounding atmosphere that currently makes surface life impossible. In the case of terraforming Venus, therefore, it is essentially atmospheric alteration that must be performed in order that life might eventually exist upon its surface.

This may seem like a tall order, but if we think about it, in a timeframe of less than 200 years, human industry has changed (though in the wrong way for our survival) the atmosphere of the Earth. This observation alone provides us with the very real sense that atmospheric manipulation on a planetary scale is entirely possible, and that it is possible on a timescale of centuries rather than millennia. Indeed, the term geoengineering has recently been introduced to the scientific lexicon to describe the manner in which the harmful effects of global warming might be ameliorated.[2]

Although Venus and Earth can be thought of as planetary doppelgangers, it is the planet Mars that is most often called the Earth's twin. At first glance this seems a rather odd statement. In Earth-units, Mars has a mass, radius, and surface gravity of 0.107, 0.532, and 0.38, respectively. Indeed, Mars is nothing like the Earth in physical terms. It is in this (admittedly semantic) respect that Mars cannot be terraformed (that is, made into something like the Earth), but it can be made habitable, at least in a dynamical sense, as will be discussed in Chapter 6. In addition, it is now clear that Mars was a very different world in the past, and in some sense terraforming it in the future will be a partial process of reinstituting what was once there, when the Solar System was much, much younger.

The term *planetary ecosynthesis* has also been used to describe the manner in which Mars might be transformed into a life-supporting domain, and this expression gives us some sense of the great complexity of the problem at hand. An ecosystem is typically described as a natural setting that consists of a multitude of species of plants, animals, and microbacteria that function and interact within the same environment. To make Mars habitable, therefore, very specific ecosystems will have to be nurtured and sustained. Canadian biophysicist Robert Hall Haynes (1931–1998) further coined the expression *ecopoiesis* (from the Greek words for *house* and *making*) to describe the deliberate production of new ecosystems on other planets. In addition, inherent to the meaning of the word "ecosystem," the process of ecopoiesis entails the generation of a self-supporting system hosting many hundreds, if not many thousands, of subsystems that are all interacting with one another, but all of which are stable over long periods of time. But this will be a topic for further discussion in Chapter 4.

If at the heart of the terraforming (or ecopoiesis) process is the goal of making another planet habitable, the question that can reasonably be raised is, "What kind of life is the world being made habitable for?" Clearly, microbial life forms have very different requirements to, say, plants or humans. Extremophile microbes, for example, can thrive in rock pools where the temperature is 100°C, or where there is no light at all—regions in which no human being could live. Likewise, the typical winter temperature in the central Antarctic continent is about –80°C, and as far as is known, no plant, microbe, human, or other animal can survive for extended periods of time under these conditions, and yet Antarctica is very much part of the Earth, a planet that is otherwise teeming with life. As shall be seen in Chapter 4 the range of conditions necessary for life, specifically human life, to thrive are quite narrowly defined, but for the process of terraforming this is actually helpful, since it makes clear exactly what conditions must eventually be brought into existence.

Moving Forward

Terraforming is an action intended to benefit humankind, and it is concerned with creating a safe abode out of another world, one fit for human habitation (at some comfortable, but not necessarily ideal, level). Although this book is concerned with describing life-sustaining systems within the Solar System, it is not directly concerned with the origins of life (but see Vignette A at the end of the next chapter) and/or the existence of life elsewhere in the Milky Way galaxy or the greater expanse of the universe.[3] The viewpoint to be adopted throughout this book is shamelessly on the side of doing what is best for the human race.

This working approach being stated, however, does not mean that the author advocates the shameless exploitation or abuse of the Earth and the greater Solar System beyond. Humanity has much to learn about planetary stewardship and environmentalism. As human beings we must do away with the notion that our lives lie outside of nature; we are bound (at least for the present) to the "natural" Earth and we are part of the Earth, and when it comes to terraforming new worlds it is vital that humanity remembers that it is not an outside, disconnected operator, but an inside contractor with an inalienable obligation to providing good directorship. All of the above being said, the future nature that humanity should strive to be part of will, by necessity (and no doubt by design), be very different from the verdant world that surrounds us at the present time.

The Anthropocene

To us, short-lived humans, the land and sea that surrounds us, the very stuff of the Earth, seem ancient and ageless. The landscape of our distant forefathers is typically the same landscape that we live in today. The Earth's change is slow; the silent tick tock of its evolving time beats out a much slower rhythm than that of our frenzied lives, but this is not all. While the Earth ages, it also renews itself, its wrinkled and weather-warn veneer of a surface endlessly turning over in a brashness of volcanic fury and an unstoppable grinding of tectonic plate over tectonic plate. The Earth's surface, our landscape, is ever changing little piece by little piece, but we can hardly see it.

Geologists count the slow accumulations of landscape change according to the deposition of distinctive rock strata, sea-level changes, and climatic variation. We presently reside in what is called the Holocene (meaning "entirely recent") epoch, which began at the end of the last great Ice Age some 10,000 years ago. Before that came the Pleistocene (meaning "most new"), which encompasses the time of the most recent period of repeated glaciations starting as far back as about 2 million years ago.

Earth change occurs and Earth change accumulates, and the geological eras and epochs split and subdivide the changes that are displayed in the sandwiched layers of terrestrial rock. It all seems old hat. Strange-sounding names categorize the history of our planet and detailed stratigraphic measurements annotate changes that took place so far back in time we can hardly imagine them. Yet, incredibly, we live at the time of a new threshold. The Anthropocene (the "human new") is upon us, and its mark has been indelibly stamped upon the Earth.

Indeed, writing in the February 2008 issue of *GSA Today*, a magazine published by the Geological Society of America, Jan Zalasiewicz (department of geology, The University of Leicester, UK), along with 20 co-authors, has suggested that the International

Commission on Stratigraphy should call the Holocene to a close. In their article the authors note that the presence of humanity is now irrevocably etched upon Earth's geological record. A geologist living in the far distant future, for example, would easily detect the global deposition of radioactive elements resulting from the nuclear bomb testing carried out during the 1960s; this faint but enduring echo from our paranoid past has produced a distinctive atonal chord in the harmony of natural depositions.

The footprint of humanity goes back even further than the atomic bomb, however, and many distinctive markers, such as atmospheric lead levels, carbon dioxide release, human-driven extinctions of plants and animals, and alterations to the sedimentation rate as a result of damming the world's major waterways, all betray our presence. The process began about 200 years ago in the choking smokes of the Industrial Revolution, and at the time when the number of human beings climbed over the 1 billion people mark. Within the time span of just a few centuries, the presence of humanity has been duly docketed into the geological history book of Earth. We have changed the Earth, in some sense without even trying, and this leads us to imagine the incredible power that our not-so-distant descendents might wield when their attention turns to the deliberate terraforming of other worlds.

Future Worlds, Future Homes

When plotted in the global average temperature versus time into the future diagram (see Figure 2.1 below), there will be a convergence of future terrestrial worlds. By this it is meant that the atmospheres of both Mars and Venus will be terraformed (in one way or another) to support a surface temperature that falls somewhere between 0 and 100°C, and preferably a temperature that remains close to 10–15°C. With these Earth-like average temperatures, Mars and Venus can in principle support plant life and some especially adapted and bioengineered animal populations in hydrated ecospheres.

Although the terraformed worlds will, by design, converge with respect to their temperature, the composition of their atmospheres will, in all likelihood, be distinctly different from the

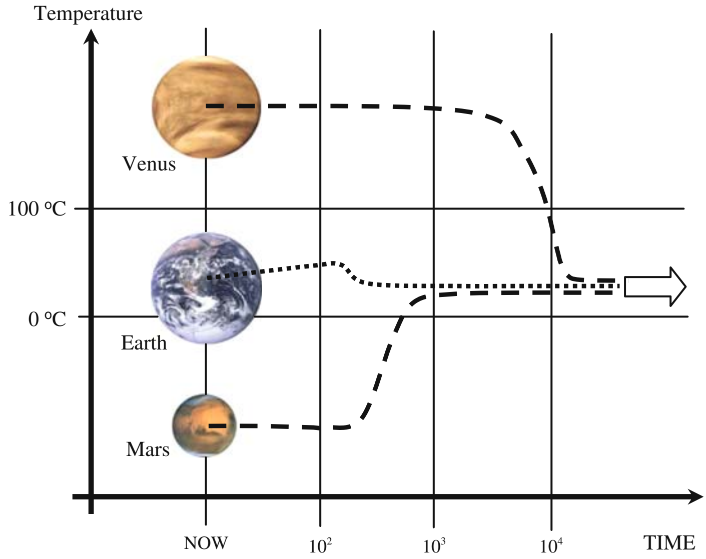

FIGURE 2.1. A schematic surface temperature versus time plot for Mars, Earth, and Venus. The Earth's temperature is shown to be increasing for the next 100–150 years as a result of global warming. Indeed, the first large-scale terraforming program to be instigated is likely to be that which will oversee the reduction of the Earth's surface temperature. The temperatures of Mars and Venus will increase and decrease, respectively, as a result of terraforming. It is suggested in this diagram that the terraforming of Mars might possibly be completed within the next several centuries, but it is anticipated that Venus won't be fully terraformed for perhaps many thousands, if not several tens of thousands, of years from the present.

Earth's, and the atmospheres will not necessarily be breathable by human beings; indeed, it is highly likely that they may never be fully life supporting in this latter respect. Why terraform, then, one might ask? Indeed, if the resultant new worlds have atmospheres that cannot support free-ranging human beings, then what is the point?

Well, the point, of course, is that the terraformed atmospheres will allow for surface water to exist and crops to be grown, and this, in principle, is all that one needs to make the human world tick. With respect to where human beings might live on a terraformed world, we need look no further than the trend that is clearly evident on Earth at the present time (a topic further discussed in Chapter 4). By the middle of this century, over half of humanity will live in cities, and cities need only two inputs to support their residents, water and food. They also, of course, need great swaths of land to recycle and dispose of their many forms of material waste.

Cities are insular, their inhabitants unaware of the greater world that surrounds them. Urbanized people live, work, play, and prosper within their immediate environments, where (at least apparently, much of the time) they thrive. Cities are cut off from the land that enables them to exist, and the regions immediately beyond the city confines have but one purpose and that is to provide recreation. Increasingly, however, even outdoor recreation is achieved within the unnatural confines of indoor arenas. The West-Edmonton Mall in Alberta, Canada (see Figure 2.2), for example, not only provides ample opportunity for thousands of people to simultaneously eat, sleep, drink, and, of course, spend their money. It also provides its residents with a funfare, a shooting range, an ice rink, a swimming pool, and an aquarium complete with submarine rides. Once inside, there is technically no reason to ever leave the mall again. All of the basic necessities of life (food, water, recreation, basic health care, commerce, a job, and accommodation) are there.

FIGURE 2.2. Europa Boulevard in West-Edmonton Mall, Alberta, Canada. Once inside this proto-city one could, in principle, live a complete life without need to ever exit its confines. The mall, which covers an area of some 570,000 m^2, provides all the basic necessities, such as accommodation, food, water, commerce, a job, recreation facilities, and entertainment.

Although West-Edmonton Mall may not be a model upon which to base future city planning, by extrapolating the urbanization trend—admittedly to an extreme—it would seem that the way in which our distant descendents will live on the Earth is moving toward a supermall-like, self-contained, environmentally insulated city existence. Clearly, such supercities will still require an input of food and water and land upon which to recycle waste; but increasingly, for so it would seem, in future centuries there will be little difference between the habitats within which human beings will live, whether situated on Earth or upon a terraformed Mars and Venus.

If humanity is moving toward a lifestyle housed within supermall-like domed cities, then this can be carried through to the terraforming process. Future humans will presumably be happy enough, perhaps one could argue because they know no better, to live a full and contented life within a domed city whether it be located on the Earth (where there happens to be a breathable atmosphere already), or on Mars or Venus (where there would probably be no breathable atmosphere outside of the city limits). As the ever-challenging architect Buckminster-Fuller argued in his 1969 book, *Utopia or Oblivion, Prospects for Humanity*, "domed living is the alternative to doomed living."

The apparent trend toward urbanization and human encapsulation will clearly require the development of what might be called environmental technologies. An initial attempt at the construction of a small-scale, environmentally self-contained domed city is exemplified by the Biosphere 2 project located in Arizona (see Figure 2.3). The technology designed to fully support human life within a totally self-contained domed city has by no means been perfected at the present time, but the process of investigation has begun, and the Biosphere 2 studies represent an important pioneering step toward our eventual living upon terraformed worlds.

The future for humanity does hold great promise, and it promises a rich and fulfilled life for many tens of trillions of people, provided, of course, that humanity manages to survive long enough to have a distant future. The future will be heavily dependent upon both old and new technologies, some of which, no doubt, haven't even been dreamed of yet, and humanity will have to learn how to wield these technologies in a holistic sense that maximizes future

FIGURE 2.3. The 1.27-ha (3.15 acres) glass structure of Biosphere 2. Constructed between 1987 and 1991, the interior contained various ecosystem regions, including a rainforest, a coral reef, a mangrove wetland, grasslands, and agricultural land. Biosphere 2 was fully isolated from the outside atmosphere, although in practice the interior atmosphere did require a small amount of external manipulation and was able to support a community of only up to eight people.

benefits for the biosphere, whether it is located on the Earth, Mars, Venus, or the many additional worlds beyond.

Economics

This will be a very brief section, since it is concerned with a topic that will have little to no influence on our main discussion. Indeed, nowhere in this book will there be any mention of how much it might cost to terraform a planet, or colonize an asteroid or a moon. Admittedly, some researchers have prepared detailed budgets and cost–benefit analyses in order to argue for the superiority of their preferred terraforming, or world-changing, scheme. To be blunt, such an approach appears to be patently absurd and a near-complete waste of time. Why? Because, in short, the commitment to terraform another world can only proceed outside of our current economic thinking and practices. The present economic fashion of demanding short-term gain over long-term investment will never be able to support a terraforming project. In short, the process cannot be financed on the basis of pure monetary return (which, of course, is not to say that money can't, or won't, be made by committing to such programs). Humanity will begin terraforming Mars and Venus and worlds beyond, not because there is any specific financial gain to be made but because it is committing itself to a long-term survival strategy, and because each new generation of human beings is prepared to invest in the future of following generations that they will never meet. There is much work that needs to be done at home, on Earth, and within ourselves, before the process of terraforming can finally begin. We will literally have to terraform ourselves before we attempt to terraform other worlds.

Notes and References

1. This scale encompasses the range from the Planck length of 10^{-35} m, at which scale the limits of currently known physics are reached, to the edge of the presently observable universe, a distance of about 10 billion parsecs ($\sim 10^{26}$ m).
2. David Keith discusses some of the geoengineering options that might be used to combat global warming in an "insight feature" article published in the journal *Nature* **409**, 420 (2001). Indeed, Keith concludes "It [is] likely that this century will see serious debate about—and perhaps implementation of—deliberate planetary-scale engineering." Oliver Morton also reports in the journal *Nature* [**447**, 132–136 (2007)] on the idea of altering the Earth's climate through geoengineering methods. Interestingly, however, he concludes his article with the statement, "In the past year, climate scientists have shown new willingness to study the pathways by which Earth might be deliberately changed.... But they are not willing to abandon the realm of natural science, and commit themselves to an artificial Earth."
3. These ideas are further discussed, for example, in M. Beech, *Rejuvenating the Sun and Avoiding Other Global Catastrophes*. Springer (2007).

3. Life in the Solar System, and Beyond

There are few better pleasures in life than the act of rummaging through the shelves of a secondhand bookstore. There is always some little treasure to be found in such places, like a small text crammed into a dark and shadowed corner, collecting dust—an obscure gem just waiting to be uncovered. One such dust-encrusted jewel discovered by the author in London, Ontario, Canada, a good number of years ago now, was a small book entitled *A Ready Reference Handbook of the Solar System*, by W. G. Colgrove.

Published in 1933, the book tells readers that it is "a concise summary of over 1,000 interesting items and deductions" about the planets. For each planet in the Solar System, Colgrove presents 60 "facts" relating to its name, mythology, markings, brightness, orbital period, and so on. Fact number 60, however, concerned the issue of habitability. For Mercury, Colgrove writes, "We cannot think of life on this planet." Well, no great surprise there, and this is still the prevalent view held by astrobiologists to this very day. The planet Mercury is, and always was, a dead world, life finding no toe-hold upon its craggy, cratered, and Sun-baked surface.

What about Mars? Here again, we find no surprises in our 1933 text, and Colgrove surmises, "It would seem quite reasonable to believe that Mars is habitable." For the planet Venus, however, we come across a surprise when Colgrove explains, "It seems quite reasonable to think that here is a planet fit for human habitation." Here we find a remarkably different perspective to that held today. Indeed, Venus has the highest surface temperature of all the planets within the Solar System, and its atmosphere presses down with a force 95 times greater than that experienced at the Earth's surface. Venus, from our modern perspective, is about the last place in the inner Solar System where human beings and or any other life form might possibly live.

It is not our intention to ridicule in any way Colgrove's comments on the habitability of Venus, but they do make the useful

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point: since the publication of his book and the writing of this one, only 75 years have elapsed (the duration of a good human lifetime), and yet so many things, not least our knowledge of the planets, have changed dramatically within this time.

Another wonderful find in a London secondhand bookstore was the short, but colorfully illustrated, text, *Our Solar System* by Gaylord Johnson. Published for the National Audubon Society in 1955 (a brief 53 years ago), Johnson comments, "altogether the prospects for the existence of life on Venus seem poor." Certainly, the swing of opinion away from Venus being habitable had begun by the 1950 s, but it was still not ruled out absolutely. Indeed, yet another find in a secondhand bookstore, this time constituting a set of trade cards originally distributed with Beano Bubble Gum packets in 1956, entitled The *Conquest of Space*, shows astronauts landing on the dry, desert-like surface of Venus, complete with a thorn tree in the foreground (Figure 3.1).

The first direct measurements of the composition and temperature of the Venusian atmosphere were made in October of 1967 (a mere 41 years ago) by the Soviet Space Agency's Venera 4 spacecraft. Venus turned out to be a hellish world with an atmosphere predominantly composed of carbon dioxide and a surface temperature of 460°C. Ever since the time of that brief atmospheric plunge by the Venera 4 spacecraft our minds-eye image of Venus has been

FIGURE 3.1. "What the first space travelers might see beneath the dense Venusian clouds." From the "Venus" trade card forming part of *The Conquest of Space* series first distributed with Beano Bubble Gum in 1956.

irrevocably transformed from a potential second Eden to a nightmarish world where only the tormented souls from a Hieronymus Bosch painting might reside.

Although our understanding of the Solar System (which we further discuss in the next chapter) has changed dramatically during the past quarter-century, we still know very little about the potential for indigenous planetary and moon life. What is truly remarkable about the present times, however, is that we may well be the first generation of human beings to actually know for sure if life exists, or once existed, elsewhere in the Solar System, and we may also be the first generation to know if life exists upon planets orbiting stars other than our Sun. Not only this, the current generation and its immediate descendants may be the first to initiate the process of terraforming the planet Mars. We truly live in exciting times.

Mars: The Once and Future Abode of Life?

The planet Mars, the celestial symbol of war and strife, shines a dull red color in our earthly sky; it is truly different in appearance from the other planets, which shine with a resplendent silvery glow. Indeed, this malevolent orb, which casts its one-eyed Voldamortian[1] gaze upon us, can affect our bodily humors, or so the astrologers of yesteryear would tell us, and it can determine the outcome of conflict and dastardly enterprise. None of us really believes in such astral influences anymore, but we do know that if Mars isn't a deathly world, it is an apparently dead and decidedly barren one (Figure 3.2).

Both Colgrove and Johnson, the authors of the treasures we found in secondhand bookstores, argue that Mars is habitable, although Johnson, writing in 1955, scales back the claim by stating that only plant life can flourish there. That even plant life is not possible on the surface of Mars was not revealed to us until July of 1965 when the Mariner 4 spacecraft dashed past the Red Planet to reveal a barren and cratered world. Indeed, the conditions that currently prevail on Mars (discussed in more detail in Chapter 6) clearly preclude the existence of anything other than bacterial life