



**ASTRONOMERS'
UNIVERSE**

Martin Beech

Terraforming

*The Creating of Habitable
Worlds*

 **Springer**

Astronomers' Universe

Other titles in this series

Origins: How the Planets, Stars, Galaxies,
and the Universe Began

Steve Eales

Calibrating the Cosmos: How Cosmology Explains Our
Big Bang Universe

Frank Levin

The Future of the Universe

A. J. Meadows

It's Only Rocket Science: An Introduction to Space
Enthusiasts (forthcoming)

Lucy Rogers

Martin Beech

Terraforming: The Creating of Habitable Worlds

 Springer

Martin Beech
Astronomy Department
Campion College
The University of Regina
Regina, SK, Canada S4S 0A2
martin.beech@uregina.ca

ISBN 978-0-387-09795-4 e-ISBN 978-0-387-09796-1
DOI 10.1007/978-0-387-09796-1

Library of Congress Control Number: 2008936485

© Springer Science+Business Media, LLC 2009

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

springer.com

*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.

Table of Contents

1. Prolog: The Big Guns of Kugluktuk	1
Summer, the Year 2100	1
Notes and References	4
2. Introduction	7
What's in a Word?	9
Moving Forward.....	11
The Anthropocene.....	12
Future Worlds, Future Homes.....	13
Economics.....	17
Notes and References	18
3. Life in the Solar System, and Beyond	19
Mars: The Once and Future Abode of Life?	21
Life Express.....	26
The Miller–Urey Experiment	28
Panspermia: The Bigger Picture	31
Life and Death Clouds.....	35
Vignette A: What Is Life?	37
The Rights of Microbes	40
Notes and References	41
4. The Limits of the World.	45
Home on the Range: A Brief History of the Solar System	46
The Blue Marble	53
Breathing Room	56
A Magnetic Shield	59
Humanity's Footprint.....	61
We, the Tikopia	67
The Aging Sun	68
Back to the Present.....	74
Vignette B: The Viking Landers	75
Notes and References	79
5. In the Right Place at the Right Time	81
Planetary Temperatures	82
Atmospheric Temperature and Pressure	88

Phase Diagram of Water	93
The Habitable Zone	96
Atmospheric Retention	97
The Greenhouse Effect	101
The Tail Wagging the Dog	103
Feedback Cycles and Stability	105
The End of the Biosphere	110
The Formation of Terrestrial Planets	112
Super-Earths	118
Vignette C: Kepler's <i>Somnium</i>	119
Notes and References	122
 6. The Terraforming of Mars	 125
The Measure of Mars	128
Whither the Water?	136
The Opening Salvo	138
Altered States: The Means of Terraforming Mars	142
Increased CO ₂ Abundance	146
The CO ₂ Runaway	147
Super-Greenhouse Gases	151
Albedo Change and Increased Insolation	154
The Phases of New Mars	157
The Times of Their Lives	162
Worldhouse	165
Near-Term Developments	165
Vignette D: Daisy World	167
Notes and References	171
 7. The Terraforming of Venus	 175
The Moist Greenhouse Effect	182
Cloud Life	183
Perelandra Remade	185
Atmospheric Blow-off, Cooling, and Mining	186
Roman Blinds, Spin Up, and Spin Apart	191
Back to Basics	194
Getting CO ₂ Stoned	196
A Cold New Dawn	197
Surface Turnover	199
Flying High	201
A Distant Dawn	203
Vignette E: Back to the Moon	203
Notes and References	206
 8. An Abundance of Habitats	 211
The Moon's a Balloon	212

Hot-Footed Hermes	216
A Fragmented Neighborhood	220
Life on a Dwarf Planet: Ceres World.....	222
Living in the Clouds	225
Supramundane Planets and Shell Worlds	226
O'Neill Colonies and Orbiting Cities	229
The Coming of a Second Sun	230
Earth Shift and a Synthetic Sun	235
Dyson Spheres and Jupiter	236
The Galilean Moons: Food for Thought	238
The Deeper, Darker, Colder Solar System	242
The Pull of More Distant Horizons	245
Other Worlds Abound	246
Future Prospects	248
Habitable Exoplanets and Biomarkers	251
Vignette F: The Mysterious Titius–Bode Law	254
Notes and References	257
Epilogue	261
Internet Resources.	265
Glossary of Technical Terms	269
Appendices.....	273
A. Blackbody Radiators	273
B. Accounting for Greenhouse Gases.....	275
C. A Terraforming Simulator Model for Mars.....	277
D. Population Growth and Lily World.....	281
Index	289

I. Prolog: The Big Guns of Kugluktuk

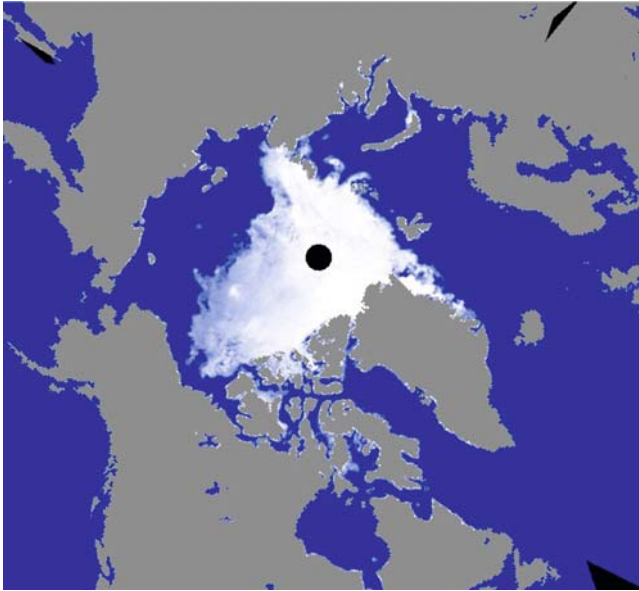


FIGURE 1.1. Satellite view of the Arctic ice coverage. On 15 August 2007, the area covered by the Arctic ice sheet reached its lowest ever recorded value of 5.31 million square kilometers. The thinning and reduction in size of the Arctic ice fields has been accelerating over recent decades as a consequence 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.

2 Terraforming: The Creating of Habitable Worlds

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

4 Terraforming: The Creating of Habitable Worlds

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,

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-worn 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

14 Terraforming: The Creating of Habitable Worlds

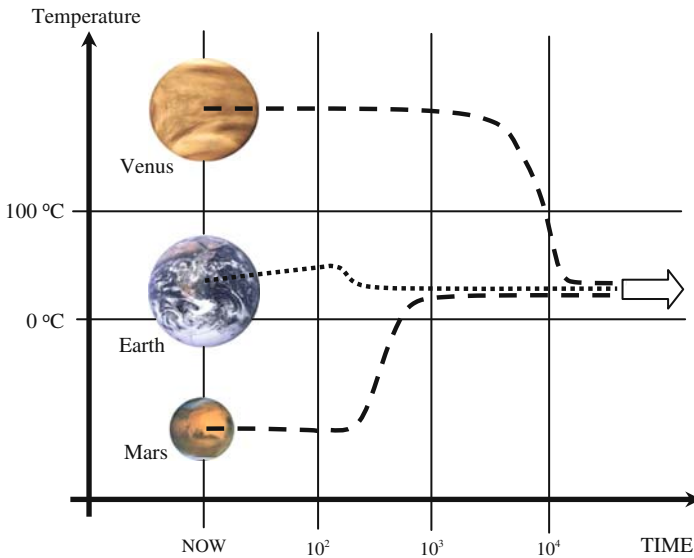


FIGURE 2.1. A schematic surface temperature versus time plot for Mars, Earth, and Venus. The Earth's temperature is shown to be increasing for the next 100–150 years as a result of global warming. Indeed, the first large-scale terraforming program to be instigated is likely to be that which will oversee 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 m², 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

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 1950s, 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 Voldamortian¹ 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



FIGURE 3.2. A dry, possibly lifeless barren vista of Mars as recorded by NASA's Mars rover called Opportunity. Image courtesy of NASA.

living there now. Just as with Venus, so our understanding of Mars has changed dramatically during the past 50 years.

Although our hopes of finding distinctive indigenous life on the surfaces of Mars or Venus have been reduced to near zero over the past half-century, Mars may yet come back to surprise us. The mighty Martian microbe is currently a much-sought-after beast, and as this chapter was being written, the NASA Phoenix Lander mission (Figure 3.3) was successfully launched, and is on its way to



FIGURE 3.3. An artist's impression of the Phoenix Lander on Mars. Image courtesy of NASA.

look for microbial life in the periodically watered soils close to Mars' northern polar cap. Many researchers expect that microbial life will be found on, or as is more likely, below the surface of Mars, and should this expectation be confirmed, then the hope of finding indigenous life elsewhere in the Solar System is greatly improved. More than this, however, if life has managed to survive on Mars, then it is already a habitable planet (at some level), and from the terraforming perspective, this is a great head start. Rather than starting from scratch, one can hope to build upon what already exists and thrives. Genetically engineered indigenous Martian microbial life might just be the tool needed to help transform the planet into a state that can support future human colonies.

The Phoenix Lander mission, and the variously planned follow-up surface exploration and sample-return missions, may confirm the existence of present-day Martian microbial life (time will tell, while we wait with baited breath). In the meantime, however, before the *in situ* results are gathered in, there are a number of observations that hint at the possibility that life did exist on Mars as recently as perhaps a few hundred million years ago. Even more incredibly, the evidence for this possibility is held inside the interiors of rock fragments that were blasted from the surface of Mars and that now reside on the Earth as meteorites.

One of the more recent invasion attempts by Mars began on 28 June 1911. Out of the clear, azure blue skies above El Nakhla El Baharia, Egypt, a rain of blackened stones pelted into the Sun-baked ground. It was 9:00 a.m. local time. The first warnings that something tremendous had happened were the rising sounds of thunderous booms that rolled and thudded across the landscape. Their attention caught, local observers glanced heavenward, and their eyes beheld a long, braided cloud of smoke that writhed in the sky, slowly twisting and turning like some tormented snake.

Rumors soon started to spread. Strange stones had apparently fallen after the strange celestial sounds had passed. Within a few days, some 40 rocks, weighing in at a total mass of about 10 kg, had been collected. It was claimed that one of the stones had struck and killed a dog, but there is no real evidence for this having actually happened. The Nakhla meteorite—as the fall of stones is now collectively known—was soon recognized as being oddly different

from other meteorites, although its Martian origins² were not to be discovered until many years later.

Time slides forward 73 years. Moving from the scorching desert heat of Egypt, our gaze shifts to the frigid ice-covered desert of Antarctica—a world away from Nakhla. A bundled-up, parka-clad field researcher working in the Allan Hills area east of the McMurdo Research Station stoops to pick up a rock. Lying exposed on the wind-blown surface ice, it is clear that there is something odd about the find, which is obviously a meteorite. Stored and carefully cataloged, the frozen meteorite is eventually given the less than inspiring name ALH84001. The first three letters identify the collection site (Allan Hills), the 84 indicates the year in which it was found (1984), and the 001 indicates that it was the first meteorite studied from the 1984 Antarctica collecting season. ALH84001 turned out to be another Martian meteorite.

There are currently 36 recognized Martian meteorites,³ but Nakhla and ALH84001 are extra special—according to some researchers—in that they betray evidence for interior alteration due to microbes, Martian microbes, that is. The hubbub began in August of 1996, when David McKay (NASA, Johnson Space Center) and co-workers published a remarkable paper in the prestigious

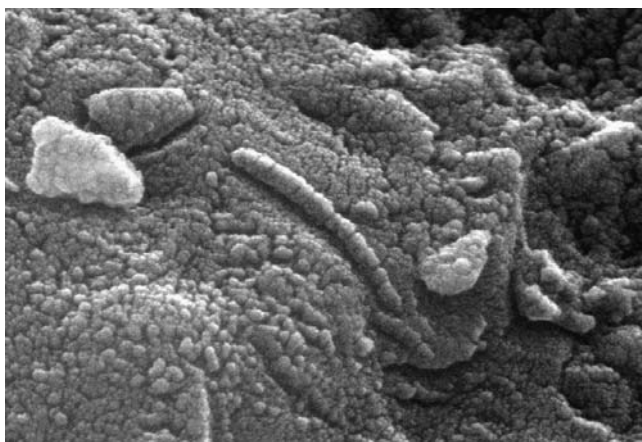


FIGURE 3.4. Electron microscope image of a postulated microfossil in Martian meteorite ALH84001. Most researchers now believe that the segmented, worm-like structure in the center of the image is not actually a fossilized bacterium but a chemically produced inorganic artifact.

research journal *Science*. Their claim was Earth shattering in potential; they had found evidence for the existence of Martian bacteria in ALH84001 (see Figure 3.4).

The McKay et al. research paper caused a worldwide buzz of interest. Here, for so it was claimed, was a whole series of observations, admittedly none of which was entirely conclusive, but when all viewed together were highly suggestive that life had both emerged and thrived on the Mars in the distant past.⁴ Subsequent studies by many hundreds of researchers have certainly weakened the initial claims outlined by McKay's group, and although it is no longer clear that ALH84001 presents any direct or unambiguous evidence for the existence of past life on the Mars, there are still many researchers who feel that the ALH84001 data hasn't been totally explained or annulled. The research continues.

While work on ALH84001 carries on in laboratories around the world, McKay and co-workers have more recently suggested, at the 2006 Lunar and Planetary Science meeting in Houston, Texas, that signs of indigenous biotic alteration can be seen in the Nakhla meteorite (Figure 3.5). Specifically, a carbon-rich substance has been found to permeate some of the small cracks observed within a small sample of the meteorite. This material, McKay and co-workers note, is similar to that deposited by microbes in volcanic glass found in the Earth's oceans.

It is probably fair to say that the jury is still out with respect to the detection of *in situ* microbe alteration of Martian meteorite material. There are hints at possible microbial alteration, but

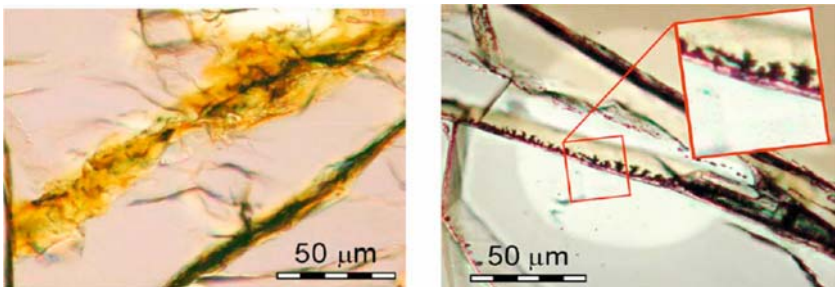


FIGURE 3.5. Very-high magnification image of dark veins within the interior of the Nakhla meteorite. It has been suggested that the dendritic features seen extending from the vein walls were caused by microbiotic activity while the rock was on Mars.

many alternate hypotheses can be formulated. This is the very stuff that great scientific debates are made of. The ultimate test for the presence of past (even current) life on Mars, however, will have to wait for a few decades, yet while we await (with ever-growing anticipation) for material samples collected *in situ* on Mars to be returned to the Earth.

Life Express

The once-thought quiet history of the Solar System has, and will continue to be, punctuated by violent collisions. Wayward comets and asteroids continually scuttle through the inner Solar System, and every now and then a collision must inevitably occur. The circular pockmarks of such impacts abound, and no old surface, whether on a planet or a moon, is free from the blemishes of past encounters.

In the previous section we examined the evidence for the past existence of microbial life on Mars via the study of Martian meteorites recovered on Earth. The impact processes that resulted in the ejection of material from Mars into space, however, is not unique to that planet, and there is every reason to suppose that there are terrestrial, Venusian, and even Mercurian meteoroids orbiting (both now and in the past) the Sun as a result of ancient impacts. There is not just a Martian invasion of Earth going on; there is also a terrestrial invasion of Mars, Venus, and Mercury. Indeed, there is a veritable communal interchange of surface material between all of the planets and moons within the Solar System.

Canadian researcher Brett Gladman (University of British Columbia) has developed a number of detailed numerical models that follow the orbital evolution of material ejected from the planets, and he finds that the interexchange of material can occur on relatively short timescales. In a recent study,⁵ for example, Gladman and co-workers found that material lofted from the Earth during a large crater-forming event can reach and impact upon either the surface of Mars or Venus within 30,000 years of being ejected. Something like 0.1 % of the material ejected from the Earth will, in fact, reach Venus, and about 0.001 % will reach Mars.

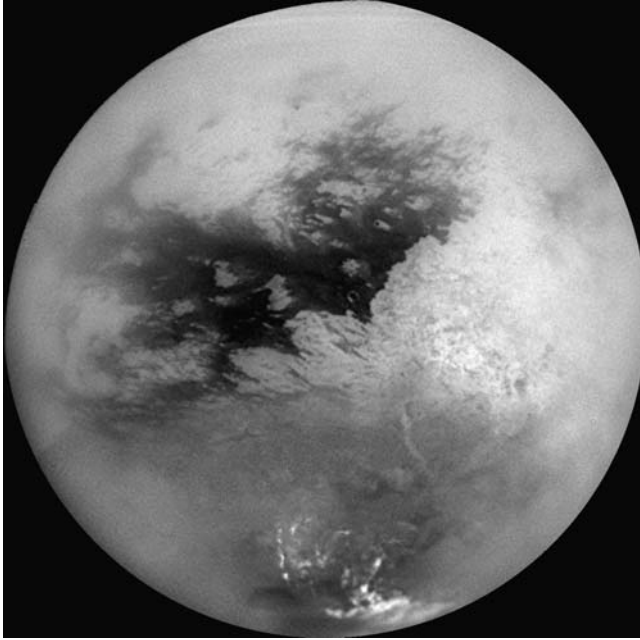


FIGURE 3.6. Titan, Saturn's largest moon, is the only satellite within the entire Solar System to have an extensive atmosphere. The atmosphere is primarily composed of molecular nitrogen (N_2) and methane (CH_4). Image courtesy of ESA/NASA.

Certainly, the amount of material exchange is small, but it raises the possibility that past life on Mars was, in fact, seeded from the Earth, the microbes being carried to their new home within the cracks and fissures of terrestrial meteorites. Gladman and co-workers⁶ also find that small quantities of terrestrial material can find their way to the moons Titan (Figure 3.6) and Europa (Figure 3.7), the latter moon being one of the strongest candidate worlds for supporting life at the present time (see later).

The concept of escape velocity will be discussed in Chapter 5, but for the moment we need only note that the escape velocity for material ejected from Mars is less than half of that required for material to escape from the Earth. This condition dictates that it is easier for material to be ejected from the surface of Mars than it is from the surface of Earth,⁷ and accordingly, Gladman finds that on a timescale of 15 million years perhaps, as much as 5% of the material ejected from Mars will ultimately find its way to the Earth's

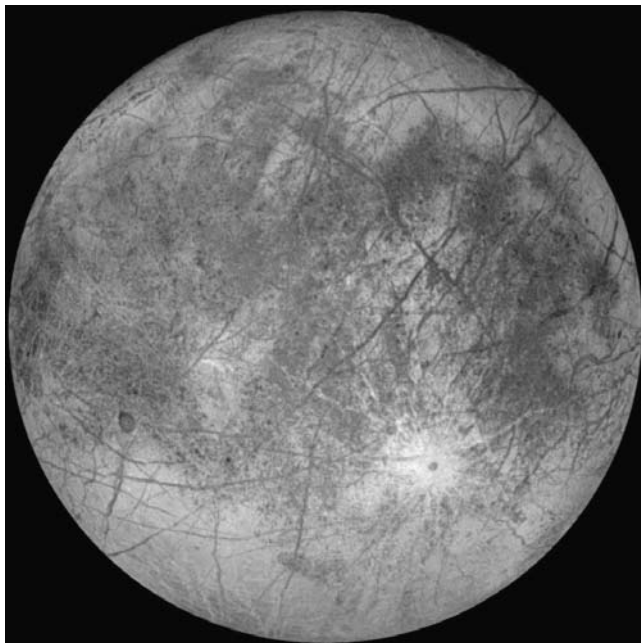


FIGURE 3.7. Europa, the second largest of Jupiter's four Galilean moons. This satellite has an extensive outer icy mantle, but the conditions in the subsurface regions are suitable for the existence of liquid water. The clear presence of an interior global ocean was first demonstrated through magnetic anomaly measurements made by instruments carried aboard the Galileo spacecraft. Image courtesy of NASA.

surface in the form of meteorites. In fact, about one in every 100 meteorites that falls is estimated to be from Mars! This turns the life-transport table upside-down, and there is a small possibility that life on the Earth was actually seeded from Mars.

The Miller–Urey Experiment

The deep philosophical questions relating to how life arose on the Earth (and presumably elsewhere in the rest of the universe) will not concern us in this book. It does seem worthwhile, however, to spend a little time reviewing one of the classic laboratory experiments designed to simulate the chemical conditions under which life first arose on the Earth and possibly upon Mars.

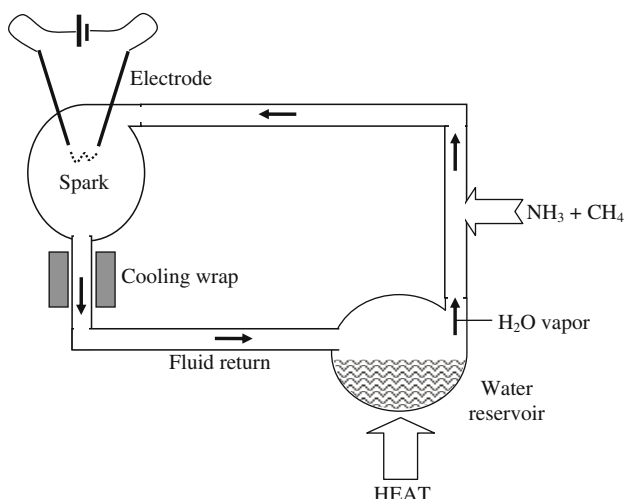


FIGURE 3.8. A schematic layout of the classic Miller–Urey experiment.

The experiment in question was developed by Stanley Miller and Harold Urey at the University of Chicago during the 1950 s. The aim of their experiment was to see if complex organic molecules could be produced in a methane- and ammonia-rich atmosphere. The experiment consisted of two connected chambers (Figure 3.8). The first chamber was partially filled with pure water (representing the early oceans), and this was heated to produce water vapor. Various quantities of methane and ammonia were added to the water vapor, and this mixture was taken to represent the atmosphere. The atmospheric mixture was then channeled into a second chamber that contained two sparking electrodes, which simulated atmospheric lightning. The bottom part of the atmosphere-spark chamber was cooled so that the gas could condense (representing a rain-like stage), and the condensed fluid was then circulated back into the first liquid-water-containing chamber. The experiment was then allowed to run continuously for a week.

The results from the experiment were remarkable. The water chamber soon began to change color, becoming a murky brown, and subsequent analysis showed that many different types of complex molecular chains had been constructed. No one expected life itself to arise, but it turned out that many of the key ingredients for life were produced, including all of the amino-acid bases required to

make deoxyribonucleic acid (DNA), the essential heredity molecule that enables life on Earth to reproduce and evolve.

Many variants on the Miller–Urey experiment have been constructed over the years, and a number of significant changes to the original setup have been introduced. The most important change since the original experiment, however, relates to the assumed composition of the Earth’s original atmosphere. Astronomers and chemists now understand that Earth’s initial atmosphere was rich in carbon dioxide (CO₂), rather than just rich in water vapor, methane, and ammonia, and while introducing CO₂ into the experiment does reduce the yield of organic molecules, it does not negate the conclusion of the initial experiment that the key molecules for life can evolve on the young Earth.

Still further variants on the Miller–Urey experiment use ultraviolet (UV) radiation, rather than spark electrodes, to power the molecular reactions; in these cases it was a simulated Sun that was providing the energy for the chemical reactions rather than simulated atmospheric lightning.

In spite of all of the variant Miller–Urey-type experiments that have been run, the end result has remained essentially the same, and it is clear that the complex carbon-chain molecules essential for the development of life will invariably be formed within young planetary oceans and atmospheres. This result in turn leads us to suppose that there are, in fact, no specific reasons to believe that life might not have also appeared on both the young Mars as well on the young Venus. It is interesting to note, however, that the prevailing consensus among researchers is that life could not have arisen in an atmosphere as oxidizing as the Earth’s is today; this in turn leads us to the conclusion that a planet can have an atmosphere that makes it habitable, but upon which indigenous life will not appear.

While *in situ* synthesis of complex organic molecules will take place, at some level, within all young planetary atmospheres, it is now clear that there are also external sources of organic material that might be brought to a young planet. The rare carbonaceous chondrite meteorites⁸ are, for example, known to contain complex organic molecules (Figure 3.9), and so, too, are cometary nuclei. It is also clear that such objects must have rained down into the atmospheres of the early Earth, Venus, and Mars, delivering their



FIGURE 3.9. A fragment from the Tagish Lake meteorite that fell in northern British Columbia, Canada, in 2001. A structurally unique carbonaceous chondrite-type meteorite, the Tagish Lake meteorite contains numerous organic compounds. Image courtesy of NASA.

precious molecular cargo into the chemical maelstrom from which life eventually arose (at least on Earth).

Panspermia: The Bigger Picture

It was suggested earlier that the exchange of impact-launched material between the planets might have resulted in the transport of viable microbial life from one location to another. This argument can, in fact, be taken further—much, much further. Not only will the material ejected from a planet by a large impact potentially end up on another planet or moon within the Solar System; a small fraction of the material will also end up in interstellar space. It is indeed possible (though admittedly highly improbable) that material from Earth, or early Mars carrying frozen, but viable, microbial life has found its way to planets orbiting other stars. It is a long shot, literally, but we may have distant (in space and time) cousins living many light years away.

The tenacity of bacterial life and its ability to survive long periods of dormancy is exemplified by the recent discovery and extraction, by Raúl Cano and Monica Borucki (California

Polytechnic State University, San Louis Obispo), of viable bacterial spores from the gut of a hapless bee that was caught some 25–40 mya and entombed in what is now Dominican amber.⁹ Kay Bidle (Rutgers University, New Jersey) and co-workers have also been able to extract degraded but viable bacterial spores from material extracted from Antarctic ice fields, with burial ages ranging from between 100,000 to 8 million years old.

The idea of panspermia, meaning life or seeds everywhere, is not a new one, but we can at least now identify one possible seed-transport mechanism—porous chunks of rock blasted into space from the surface of the Earth and possibly from early Mars and Venus. Indeed, a detailed numerical study conducted by Jay Melosh and Brian Tonks (Lunar and Planetary Laboratory, University of Arizona) in the mid-1990s found that about 20% of the impact ejecta from both Earth and Mars are eventually thrown out of the Solar System through gravitational interactions with Jupiter. These numerical results, Melosh later argued,¹⁰ indicate that something like 15 Martian rock fragments (ejected into space by asteroid impacts) larger than 10 cm across will leave our Solar System for interstellar space per year. The study further indicates that upon entering interstellar space the typical speed of the fragments is about 5 km/s.

With this information we can do a back-of-the-envelope calculation. Since the distances to stars are more typically measured in light years¹¹ we first need to do a few unit conversions, and accordingly: $5 \text{ km/s} = 1.58 \times 10^8 \text{ km/yr} = 1.67 \times 10^{-5} \text{ light years per year}$. In other words, it will take just under 60,000 years for each Martian fragment leaving the Solar System to travel 1 light year away from the Sun.

Now, the closest star to the Sun is the M-dwarf star Proxima Centauri, and it is 4.22 light years away. The minimum time for a Martian rock fragment to travel as far as the closest star, therefore, is about 250,000 years. In 10 million years, our spore-carrying Martian rock fragment might travel as far as 16.7 light years from the Sun, and there are about 50 stars within the sphere of space having this travel distance as its radius. Remarkably it is known that at least 6 of these 50 or so nearby stars have Jupiter-mass companion planets, and there may also be as-yet undetected Earth-sized planets orbiting these same stars.

Although appropriately shielded microbes might be transported, in a viable state, to stellar distances, the probability of actually hitting a habitable planet (or at least one that can nurture the microbes) is very, very small. Accordingly, the odds are very much against the possibility that the life found within our Solar System was seeded by interstellar meteorites carrying extraterrestrial bacterial spores. But as everyday life teaches us, just because the probability of an event occurring is very low, this doesn't mean that it can't happen.

As with the exchange of impact-ejected material between the planets of our Solar System, panspermia also operates both ways, and it is possible that the seeds of life were brought to the Earth from interstellar space. We have already seen that bacterial spores can survive, in a dormant state, for many millions of years, but the question that now arises is whether the spores can survive atmospheric entry to Earth or Mars.

The lowest-possible Earth-encounter speed for an interstellar rock fragment is 11.2 km/s (this, in fact, is the Earth's escape velocity, which is discussed later in Chapter 5), and accordingly large amounts of kinetic energy will have to be dissipated as the rock fragment descends toward the Earth's surface. Typically, some 90–95% of the initial meteoroid mass will be vaporized during the atmosphere flight of a meteorite-producing encounter, so it is only the inner core of a rock fragment that will reach the ground. This means, of course, that the transporting rock fragment must be reasonably porous so that the microbes can penetrate into its deep interior. This inward migration will also help shield the microbes from, for example, the potentially cell-destroying effects of UV radiation during their space odyssey.

The porosity condition described above, interestingly, sets up conditions that can be tested. One such experiment has been conducted by John Parnell (University of Aberdeen, Scotland) and co-investigators who arranged for a microbe-bearing hemispheric granite block (Figure 3.10) to be attached to the side of a reentering Russian space agency Foton space capsule. Under these controlled conditions, the ability of terrestrial microbes to withstand the high acceleration produced during the spacecraft blast-off, a near 2-week exposure to the cold vacuum of space and then the heat blast of reentry were studied, and amazingly, viable microbes were found within the charred remains of the granite block upon its return to the Earth.



FIGURE 3.10. Recovery of the ESA Foton-M3 capsule (top) in the Khazkh Desert on 26 September 2007. The image to the lower right shows the microbe-bearing granite rock prior to launch. The image on the lower left shows the granite hemisphere after reentry. Image courtesy of ESA.

Additional laboratory experiments carried out by Dieter Stöffler (Museum für Naturkunde, Berlin) and co-workers¹² have shown that bacterial spores can withstand the tremendous shock pressures that will result in the process of rock ejection during an asteroid impact upon the surface of a planet. Considering the possibility of Martian microbes being brought to Earth, Stöffler et al. note that the Nakhlite class of meteorites are the least shock processed of the various Martian meteorite types recognized (see Note 2), and accordingly they are the most favorable and efficient microbe-transfer vehicles. This experiment-based conclusion interestingly supports, at least in principle, the suggestion by David MacKay and co-workers that Martian microbes have caused alterations to the interior veins of the Nakhala meteorite (see Figure 3.5).

Although only a handful of centimeter-sized and larger rock fragments might leave the Solar System for interstellar space per

year, the number of smaller millimeter to micron-sized fragments is very much larger. This observation, Alexander Arkhipov (Institute of Radio Astronomy, Ukraine) suggests,¹³ might indicate that microbes are more efficiently carried into interstellar space on small grains and space debris rather than within the interiors of large rock fragments. Indeed, Arkhipov suggests that every star system containing a life-sustaining planet might be surrounded by a vast infection zone. Reaching out as far as several light years from the parent star, any other star passing through the infected region could itself become “contaminated,” or an exchange of microbial spores might take place. From the known number and motion of stars within the solar neighborhood, it can be estimated that the Sun will suffer an encounter with another star at a closest approach distance of 2 light years once every 70,000 years. This is a very short time interval, and Arkhipov argues that it is highly likely, therefore, that life on Earth was seeded by the close passage of planet-bearing star system. The other ramification of the Astroinfect principle proposed by Arkhipov is that life should be highly abundant within our galaxy, and that any star system containing a habitable planet should, in fact, also be life supporting.

Life and Death Clouds

Sir Fred Hoyle was a great, if not controversial, thinker. He was always one to think “outside of the box,” and he was apparently never happier than when challenging accepted opinions. Later in his eventful life, Hoyle collaborated with Chandra Wickramasinghe (University of Cardiff, Wales) and published a whole series of research papers and several books outlining the idea that the viruses responsible for diseases, such as smallpox, influenza, whooping cough, and bubonic plague, fell to Earth from interstellar space—that is, that such bacteria essentially permeate the entire galaxy. Indeed, Hoyle and Wickramasinghe argued that the wavelength dependency of interstellar extinction,¹⁴ relating to the systematic dimming of starlight with distance, is partially due to bacterial spores mixed into the gas and dust (the interstellar medium—ISM) that pervades the disk of our Milky Way galaxy. This

idea has certainly not met with any great acceptance from either the astronomical or medical communities, and it is often roundly dismissed as being completely absurd. But as with many of Sir Hoyle's grander ideas, there is much in his theory that is provocative food for thought.

Although Hoyle and Wickramasinghe have suggested that the interstellar medium might seed the Earth with deadly diseases (and possibly the seeds of original life), others have argued that advanced extragalactic civilizations might initiate a program of directed panspermia. In this case, specially selected bacteria and microorganisms are deliberately launched aboard an appropriately designed (and nurturing) space capsule into interstellar space. Michael Mautner (Lincoln University, New Zealand) has championed the idea of propagating terrestrial organic life throughout the Milky Way galaxy.¹⁵ Indeed, the Society for Life in Space (SOLIS) argues that there are sound ethical grounds for adopting a directed panspermia initiative, building upon the premise that "where there is life there is purpose [and that] the purpose of life is self propagation." Directed panspermia can proceed in many ways, and one can attempt to seed life directly on an already formed planet (which might, of course, need terraforming first), or one might impregnate an active star-forming region such that the seeds of life are in place from the very first moments that a suitably constructed planet appears. Directed panspermia is an entirely altruistic exercise, but as Maunder writes, "promoting life in this manner endows human existence with a cosmic purpose."

How to protect the Earth from the plague-infested clouds that might permeate the ISM, and the launch of interstellar probes for the direct seeding of space with microscopic life forms, are issues and actions that have yet to be initiated (or even agreed upon). What the possibilities do imply, however, is that life might potentially be found not only on any nurturing site within our Solar System but also at any nurturing location within the entire the galaxy. They also indicate that understanding the origins of life on Earth, already revealed as a complicated enough topic, might be even more convoluted (and even more cosmic) than hitherto envisioned (see Figure 3.11). We truly live in intriguing times.

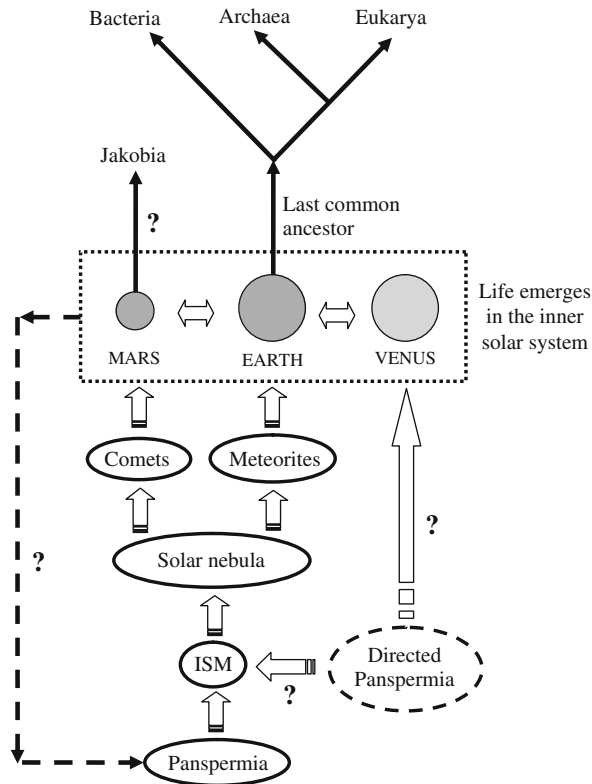


FIGURE 3.11. A schematic revision to Figure 3.12. It is not currently clear whether life first originated in our Solar System on Venus, Earth, or Mars. It is entirely possible, too, that the basic ingredients for life, maybe even life itself, were seeded by cometary and/or meteorite impacts on any of the three inner Solar System planets. In addition, it is not beyond the realm of possibility that life was seeded directly on one of the inner planets, or that the solar nebula itself was seeded by directed panspermia. The dashed line indicating that life might be transferred from our Solar System to the interstellar medium (ISM), resulting in panspermia conditions, is illustrative and not intended to indicate a feedback mechanism at work. The Jakobia lifeline emanating from Mars in this diagram is further explained in Vignette B at the end of Chapter 4.

Vignette A: What Is Life?

Defining Life

There is no simple definition that encapsulates the essence of what it means to say that something is alive. We know at the very least

that life is tenacious, and on Earth it thrives, or at least can survive, in any environment where liquid water exists. This includes places where the temperature ranges from the freezing point of water to its boiling point and incorporates locations from the highest mountaintops to the claustrophobic depths of the deepest mines and the oppressive darkness of the abyssal sea. Certainly, life as we know it on Earth is a series of aqueous chemical reactions, and accordingly we take something to be alive if it satisfies the following list of criteria:

1. *It is chemical in essence.* By this statement we exclude, for example, mechanical robots, no matter what their computing power might be, from the list of living entities.
2. *It exploits thermodynamic disequilibrium.* This means that living entities can extract energy from their surroundings.
3. *It takes advantage of the covalent bonding properties of carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur.* This statement describes the manner in which a living entity builds structures, manages its energy flow, and transfers information between its parts.
4. *It is able to reproduce.* This means that it can generate copies of itself under the direction of a molecular code (DNA) whose characteristics are inherited.
5. *It undergoes Darwinian evolution.* By this it is understood that in the reproduction stage, random mutations can occur, and these mutations are then subject to natural selection.

No doubt additional items could be added to our list, but they would do little to clarify the problem already at hand. It is still not known, for example, how inanimate molecular matter was able to transform itself into animate matter that can be called alive under the conditions laid out above. Indeed, the working of this particular miracle is presently well beyond our collective scientific ken. But this, luckily for us, is not our major concern. That life does exist and that it can be recognized is all that we need to know at this stage (see Figure 3.12). For us the issue is how life might be nurtured, and in what sort of environments is life likely to be found within the Solar System.¹⁶

Although terraforming is most often presented in terms of how an environment might be altered in order to sustain human life, the

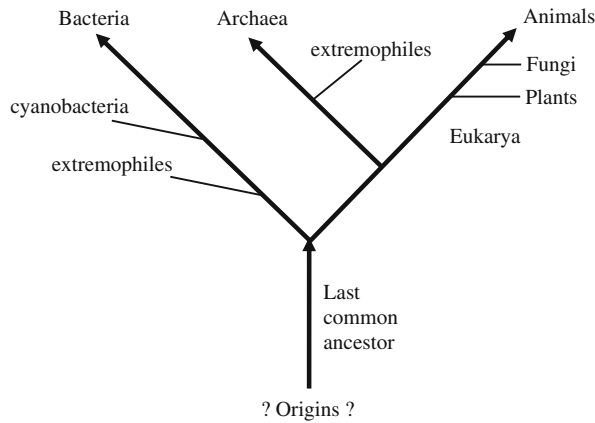


FIGURE 3.12. The tree of terrestrial life. All life on Earth is derived from a (last) common ancestor that first appeared some 3.8 billion years ago. Three main branches to the tree are now recognized, and these represent the bacteria, archaea, and eukarya. From each of these major branches radiate many millions of smaller stems (not shown in the diagram) leading to all of the animals, plants, and microbes that have ever existed. Bacteria are single-celled microorganisms that are typically a few thousands of a millimeter in size. Eukaryotes are organisms that have more complex cell structures (especially with respect to their having a nucleus in which the cells' genetic material is stored) than bacteria and archaea. Archaea are again single-celled organisms that have no nucleus, making them similar to bacteria, but detailed biochemical studies find that they are more closely related to eukaryotes. Many of the archaea are extremophiles that thrive in environments where other life forms would soon die, such as in high salinity pools and hot springs where the temperature can exceed 100°C . Some extremeophiles, however, are derived from the domain of bacteria. The cyanobacteria are one of the oldest life forms on Earth, and they generate their energy by photosynthesis, releasing oxygen into the atmosphere in the process. It was the appearance of such oxygen-producing organisms that caused the Earth's original atmosphere to slowly change from a reducing one to an oxidizing one. This dramatic change in the Earth's atmospheric composition took place between 3 and 2.5 billion years ago.

approach adopted in this book will be more along the lines of how might an ecosystem, where life already exists, be altered or nurtured such that it might support human life. Here we are shamelessly (or perhaps shamefully, depending upon one's attitude) adopting the approach that there is nothing inherently wrong with nurturing and reaping the abundant harvest of resources that exists within our Solar System. In Chapter 4 we will consider the prospects for finding life beyond Earth, both in the past and the present,

and this will hopefully provide us with a basic understanding of what kind of exotic environments planetary engineers will one day have to work with.

The Rights of Microbes

The philosophical study of moral principles, or ethics, is an intellectual minefield at the best of times, and perhaps only the very wary should really tread its tortuous paths. As with most topics in philosophy, however, there is typically no long-term right or wrong answer to any question that might be posed. The other point about philosophy is that, perhaps sadly, virtually all practicing scientists and engineers completely ignore it (unless forced not to do so by law, as in the case of, for example, medical research).

Opinions on what are good and bad things change with time and civilizations. This being said, there are basic ethical rules that, as human beings, we hope to live our lives by. For example, it is usually taken for granted (at least in the modern era) that all human beings have equal rights and freedoms with respect to the religion and lifestyle that they might choose to practice. It is deemed ethically unsound, for example, to enslave or exploit a person just because of their ethnicity or societal status at birth. It is also deemed ethically incorrect to kill or displace a distinct race of people from their traditional homelands simply because a stronger (usually meaning stronger militarily) society wants new land.

Although most people would probably agree with such basic ethical stances, history certainly tells us that humanity has never truly lived up to such ideals and further, when it comes to the idea of extending ethical rights to animals and the environment, the arguments often becomes highly polarized and downright heated.

What about dealing with life on other planets? Do alien microbes have rights? To begin with, it is clear that if life exists on any of the other planets or moons within our Solar System, then it is neither intelligent nor technologically advanced (well, by any reasonable human standards). At best, some microbial life forms might cling to a precarious existence on the planet Mars at this time, and they might also be able to eke out an existence on a few of

the moons of Jupiter (Europa, in particular) and perhaps also of Saturn (i.e., possibly Enceladus).

On Earth, no microbial life form has ever been granted the ethical right to prosper or exist; indeed, they are actively annihilated in many cases, and this is the situation even though it is the microbes that underpin the very existence of all higher life forms on the planet. In reality, microbes really rule the world.

Would or should, therefore, the discovery of microbial life on Mars change our outlook with respect to exploring the planet and eventually terraforming it? Recognizing that many different viewpoints exist on this topic, the author supposes that all that can be done at this stage is to place his own cards on the table, and the response is, don't stop—keep exploring. There does not seem to be any reasonable or fully convincing argument to explain why Martian microbes, should they exist, be afforded protective rights over and above, say, the microbes on Earth, and why their existence should stand in the way of the potential for greater human happiness. Other researchers will, no doubt, beg to disagree with such statements,¹⁷ but at this stage we shall have to agree to disagree. Accordingly, the approach to be adopted in the following chapters is that the transformation of at least the Martian and Venusian atmospheres should, indeed must, commence within the next several centuries, and the process should proceed by any and all means possible. Concomitant to these terraforming projects, it is also assumed that the continued development of lunar settlements, as well as the development of asteroid-based industries will also proceed with all possible haste.¹⁸

Notes and References

1. I am assuming that the adventures of Harry Potter are now sufficiently well known that the intended use of this word is clear.
2. The identification of Mars' meteorites is based upon their young formation age, and according to the chemical analysis of the very small amounts of gas trapped within small shock-melt pockets of glass. Indeed, the gases trapped within the meteorites are an exact match for the Martian atmosphere. Four main Martian meteorite groups are recognized: shergottites, chassignites, Nakhalites, and ortho-pyroxinates.

42 Terraforming: The Creating of Habitable Worlds

3. The Mars Meteorite Compendium web page provides access to a detailed database on all officially recognized Martian meteorites: <http://curator.jsc.nasa.gov/antmet/mmc/index.cfm>.
4. David McKay et al., Search for past life on Mars: possible relic biogenic activity in Martian meteorite ALH84001. *Science* **273**, 924–930 (1996). The estimated formation age for ALH84001 is 4.5 billion years.
5. Brett Gladman et al. Impact seeding and reseeding in the inner solar system. *Astrobiology* **5**(4), 483–496 (2005).
6. Brett Gladman et al, Meteoroid transport to Europa and Titan. Paper presented at the Lunar and Planetary Society Meeting XXXVII (2006)—paper: 2165.
7. In addition to the difference in the escape velocities of the Earth and Mars, which are 11.2 km/s versus 5.2 km/s, respectively, the Earth has a much denser atmosphere than Mars, and this will have an effect upon both incoming and outgoing material.
8. These are the least heat processed and among the rarest of known meteorites.
9. Raul Cano and Monica Borucki, Revival and identification of bacterial spores in a 25- to 50-million-year-old Dominican amber. *Science* **268**, 1060–1064 (1995). See also, Kay Bidle et al. Viral activation and recruitment of metacaspases in the unicellular coccolithophore, *Emiliania huxleyi*. *Proceedings of National Academy of Science* **104**(14):6049–6054 (2007).
10. Jay Melosh, Exchange of meteorites (and life?) between stellar systems. *Astrobiology* **3**(1), 207–215 (2003).
11. The light year (ly) is a derived unit of measure, based upon the distance that a light ray will travel in 1 year. It is equivalent to a distance of 9.4605×10^{15} m. The parsec (pc) is the more fundamental measure of astronomical distance, with 1 parsec being defined as the distance to a star with a parallax of 1 arc second. The conversion is: 1 pc = 3.2615 ly.
12. Dieter Stöffler et al., Experimental evidence for the potential impact ejection of viable microorganisms from Mars and Mars-like planets. *Icarus* **186**, 585–588 (2007).
13. Alexander Arkhipov, New arguments for panspermia. *The Observatory* **116**, 396–397 (1996).
14. Michael Mautner, *Seeding the Universe with Life—Our Cosmic Future*. Legacy LB Books, Christchurch, New Zealand (2004). See also, Michael Mautner, Directed panspermia 2. Technological advances toward seeding other solar systems and the foundation of panbiotic ethics. *Journal of British Interplanetary Society* **48**, 435–440 (1995). This subject has also been reviewed by Bill Napier, A Mechanism for Interstellar Panspermia. *Monthly Notices of the Royal Astronomical Society* **348**, 46–51 (2004).

15. F. Hoyle and C. Wickramasinghe, *Life on Mars: The Case for a Cosmic Heritage*. The Clinical Press, Redland, UK (1997).
16. The National Research Council of the National Academies has recently published a comprehensive review on *The Limits of Organic Life in Planetary Systems*. (The National Academies Press, Washington, D. C., 2007). Douglas Fox also discusses the origins and evolution of life in different environments in his *New Scientist* magazine article [9 June, 34–39 (2007)], Life: But Not as We Know It.
17. Martyn Fogg, Terraforming pioneer and long-time advocate of planetary engineering, discusses at great length the many issues of Martian microbial ethics in the ethical dimension of space settlement. *International Academy of Aeronautics-IAA-99-IAA.7.1.07*. (1999).
18. M. Beech. Terraformed exoplanets and SETI. *Journal of the British Interplanetary Society*, 61 (2), 43–46 (2008).

4. The Limits of the World

On 24 May, 1543, Nicolaus Copernicus lay on his death bed. He had been incapacitated for some time, an earlier stroke having left his entire right-hand side paralyzed and useless. For well over the last quarter-century of his life, Copernicus had been working on a new and a radical theory concerning the structure of the heavens, and finally, on the day of his death, so the story goes, his faithful helper George Donner gently raised the invalid astronomer so that he might see the first pages of his newly printed magnum opus, *On the Revolutions of the Heavenly Spheres*.

While the youthful and oft times wayward mathematician George Joachim Rheticus looked after the publishing details of his great text, Copernicus was probably only vaguely aware that his new ideas had finally been brought into print. Such was the sadness that permeated the final hours of this great philosopher. As Copernicus set out upon his final journey, his newly published text set the Earth on a new and fantastic journey of its own. Wrenched from the very core of the then-known universe, Copernicus put the Earth in motion. This new philosophy that poet John Donne complained “put all in doubt,” set Earth adrift in space, third planet out from the Sun. Transposed one with the other, the Sun replaced Earth at the center of all things, for, as Copernicus wrote, “Who would place this lamp of a very beautiful temple in another or better place.” While no longer the stationary socket about which the great axle of the celestial sphere indomitably turned, the Earth was still a special place since it was (and, of course, still is) the cradle and home of humanity.

Home on the Range: A Brief History of the Solar System

Astronomers only slowly warmed to the Copernican hypothesis. Indeed, Copernicus having had absolutely no proof or way to demonstrate the truth of his claim that Earth moved about the Sun, practicing astronomers had no good reason to adopt his strange new ideas. Inevitably, however, those with inquiring minds were won over, and the detailed workings of the Solar System, as we would come to call it, began to emerge. However, it was a complex scientific and sociological struggle, and many prejudices had to be overcome before the Earth could become, in the minds of the scientific community, a freely moving planet.

The astronomers of antiquity knew of seven planets, and in order from the Earth, they were the Moon (now recognized as a permanent Earth satellite), Venus, Mercury, the Sun (now, of course, known to be a star), Mars, Jupiter, and Saturn. William Herschel discovered the first new planet not known to the ancients when Uranus moved across his gaze on 13 March 1781. Then, trusting in the physics of Newton's gravitational theory and the ever-increasing accuracy of the astronomers observations, J. C. Adams and J. Leverrier independently predicted the existence of a new planet beyond the orbit of Uranus. The new planet, Neptune, was accordingly swept up by Johann Galle at Berlin Observatory, on 23 September 1846. Neptune's discovery was testament to the greatness of the human intellect, the power of mathematics, the tenacity of astronomers to produce ever more accurate star maps, and the skill of engineers to manufacture fine optical instruments.

Prior to the discovery of Neptune, Giuseppe Piazzi had discovered on 1 January 1801, what he thought might be the missing planet between Mars and Jupiter. Guided in his quest by the mysterious Titius-Bode law (see Vignette F after Chapter 8), Piazzi had in fact discovered Ceres, the first and largest of the main-belt asteroids. Three more asteroids were discovered in short order, Pallas in 1802, Juno in 1804, and Vesta in 1807. Rather than there being a single planet between Mars and Jupiter, there were four, and indeed, the number of objects in this region is now known to be well in excess of many hundreds of thousands.

By the beginning of the twentieth century, the Solar System was known to be composed of the Sun, the central hub, eight planets (Mercury out to Neptune), and several hundred asteroids. In addition, it held at least 20 short-period comets. Long thought to be harbingers of doom, the fleeting appearances of comets and their ever-varying tails trailing behind them, were well known to all ancient peoples. Indeed, the first written record concerning the appearance of a comet dates back to 674 BC, and is marked on a Babylonian clay tablet now residing in the British Museum.

The periodicity of at least one comet was established in 1785, with the first predicted return of Halley's comet. With an orbital period of about 75 years, for most people, Halley's comet is a once-in-a-lifetime heavenly spectacle, and the ancient and modern records indicate that the comet has been dutifully recorded at regular intervals over the past 2,246 years. It was during the 1685 return, however, that Edmund Halley, with the invaluable mathematical aid provided by Sir Isaac Newton, was able to determine its orbital elements. Unlike the planets that move in nearly circular orbits (Johann Kepler had revealed in his 1609 publication *Astronomy Nova* that in fact the orbits are slightly elliptical), Halley's Comet moves along a highly elongated path, taking it nearly twice as far from the Sun at its aphelion point as the orbit of Saturn, then the outermost-known planet. Halley had doubled the size of the Solar System in one well-determined mathematical swoop.

The scale of the Solar System is usually measured in terms of the size of the Earth's orbit, and this is conveniently expressed as 1 astronomical unit (AU). Since the Earth's orbit is elliptical, the astronomical unit is actually the half-diameter of its longer axes (see Figure 4.1). In addition to defining the distance scale, the Earth's orbit is also used to define the inclination of other bodies that orbit the Sun. The plane of the Earth's orbit is called the ecliptic, and the orbital inclination is by definition zero. Figure 4.2 shows how the orbital semimajor axis and orbit inclination varies for the planets and the main belt asteroids.

Spurred on by the observation (now known to be entirely spurious) that the motion of Neptune did not hold true to its predicted path, Percival Lowell set out to find its orbital perturber, which he reasoned must be another planet. The hunt was on, and the diligent Lowell Observatory staff astronomer Clyde

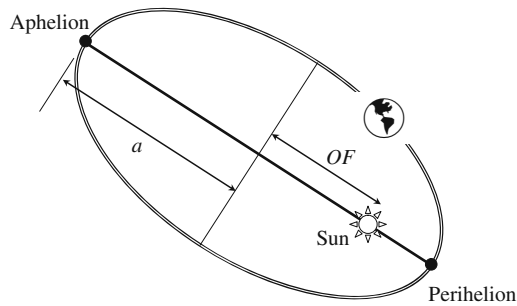


FIGURE 4.1. A schematic diagram of the Earth's orbit. The eccentricity (greatly exaggerated in this diagram) is defined as the ratio $e = OF/a$, where a is the semimajor axis. By definition, the semimajor axis of the Earth's orbit is taken to be 1 AU. A circle has an eccentricity $e = 0$ and for Earth $e = 0.0167$. The closest and most distant points of a planet (comet or asteroid) from the Sun are called the perihelion and aphelion points. This diagram encapsulates Kepler's first law of planetary motion, which says that planetary orbits are elliptical, with the Sun located at one focus. This law applies equally to comets, asteroids, and Kuiper Belt objects—indeed, it applies to any object that orbits around another under the influence of gravity.

Tombaugh eventually found Pluto on two photographic plates exposed on 23 January and 29 January of 1930. Orbiting the Sun at an average distance of some 40 AU, Pluto takes 250 years to complete its heliocentric rounds.

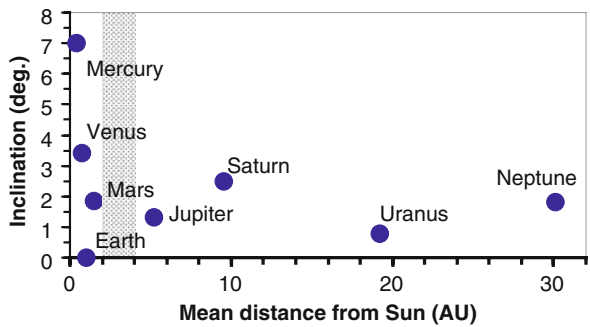


FIGURE 4.2. The distribution of the planets within our Solar System. The diagram shows the orbital inclination for each planet, measured relative to the ecliptic, against the distance of the planet from the Sun in AU. The shaded band between Mars and Jupiter indicates the location of the main-belt asteroid region. Note that the planets are much more tightly packed in the region inside Jupiter's orbit than in the region beyond it.

From the very outset, Pluto was revealed as an odd world. It was small (indeed, it is smaller than the Earth's Moon), of low mass, and its orbit has a very high 17° inclination to the ecliptic (nearly 2.5 times greater than that of Mercury's orbit). With the exception of a few comets, the orbit of Pluto appeared to mark the edge of the Solar System.

It was clear, however, that the gravitational influence of the Sun must stretch much further than the 40 AU demonstrated by Pluto's orbit. Indeed, the gravitational influence of the Sun must stretch half-way to the nearest stars (or further, depending upon the individual masses of the Sun's closest companions). The closest star system to the Sun is the triple grouping of Proxima Centauri and Alpha Centauri A and B. Although Proxima is the star closest to us, it is a low-mass star weighing in at about one-third of the Sun's mass; the dominant member of the Centauri group is Alpha Centauri A, which is, in fact, a Sun-like star. Located 1.34 parsecs (276,395 AU) in the direction of the Centauri triple system the Sun's gravitational influence will stretch to the mid-way point some 138,197 AU from the center of our Solar System.

If we take the semimajor axis of Pluto's orbit to define the volume of planetary space within our Solar System, then some 41 billion such volumes could fit into the region, with a radius stretching half-way to Alpha Centauri A. Surely such a vast volume of space must contain something more than matterless void? Of course, it does. Writing a seminal research paper in 1950, Dutch astronomer Jan Oort argued that the outermost regions of the Solar System must be delineated by a vast swarm of comets. It is now believed that of order 10^{12} – 10^{13} cometary nuclei roam the expanses of this vast, bitterly cold, outer reservoir that delineates the very limits of the Sun's gravitational pull. With orbital dynamics controlled by the fleeting passage of close-approaching stars, and the ever-present pull of the Milky Way galaxy, Oort Cloud comets (for so they are named) are intermittently perturbed into the inner Solar System. Their journey, however, is long and slow, the appearance of any tail and coma not starting until they pass within about 2.5 AU of the Sun. Then, for a brief few weeks, they blaze across our night sky in all their glory, eventually to sweep around the Sun and head off, once more, into the cold depths of the outer Solar System.

The outer boundary of the Solar System (the Oort Cloud) is neither spherical nor fixed in size. It is a dynamic boundary set by the ever-varying location and distribution of nearby stars and giant gas clouds that lurk in the disk of our Milky Way galaxy. Not only is the outer boundary of the Oort Cloud in continuous readjustment and motion, but so to is the inner boundary located a few tens of thousands of AU from the Sun. In this region, the weak but ever-present driving of a galactic gravitational tide slowly acts to feed cometary nuclei either into the cold depths of outer space, or the relative warmth of the inner Solar System. Indeed, the life of a comet is never a quiet one, and all its future holds is continued change.

Not only was it realized in the 1950s that the outer reaches of the Solar System were populated by a vast swarm of cometary nuclei, Dutch-American astronomer Gerald Kuiper also suggested at that time that a swarm of icy bodies should orbit the Sun in the same plane as the planets, but with orbital radii in excess of 40 AU. On 30 August, 1982, this bold theoretical prediction was proved true with the discovery by Jane Luu and David Jewitt (Institute of Astronomy, Hawaii) of the object named 1992 QB1—the first of the Kuiper belt objects (KBOs). Sixteen years since the first discovery, over 1,000 KBOs have been cataloged, with many having orbits that carry them thousands of AU from the Sun. It is presently thought that perhaps 70,000 KBOs larger than 100 km in diameter reside in the zone from 40 to 50 AU from the Sun. In the regions beyond 50 AU reside the scattered KBOs, with large eccentric orbits and perihelia no closer than 35 AU. The scattered KBOs have a range of orbital inclinations, but their distribution is essentially that of a disk that flares outward the further one moves away from the Sun. Figure 4.3 shows a schematic diagram of the main structures that constitute our Solar System. Although the planetary region, stretching at its greatest extent some 30 AU from the Sun, will be the domain of future terraforming operations, the regions beyond afford humanity with one of the most important resources for life—water. Ignoring the KBOs for the moment, if we simply assume that each cometary nucleus in the Oort Cloud has a diameter of 5 km, then the quantity of water ice stored in that region amounts to a staggering 10^{26} kg; this is equivalent to about 40 Earth's worth of ice.¹ There is absolutely no reason why future generations should go thirsty, which is not to say that mining cometary ice in the far reaches of Solar System will be easy, but it is the sort of process that a robot could do very well.

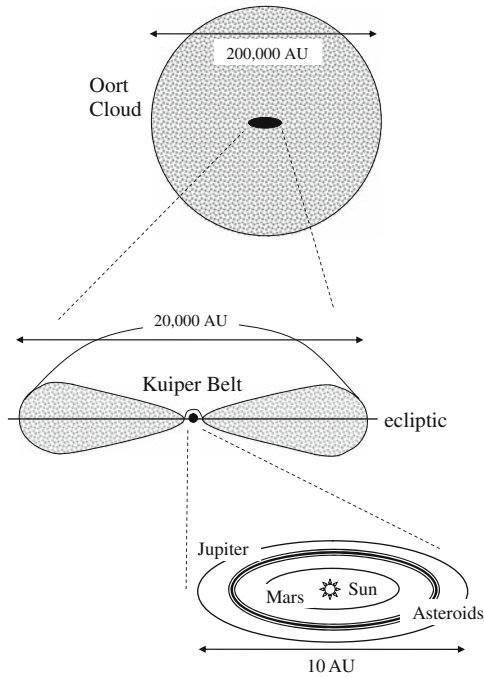


FIGURE 4.3. A schematic diagram of the extent and scale of the entire Solar System.

The astute reader will probably have noticed by now that Pluto has not been included in the list of planets. There are good reasons for this, but the reasons are not obviously clear ones (even to present-day astronomers). The problem is partly a question of semantics and partly a result of our increased understanding of the complexities of the Solar System and its origins. Indeed, the Solar System is a dynamic, ever-changing, ever-interacting system of trillions of objects, and while the planets might be the most obvious and largest objects (apart from the Sun, which truly dominates with respect to mass and size), they also form a diverse group of structures (as we shall see later on).

The problem of categorizing the Solar System objects is not a new one, and the number of recognized planets has varied from 6 to 11 over the centuries (see Figure 4.4). The most recent changes with respect to the conditions required for planetary status were introduced by the International Astronomical Union (IAU) in the summer of 2006. We need not worry about the classification details here,² but at the IAU meeting it was decided that the Solar System

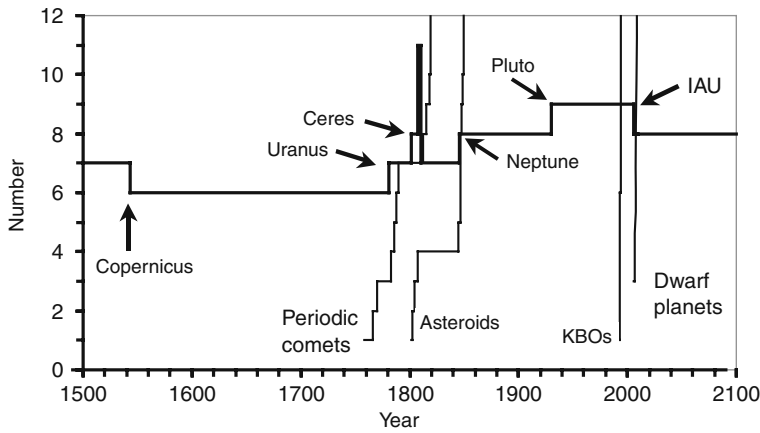


FIGURE 4.4. An historical look at the number of recognized planets, asteroids, periodic comets, Kuiper belt objects, and dwarf planets. The line indicating the number of dwarf planets is a guess; the number officially recognized at the present time is three.

contains eight planets, Mercury out to Neptune, and three dwarf planets: Ceres, Pluto, and Eris. Although Ceres resides in the main-belt asteroid region located between Mars and Jupiter, both Pluto and Eris orbit beyond Neptune, and, in fact, Eris is currently the largest-known dwarf planet, its diameter being about 200 km larger than that of Pluto. Technically the designation asteroid no longer applies, all such objects are now being considered as small Solar System bodies.

Table 4.1. In order of decreasing physical size, the approximate orbital extent and physical number of objects that delineate our Solar System.

Object	Region (Scale in AU)	Number
Planets	0.3–30	8
Dwarf planets	2.7 AU (Ceres) and 40–10 ⁴	3
Main-belt asteroids	2.1–5.2	10 ⁶ ⁽¹⁾
KBOs	40–10,000	70,000 ⁽²⁾
Periodic comets	0–100	185 ⁽³⁾
Oort cloud comets	0 to 10 ⁴ –10 ⁵	10 ¹² –10 ¹³ ⁽⁴⁾

Key:
⁽¹⁾This is the estimated number of asteroids in the main-belt region with diameters greater than 1 km.
⁽²⁾This is the estimated number of classical KBOs with diameters in excess of 100 km located in the region from 40 to 50 AU from the Sun.
⁽³⁾This indicates the number actually cataloged and which have been observed at least twice.
⁽⁴⁾This indicates an estimate of the total number of cometary nuclei within the Solar System.

Irrespective of what one chooses to call the multitude of diverse objects that constitute the Solar System, it is certainly clear that the Earth is far from being alone in its annual journey around the Sun. Table 4.1 is an attempt to account for the number of objects in the Solar System in terms of physical size, orbital distribution, and number. Copernicus, it seems certain, would have been amazed by the modern Solar System, not least for the fact that it contains many trillions of objects with orbits that change and slowly dance around the central Sun, that most beautiful of lamps.

The Blue Marble

Although the Earth (Figure 4.5) is far from being alone in the vastness of the Solar System, our focus and interests for the moment will be decidedly parochial. Asteroids, cometary nuclei, and KBOs



FIGURE 4.5. Planet Earth, or the Blue Marble, as it has been called. This photograph was taken by astronauts aboard the Apollo 17 command module (Image courtesy of NASA).

will have a role to play in our later discussion, but it is the Earth itself, and the planets within 0.5 AU of the Earth (namely, Mars and Venus), that will hold our specific attention. In this section, and the ones that follow, we will look at the Earth from the inside and from without, and we will also look at some of the present-day environmental and overpopulation problems that highlight the fact that the Earth is a finite world and has very definite limits as to what it can tolerate. Before other worlds can be successfully terraformed, humanity must first learn to live within the boundaries of the Blue Marble.

Tables of numbers do not make for particularly interesting reading, but they do have the great advantage of presenting a lot of useful information in a relatively small space. The basic features of the planet Earth, in numerical form, are revealed in Table 4.2.

A number of the Earth's characteristics listed in Table 4.2 have already been described (i.e., the mass, radius, and orbital semimajor axis), or are hopefully obvious, the implication and meaning of the other terms, not so far discussed, will be introduced in the sections to follow. For the moment let us concentrate on the Earth's surface characteristics.

Beyond the sterile numbers displayed in Table 4.2, the Earth is a dynamic and truly magnificent place. It encompasses many diverse environments, and is composed of a vast range of mineral

Table 4.2. The tabulated Earth. Data gathered from various geological and astronomical tables.

Characteristic (units)	Quantity
Total mass (kg)	5.9742×10^{24}
Average radius (km)	6371.0
Polar [equatorial] radius (km)	6356.75 [6378.14]
Surface area (km ²)	5.101×10^8
Bulk density (kg/m ³)	5,517
Average surface temperature (°C)	15
Escape velocity (km/s)	11.2
Surface gravity (m/s ²)	9.80665
Sidereal spin rate (hours)	23.9345
Spin velocity (at equator—km/s)	0.465
Obliquity (°)	23.4393 (year 2000)
Magnetic field (Tesla)	5×10^{-5}
Sidereal (orbital) period (day)	365.256
Average distance from Sun (km)	1 AU = 1.496×10^8
Average orbital speed (km/s)	29.786

Table 4.3. Comparison of the land and sea regions of the Earth.

	Area (10^6km^2)	Percent coverage	Mass (kg)	Average height/depth (km)	Extreme height/depth (km)
Land	149	29.2	5.6×10^{11} ⁽¹⁾	0.84	8.84 (Mt. Everest)
Ocean	361	70.8	1.4×10^{21}	3.8	10.55 (Mariana Trench)

⁽¹⁾ Calculated according to the volume of land above sea level (surface area times the average height) multiplied by 4500 kg/m^3 , the average density of rock.

deposits and active landscapes. Water, the key ingredient for the sustenance of life (as discussed in Chapter 5) exists simultaneously on its surface in three phases: solid, liquid, and gas. The water reserves of the Earth's oceans outweigh those of the landmasses, and indeed, over 70% of the Earth's surface is covered by rolling seas. Table 4.3 provides the raw numbers.

About 3% of the Earth's surface is permanently covered in ice (at the present time), and if all of this was to melt, then the water level would rise by perhaps as much as 75 m—a change that would have absolutely no effect upon the Earth itself but that would devastate numerous ecosystems, animal species, and of course, humanity, since the majority of people live in low-lying coastal regions. Indeed, as the Earth continues to warm at the present time, certainly partly as a direct result of industrial emissions, numerous South Pacific Islands are finding that their land base is disappearing beneath the sea.³ Although this is not a book about the problems of global warming, the key point that we need to take on board is that the Earth does change; it is not a static sphere, and colossal rearrangements of land, ice, and ocean can and do occur. Indeed, they are a vital and vibrant part of the process that makes life on Earth possible.

There is a small outflow of energy through the Earth's crust, indicating that it must have a hot interior. The billowy, snake-like forms of pahoehoe lava that have formed and continue to reshape the Hawaiian Islands, as well as the unstoppable rains and drifts of suffocating ash witnessed, for example, during the devastating eruption of Mt. Pelée on the island of Martinique in 1902, bear witness to the continual resurfacing of the land, and to the high temperatures of the Earth's interior regions.

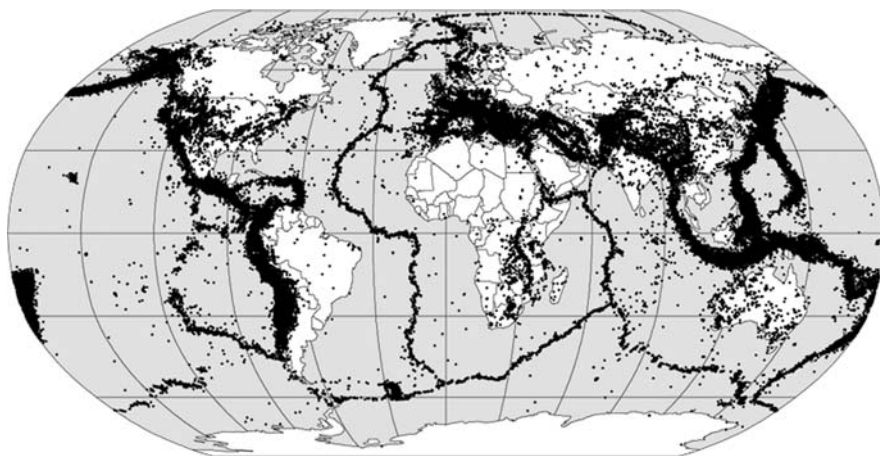


FIGURE 4.6. Epicenter locations of 358,214 earthquakes recorded between 1963 and 1988. The epicenters cluster along the Earth's tectonic plate boundaries.

Earthquakes also bear testament to the reshaping and rearrangement of the land. These vast upheavals turn, for a few agonizing seconds, the familiar solid Earth into an unfamiliar and often deadly fluidized bed that can cause mighty buildings to collapse and trigger lethal tsunamis. Intimately connected, the volcanoes and earthquake zones fall along the boundaries of the Earth's major tectonic plates (Figure 4.6), which grind past and slowly slide over and under each other with an unstoppable force powered by the underlying convective turnover of the Earth's mantle.

The earthquakes and volcanoes that at first glance seem so destructive to life are, in fact, essential for its very existence. As we shall see later on (in Chapter 5), the gases vented by billowing volcanoes and the material subducted at plate boundaries play a vital role in regulating the levels of gases, such as CO_2 and sulfur dioxide (SO_2), in the Earth's atmosphere. These, as we shall also see in Chapter 5, play a pivotal role in regulating the Earth's temperature.

Breathing Room

Above the surface of the Earth sits the atmosphere, a tenuous shield of diaphanous gas. Being approximately 150 km deep, the atmosphere represents about 2% of the Earth's radius. By mass, the

atmosphere contains some 5.3×10^{18} kg of gas, which corresponds to about one one-millionth of the mass of the Earth.

The atmosphere, our breathing room, is a staggeringly small, but very special region of the Earth. By volume, the two main components of the atmospheric gas are molecular nitrogen (N_2) and molecular oxygen (O_2). Nitrogen accounts for 78% of the volume of the atmosphere and oxygen for a further 20.9%. The composition of the atmosphere now, however, is not what it first was, and as Chapter 5 will explain it was the appearance of life that slowly polluted and then changed the chemical makeup of the Earth's thin gaseous envelope. Water vapor (H_2O) is a minor constituent of the Earth's atmosphere, but it makes the atmosphere wet, and this effect results in the formation of clouds. At any one time, there is a near 50% coverage of the Earth's surface by fragmented cloud banks, and this has important consequences for its heat balance. Figure 4.7 provides a dramatic overview of the Earth's upper atmosphere, revealing billowing cumulonimbus clouds (the thunderheads associated with powerful rain storms) and a rising Moon. Although the atmosphere is extremely tenuous in its outer reaches, there are still enough molecules to interact with an ever-incoming rain of tiny meteoroids derived from the outgassing of comets and the steady grinding down through collisions of the asteroids. Shooting stars—faint, transient scratches of light that cut across the celestial vault—are the fleeting death throws



FIGURE 4.7. The Earth's upper atmosphere and the Moon (STS-35 image courtesy of NASA).

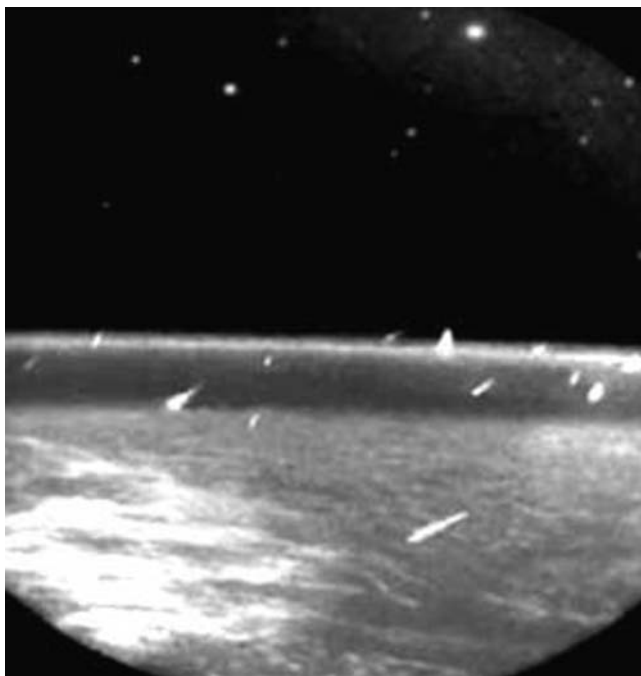


FIGURE 4.8. Small microscopic grains ablating in the Earth's upper atmosphere during the Leonid meteor shower in 1997. These millimeter-sized grains were ejected from periodic comet Tempel–Tuttle and encounter the Earth's upper atmosphere at speeds of 71 km/s. At these speeds, even a 1 mm-sized grain carries as much explosive energy as a hand grenade. The stars in the constellation of Aries are visible in the background (Picture courtesy of NASA ARC and P. Jenniskins).

of millimeter (and smaller)-sized meteoroids, their diminutive bodies being ripped apart by energetic collisions with atmospheric molecules residing at altitudes between 100 and 80 km (Figure 4.8).

Not only does the atmosphere shield us from the continual rain of solid particles that pummel Earth as it orbits the Sun, but it also shields us from the harmful radiation that the Sun emits into space. Indeed, it is the shielding by the atmosphere of the very short wavelength UV, X-ray, and gamma-ray radiation that enables life to exist and thrive on the Earth's surface. The ozone (O_3) layer, for example, that encircles the Earth in a broad shell located between 15 and 35 km altitude plays a vital role in absorbing incident UV-b and UV-c radiation. Without this protection, cell mutation would be rampant, and life as we know it would not exist.

A Magnetic Shield

Deep within the inner-core regions of the Earth, the temperature and pressures are sufficiently high that iron is rendered into its liquid form. Twisted and churned by convection and rotation, the molten iron acts just like a dynamo and a magnetic field is generated. While the magnetic poles are known to wander and drift across the Earth's surface, and have been known historically to flip orientations (north becoming south), the geomagnetic field provides an invisible reference system.

Darwinian selection has not failed to notice and utilize the Earth's magnetic field, and many birds, insects, and bacteria use it for navigation and orientation purposes. Indeed, the ancient mariners realized long ago that the mysterious loadstone always pointed along the north-south meridian, and this knowledge enabled them to steer (as safely as the seas would allow them) to their destinations (see Figure 4.9). Not only is the existence of the Earth's magnetic field betrayed by the motion (or, in fact, the lack of it) of the compass needle, it is also betrayed through the rhythmical dance of auroral curtains and streamers (Figure 4.10). The aurora signals, in fact, an interaction between the Sun and Earth, with Earth's magnetic field controlling the motion of charged particles (mainly protons, electrons, and helium nuclei) blasted out from the Sun by solar flares and coronal mass ejections.

Not only does the Earth's magnetic field protect life from the direct scouring of the solar wind (lunar inhabitants will have no such natural protection), but it also shields us from cosmic rays, which are charged particles produced by distant supernovae. These particles encounter the Earth at speeds close to that of light.

The tenuous atmosphere, that thin veneer of gases that sits on top of the Earth's surface, and separates us from the killing vacuum and cold of space, along with the invisible tendrils of the geomagnetic field, are both essential to our existence. Humanity does not need to maintain or make adjustments to them. Here is the lesson for the would-be terraforming engineer: the aim should be to emulate nature, as it is found here on the Earth, rather than work against it. What we need to do is understand the terrestrial cycles and interactions, the positive and negative feedback processes (to be

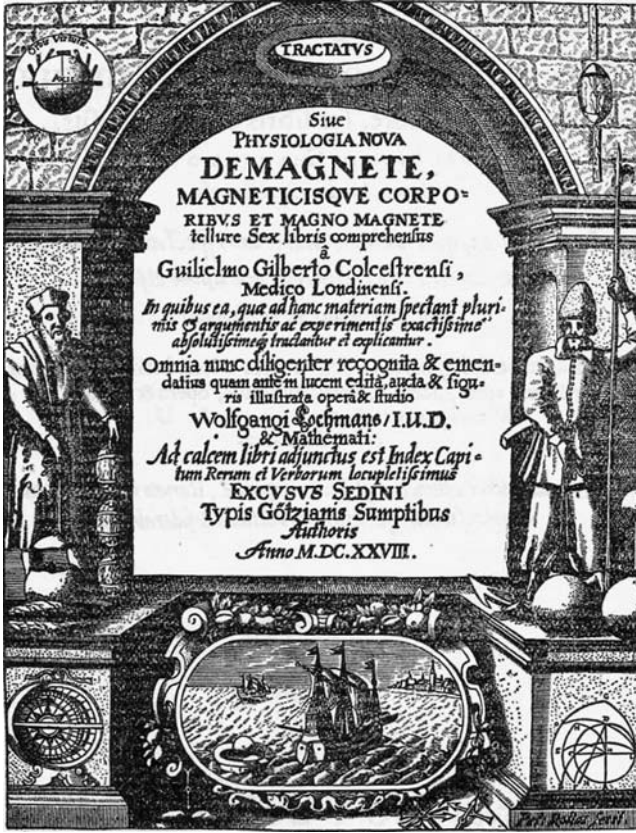


FIGURE 4.9. Frontispiece of William Gilbert's classic text *De Magnete*, published in 1628. A crude map showing the orientation (dip) of the Earth's magnetic field lines is seen in the upper-left-hand corner, while an illustration of the load-stone's application to navigation is shown at the bottom center.

discussed in the next chapter) and re-create them as far as is possible on new worlds.

This will not be easy; some of the processes cannot be directly transported to other planets. But we need not invent the conditions necessary for life to thrive. We need only understand and emulate what 4.5 billion years of interaction and evolution on the Earth have already uncovered. This is not to say, of course, that the task is simply one of engineering on a massive scale. The complexities are manifold, and we still have a great deal to learn about the workings of the Earth.



FIGURE 4.10. The aurora Australis as observed from the space shuttle. Auroral displays occur at about 80-km altitudes, and are the result of light emission from nitrogen and oxygen atoms that have been excited by collisions with charged solar particles that have been channeled into the north and south polar regions by the Earth's magnetic field. Image courtesy of NASA.

Up to this point our discussion has been directed toward the understanding of what the Earth is, recognizing its boundaries, enumerating its characteristics, and determining its place within the Solar System. Our focus now shifts to the dominant and most technically advanced animal on Earth: us, *Homo sapiens* (from the Latin “wise man” or “knowing man”).

Humanity's Footprint

According to United Nations' statistics, there were, as of July 2007, some 6.6 billion people alive on Earth. It is perhaps worth seeing that number in all of its mathematical glory: 6,600,000,000. If the names of each of these people were written on individual sheets of paper, then the resultant book of humanity would be a weighty tome 660 km thick (assuming each page is one-tenth of a millimeter in thickness), and, of course, by the time the first few pages of this great book of life had been filled in, the book would already be out of date, since something like 100 people die naturally every minute of

every day of every year at the present time. To counter-balance this sad but necessary and inevitable end of life, of order 240 new human beings enter, kicking and screaming, into this blooming and buzzing confusion of a world per minute. Indeed, the number of human beings is growing at a rate of about 75 million new mouths to feed per year.

In Table 3.2 it was revealed that the area of land where humanity might permanently live amounts to some 149 million square kilometers. Let us imagine that all of humanity decides, for no particular reason, to come together and form one giant group hug. What then might the size of the field required to accommodate all of humanity be (as of July 2007)?

This, in fact, is a very simple calculation. If we assume that each human being occupies a 1-meter square area, then to enact the group hug a total area of 6.6 billion square meters will be required. Converting the field area into square kilometers, all of humanity (with each person having 1 square meter of ground) could fit into a square field having sides of 81.2 kilometers—an area not much larger than greater London in the United Kingdom, or metropolitan New York in the United States! Humanity, in all of its bodily form, occupies an area of a mere 6,600 square kilometers. This is of order 0.004% of the Earth's landmass (or about 0.001% of the entire surface area of the Earth).

Thus, human beings as entities do not take up much room on the Earth; our literal footprint is very small. The problem, of course, with the calculation just performed is that human beings need more than 1 square meter of land upon which to live. The house in which this author lives, for example, is about 10-meters square, and this area is purely for moving about in. No food, electricity, or water is grown or generated within the house. Let us look at just one facet of what lies behind this great luxury.

The electricity consumed in the author's house is generated by SaskPower, a Saskatchewan Crown Corporation with assets amounting to some \$4.2 billion (according to its 2006 annual report). SaskPower employs in excess of 3000 people, operates three coal-fired power stations, seven hydroelectric stations, four natural gas stations, and two wind turbine facilities. A generating capacity of over 3000 megawatts is achieved, and power is supplied to more than 445,000 customers over a grand total of 155,000

kilometers of power lines. Now, clearly all this investment in generating electricity is not for the author's benefit alone, but it begins to give some idea of the massive infrastructure that surrounds the life of one person in one of the least populated provinces of Canada.

In the mid-1980s, a University of British Columbia, Canada, taskforce developed an accounting system to evaluate the environmental impact of human beings. The taskforce found that to feed and deal with the waste produced by each Canadian citizen (and there are currently about 33 million Canadians) requires about 10 acres of land (4.2 hectares = 0.042 km²). Remarkably, if the rest of the 6.6 billion people in the world were able to live to the same standards as the average Canadian, then the total area required to support the entire world's population would be about 66 billion acres, or 2.77 billion square kilometers of land. This ecological footprint is equivalent to the surface area of about five Earths (or, equivalently, about 18 times larger than the Earth's actual land area).

Although in Canada, the United States, and most of Europe people have great expectations and can simply assume that there will always be electricity, drinking water, sewage treatment, garbage removal, and food to buy in stores, the vast majority of people in the world have no such expectations or luxuries. This poverty reduces the impact of *Homo sapiens* collective footprint upon Earth, but nonetheless there is literally nowhere on Earth where the presence of humanity, either by alteration or habitation, isn't felt.

At the present time, something like 50% of humanity lives within the confines of large cities and sprawling urban areas of enhanced population density (measured as the number of people per square kilometer), and these regions alone cover about 1.5% of the Earth's landmass. This constitutes a staggering 2.2 million square kilometers of bustling roadways, industrial complexes, houses, hospitals, and humanity all compacted together in a synergistic frenzy of life, work, economics, and politics. Indeed, the area of this urban sprawl is 340 times larger than the entire human footprint area of 6600 square kilometers (our collective group hug number) derived earlier. On a geographical scale, the combined urban sprawl of humanity would just about cover the entire country of Algeria (see Figure 4.11). The hyperextended, metaphorical footprint of humanity is indeed, both very long and very broad.



FIGURE 4.11. Algeria is the eleventh largest country in the world, and has a surface area of 2.4 million square kilometers (about 3.5 times larger than that of Texas). If all of the world’s cities and towns were joined together in one sprawling mass, they would cover an area comparable to that of Algeria, and in this region, half of humanity would be housed.

At the beginning of the twentieth century, it is estimated that 10% of the world’s population lived within large towns and cities. By 2020, it is estimated that 60% of humanity will live in urbanized areas. Although cities certainly provide people with many conveniences, such as jobs and entertainment, they produce none of the key elements, specifically food and water that human beings need

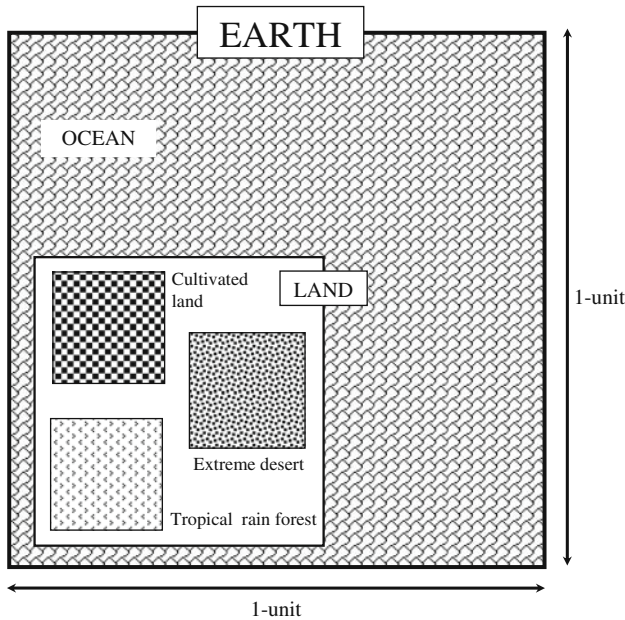


FIGURE 4.12. "Square Earth" shows the relative proportions of land area to oceans and the relative area of cultivated land, extreme desert (unfit for producing food), and tropical rain forest. Water covers 70% of the Earth's surface, and of this 97% is within the oceans, with only 0.6% being in the form of drinkable water. The 1-unit side measure corresponds to a distance of 22,585 km.

in order to survive. To feed the 6.6 billion peoples that presently reside on Earth, of order 22 million square kilometers of land (about 15% of the total land area available on Earth; see Figure 4.12) are estimated to be under continuous cultivation. This may seem to indicate that there is plenty of additional land that might be turned to food production, but this in fact is not the case. Much of the world's surface is completely unsuitable for growing crops of any kind. Extreme hot and cold deserts (i.e., the Sahara Desert and Antarctica) account for about 16% of the Earth's land area; rain forests account for another 15%, while boreal and temperate forests account for a further 25% of the area. Even if humanity was foolish enough to cut down and destroy all of the forests in the world, there would still be little hope of feeding the growing numbers of people that will be born in the next 40 years. Indeed, by 2050, it is predicted that the global human population will have swelled to some

9 billion people. The question that looms large and clear now is, "Can the world support so many hungry mouths along with their bulging cities, extended agriculture, and the billowing smokestacks of their associated industry?"

The Reverend Thomas Malthus (1766–1834) was perhaps a rather pessimistic man, but he understood human nature. He is best known today for his *An Essay on the Principles of Population Control*, published in 1798. The *Essay* is primarily concerned with ideas surrounding "the future improvement of society" and Malthus is specifically writing at odds with many of his contemporaries who felt that there were no limits to what future societies might achieve. The problem as Malthus saw it was that "the power of population is indefinitely greater than the power in the earth to produce subsistence for man." In this claim, Malthus is essentially saying that a population that keeps on growing will ultimately exhaust the capacity to feed itself, and that once the limit of the food supply is exceeded, then the population must plummet—a situation often described in prosaic modern-day language as a Malthusian meltdown. The problems associated with unchecked population growth are nontrivial, and are further discussed within Appendix 4 at the end of this book.

From a terraforming- or space-colony-living perspective, this question has very definite relevance, since these domains are, just like Earth, finite with respect to both size and resources. In his pioneering book *The High Frontier*, Gerald O'Neill argued that "the population density in the space habitats will be governed by sheer economics A key element in the humanization of space will be the unchecked continuation of the industrial revolution, the process by which average individual productivity and wealth increases." It is unnerving to realize how utterly wrong in thinking an otherwise far-sighted physicist can be. Current short-term economic practices and unchecked industrial growth will never provide a satisfactory platform for the human colonization of space—that is, if the colonization of the Solar System is to be for the greater good of all humankind. It is in this sense that we, all the peoples of Earth, had better learn how to live within the limits set by a finite system before the colonization of space and the terraforming of the planets begins. Before we terraform other planets, we will first have to transform ourselves.

It might well be that humanity's immediate future on planet Earth is looking decidedly bleak, but the key point is that we know what is happening, and we can potentially do something about it. It is our call. We know what might potentially happen in the future, and humanity does have the intelligence and hopefully the will to save itself. If we don't believe this then there really is no hope. Terraforming will eventually allow humanity to expand into the Solar System, but it is no quick-fix answer to the present-day problems of an overexploited Earth. Humanities' near-term goal must be to live within the finite limits set by its surroundings, and perhaps remarkably, to this end, there is hope for us.

We, the Tikopia

The island of Tikopia barely exists. It is a small conical extrusion above the Pacific Ocean. Situated at the far-eastern end of the Solomon Islands chain, it is home to just over 1,000 islanders. Its nearest neighboring islands are 140 km away, the isolation of Tikopia is almost absolute, and it is only rarely visited by supply ships and adventuring mariners.

From above, Tikopia is nearly elliptical in profile, being about twice as long as it is wide. The middle one-third of the island is covered by Lake Te Roto, an 80-m-deep freshwater pool that fills an old volcanic caldera. Rising a majestic 380 m above sea level, Mt. Reani dominates the far-eastern portion of the island, which has a total surface area of 4.7 km². The population density of the island is presently a staggering 213 people per square kilometer; remarkably, the population density has been higher in the past, when perhaps as many as 1,500 people called Tikopia home.

The history of the Tikopia was first outlined by New Zealand-born ethnologist, Sir Raymond Firth, who lived on the island for a year beginning in July of 1928. His book *We, The Tikopia*, published in 1936, is a wonderful read.⁴ The title itself carries for us an important message since, as Firth notes, "It is constantly on the lips of the people themselves; it stands for that community of interest, that self-consciousness, that strongly marked individuality in physical appearance, dress, language and custom which they prize."

The people of Tikopia give us hope for the future. They have survived, even thrived, on their tiny island, with a population at any one moment of about 1,000 people, for the best part of 3,000 years. An incredible number of people have lived their lives on Tikopia, and yet the island still provides for its humble citizens, and the surrounding seas are still rich with shellfish and marine life. Here is one rare and happy example of how humans can live in harmony with their environment and (for once) not overexploit the surrounding land and sea, or destroy the local vegetation, or pollute the freshwater lake that supplies them with sustenance.

The whole island is micromanaged, and no plant, shrub, or tree is overlooked with respect to its possible utility. About 400 years ago, the islanders were brave enough and, indeed, farsighted enough to destroy all of the pigs that had been imported to their tiny island. Although viewed as animals that carried great social prestige, it was also realized that these prized animals were destroying the environment that otherwise nourished them. The people of Tikopia also actively monitor and control their own population level, and one of the most important traditional roles of the island chiefs is to promote the ideal of zero population growth within their various extended families.

Firth concludes his first chapter with the comment, "In this state of isolation from the outer world, in a home of great natural beauty, adequate in the staple materials for a simple but comfortable existence, the Tikopia have shaped their life." Perhaps changing only the word "simple" to "fulfilled," these same sentiments might apply to those human societies that will eventually live on new terraformed worlds, colonized asteroids and moons, and biosphere spacecraft. Tough lifestyle decisions will no doubt have to be made by all human societies in the future, but the Tikopia show us that difficult decisions can be made in light of and in harmony with external constraints. This book is dedicated to the humble and farsighted people of Tikopia.

The Aging Sun

Although the peaceful limiting of human population growth might have no immediate technical solution, one might predict with some degree of confidence that geoengineering will be an area of

technology that will see tremendous growth over the next quarter- to half-century. The development and control of these planet-altering skills, of course, will be an essential prerequisite to the terraforming of Mars and Venus. On much longer timescales of hundreds of millions of years, however, the inhabitants of the Solar System (long-since terraformed and colonized) will have to deal with the potentially devastating effects that will be wrought by an aging and ever-more luminous Sun.

As will be explained in more detail in Chapter 5, the temperature of a planet is determined according to its distance from the Sun and upon the Sun's energy output—its luminosity. For the moment, it will be assumed that the orbital radius of a planet is a fixed quantity (this is not strictly true, and there are ways in which an orbit can be changed, but this will be discussed in Chapter 8), and accordingly, if the Sun's energy output increases so the temperature of a planet must also increase (Figure 4.13). The question at this

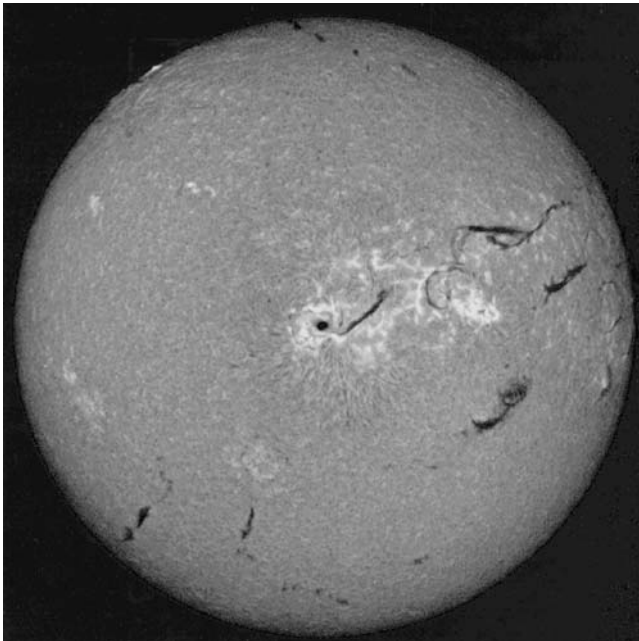


FIGURE 4.13. The Sun in hydrogen alpha light. The Sun currently radiates 3.85×10^{26} joules of energy into space per second. Three billion years ago it was 20% less luminous. Three billion years from now, it will be 30% more luminous. Image courtesy of NASA.

stage, of course, is "What is the expected change in the Sun's luminosity with time, and how will this affect the temperature of the Solar System, and Earth in particular?"

The Sun (and Solar System) is 4.56 billion years old, and detailed numerical models indicate that it is about middle aged. The nuclear fusion reactions that run within its blisteringly hot, 15-million-degree temperature core continuously converts hydrogen (H) atoms into helium (He) atoms to produce energy. The proton-proton chain allows the coming together of four hydrogen atoms to produce a helium atom, energy, and neutrinos (ν). Symbolically, the process can be written in the form $4\text{H} \Rightarrow \text{He} + 2\nu + \text{energy}$. For each conversion some 4.28×10^{-12} joules of energy is liberated, and this energy is equal to the very small mass difference between a helium nucleus (composed of two protons and two neutrons) and the original four protons. Applying Albert Einstein's famous $E = mc^2$ formula, where E is the energy, m is the mass, and c is the speed of light, the Sun must convert of order 4 billion kilograms of matter into energy each and every second of the day to power its present energy output. By human standards, this is a large amount of matter, but to the Sun, which has a mass of 1.989×10^{30} kg, this is next to nothing. Indeed, while the Sun has converted some 6×10^{26} kg of its own mass into energy (a mass equivalent to that of the planet Saturn) since it formed, this only amounts to about 0.03% of its present mass.

Just as the Earth has its carrying capacity with respect to human beings, so the Sun has its own carrying capacity with respect to how long it can continue to convert hydrogen into helium. The Sun may contain an incredible 10^{57} protons (hydrogen atom nuclei) within its interior, but not all of these are available for undergoing fusion reactions within its core (the Sun is not fully mixed within its interior). The other point is, of course, that even if all of the Sun's 10^{57} constituent protons could be mixed into its core, it is still a finite number of protons, and the day will eventually be delivered when they have all been converted into helium nuclei. "None can doubt the misery of want of food," wrote Thomas Malthus in 1798, and as the Sun goes hungry for protons in its central core, so its body will react to its dwindling diet.

The Sun's response to aging and to the consumption of hydrogen (protons) within its central core will be to increase its

luminosity and grow ever more bloated in size. The Sun will not die on the day, some 5 billion years hence, when it has consumed the

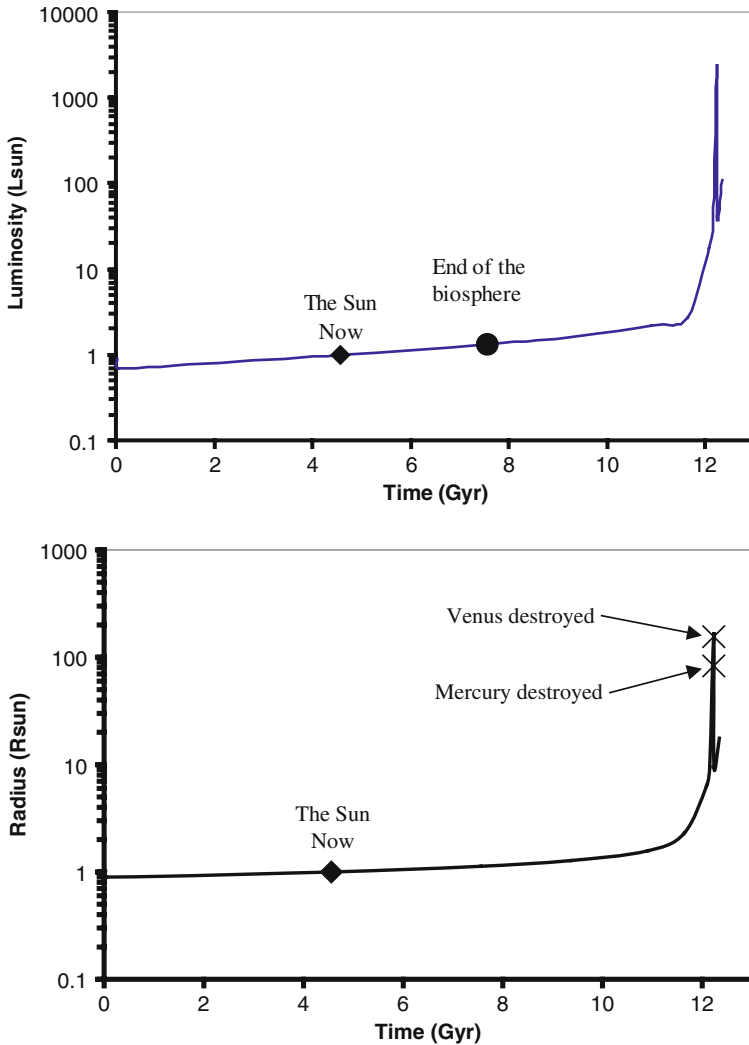


FIGURE 4.14. The change in the Sun's luminosity and radius with time. The diamond on each locus indicates the position of the present Sun, the Solar System being 4.56 billion years old. The end of the biosphere will occur when the Sun is about 35% more luminous than it is at present. Mercury and possibly Venus will be destroyed in about 8 billion years from the present, as the Sun swells up into a bloated red giant star with the onset of core helium burning. Data taken from the solar model described by Sackmann, Boothroyd, and Kraemer, *ApJ*, **418**, 457–68 (1993).

last vestiges of its central hydrogen supply. But it will have effectively snuffed out the life that it previously nurtured throughout the Solar System. Five billion years from now, the Sun will radiate almost twice as much energy into space per second than it does now (see Figure 4.14), and it will be nearly twice as large. Some 8 billion years from the present, Mercury and probably Venus will have been consumed within the Sun's rapidly growing outer envelope, and it will briefly radiate at nearly 2,000 times its present luminosity.

The blossom of youth being over with the exhaustion of hydrogen in its core, the Sun will experience a new lease on life once it starts to convert helium into carbon. During these later golden years, the Sun will grow ever-more luminous, and it will eventually swell into a roaring red giant star. Again, a limit is eventually reached, and all of the helium available to the Sun will have been converted into carbon. The Sun's blisteringly hot core will then be on its way to becoming a white dwarf. But first, with its outer layers having been cast into space by the force of furious winds, the Sun will briefly bloom into a planetary nebula—a cosmic flower of mighty proportions, being perhaps a few tenths of a parsec across (Figure 4.15).

This deadly nightshade of a solar glow, however, will be the Sun's last blush of summer, and the ionized hydrogen that constituted its florets, and which once formed its outer envelope, will gradually drift outward into the depths of interstellar space. The glory of the planetary nebula will be brief, its passage marking perhaps a time span of a few tens of thousands of years. Eventually, all that is left is the gleaming teardrop of the central white dwarf—the remnant Sun condensed to about one one-hundredth of its current size and its mass reduced to about three-quarters of its present value.

At the end of all this change, what is left? Mercury will have been completely consumed during the Sun's first ascent to the red giant branch. By the time the Sun's planetary nebula phase begins, Venus will also have been destroyed. The Earth as a planet may or may not survive; at the present time, we simply don't know for sure.⁵ At the very least, the Earth will be reduced to a blasted ball of scorched rock with no atmosphere. The end will not be a pretty sight, and the Earth's deep future is a nightmare of devastation. Jupiter and Saturn will probably survive relatively unscathed by the

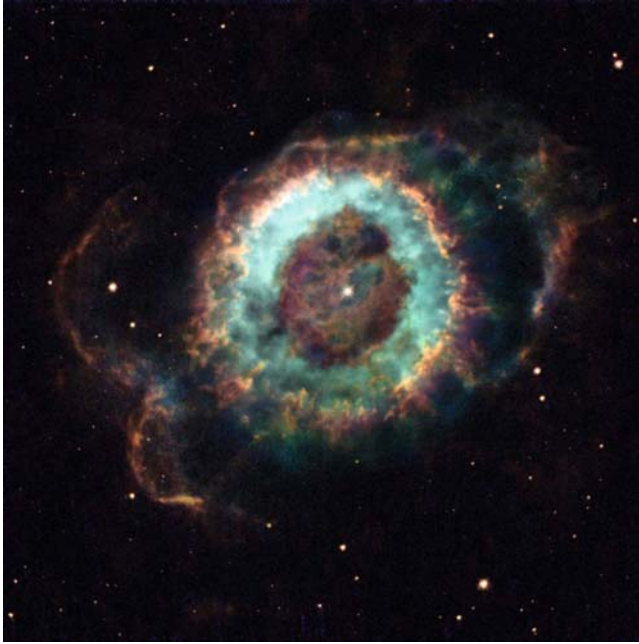


FIGURE 4.15. Planetary nebula in the constellation of Orpiuchius (NGC6369). The nebula is some 1000 parsecs distant and about 0.5 parsecs across. The central white dwarf is clearly visible, and it is the UV radiation emitted by this hot central remnant that ionizes the surrounding hydrogen gas cloud, a process that results in the production of an extended emission region. Image courtesy of NASA.

Sun's death throws. Pluto, the KBOs, and the trillions of Oort Cloud cometary nuclei, however, will have been mostly vaporized by the ever-increasing temperature of the Solar System (a consequence of the Sun's increasing luminosity with age), and all of what they once were will have been reduced to nothing more than a diaphanous wisp of water vapor.

For nearly endless millennia the white dwarf Sun will continue to cool, radiating its precious supply of internal heat energy into the cold depths of space. Many tens of billions of years from now it will become a black dwarf, a zero-temperature, zero-luminosity, carbon-rich sphere no larger than the Earth itself, and, around this dark solar remnant will orbit our dead world, slowly, ever so slowly, radiating gravitational wave energy into space. The Earth will eventually spiral into the surface of the black dwarf Sun, and the

ultimate end of all Earthly things will have finally arrived after a lifetime of perhaps 100 billion years.

All good things, for so it seems, must come to an end, and the demise of the good Earth is no exception. The Solar System's future described above certainly points toward a fiery death and a frigid afterlife for Earth, but this is only one possible train of events. In a previous book, *Rejuvenating the Sun and Avoiding other Global Catastrophes*, the author has suggested that the future gigantism of the Sun might be controllable, and its red giant and planetary nebular phases thereby avoided. The course of the deep future cannot be sidestepped, however, and the Sun will eventually become a white dwarf and ultimately a black dwarf. The question of the Sun's demise and the Solar System's death along with it, however, is one of timescale. If nothing is done to rejuvenate the Sun, then Earth will become a totally barren and lifeless husk in perhaps 2 or 3 billion years from now, and this seems such a waste. If rejuvenation is achieved, then the Sun's eventual demise can be pushed to a time perhaps 15–20 billion years hence, and with luck within this greatly extended timeframe countless trillions of people will be able to lead fruitful, happy lives on more planets than just the Earth.

Back to the Present

It would appear that humanity is at a crossroads, and it has nearly (some would say it already has) outgrown the Earth's carrying capacity. Likewise, the influence, or perhaps poor management is a better description, of human industry has reached such a level that it has altered the chemistry of the biosphere and changed climatic patterns. The Earth is suffering, and if the Earth is suffering so, too, will humanity. We are in a positive feedback loop with nature, and we ultimately defile ourselves every time we defile the Earth. But we must be positive (it is far too easy to be negative) and humanity must use all the incredible skills and intelligence that it has been blessed with to save both our future and that of the biosphere. Global warming, the unchecked harvesting of resources, and overpopulation (see Appendix 4 in this book) are the key issues that humanity must deal with in the very near future, and both

understanding and learning how to control these complex problems will be key to the successfully terraforming of other worlds in the deeper future.

In this chapter, the physical properties of the Earth have been noted and arrayed, and its place within the Solar System and future time has been explored. Our next task is to look more closely at the physical interactions that make a biosphere possible, since understanding how such exquisite and complex systems come about will be the key to terraforming both Mars and Venus.

Vignette B: The Viking Landers

Ask any newspaper reporter. There are some stories that just never die. They take on a life of their own, seemingly forever hovering in the background, always ready to be dressed down for one more airing. The saga of the biological experiments carried aboard the Viking Landers that touched down on the surface of Mars in 1976 is one such apparently never-ending story. What exactly did the experiments reveal? Was Martian life actually identified? Is there an official NASA cover-up of the results? The questions are endless, and there is much confusion about the results of the biological survey. Let us, therefore, give the story of the Viking Landers one more brief reading.

Viking 1 (Figure 4.16) touched down in the Golden Field region (*Chyse Planitia*) of Mars on 20 July 1976. About a month and a half later, on 3 September, the Viking 2 Lander touched down in Mars' Nowhere Plain (*Utopia Planitia*). Each Lander carried an identical biological experiment package consisting of four subcomponents. The first experiment was designed to identify the various chemical elements and molecular species present in the sampled Martian soil. The second experiment was designed to detect any gases that might be given off by an incubated soil sample.

To set the latter experiment in motion, a liquid complex of both organic and inorganic nutrients were added to the soil samples and a gas chromatograph was used to measure the concentrations of oxygen, carbon dioxide, nitrogen, hydrogen, and methane.

A third experiment, the Labeled Release test, produced the most controversial results and is the focus of much debate. In this

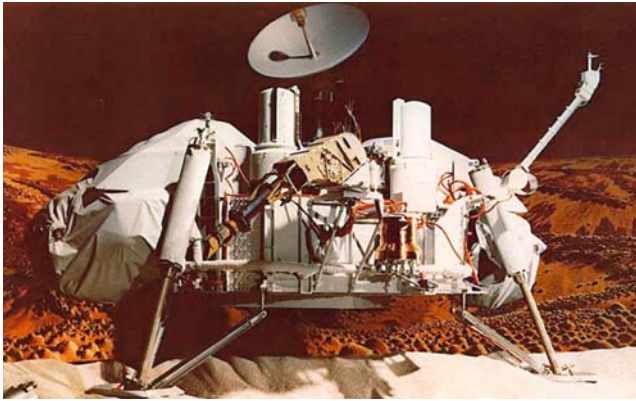


FIGURE 4.16. Model of the Viking 1 Lander. A robotic arm (seen in the center of the image, pointing downward toward the left) was used to capture and place soil samples into the various biological experiment bays. Image courtesy of NASA.

test, a sample of Martian soil was fed a drop of nutrient solution that had been specially tagged with radioactive carbon-14 (^{14}C) and sulfur-35 (^{35}S). The experiment consisted of measuring the amount of radioactive gas in the sample chamber. The key point is that any increase in the radioactivity of the gas in the chamber would indicate that one or more of the nutrients had been metabolized by Martian microorganisms.

Three variants of this test were performed. In the first experiment the soil sample was tested without prior heating; the second and third tests were made on soil samples that were heated to 50°C and 160°C , respectively. The point behind these variant experiments was that by heating the soil some (at the 50°C temperature) and then all (at the 160°C temperature) of the microbes should be killed off, and this would be reflected in the radioactivity levels measured in the experimental chamber. In the latter case, for example, there should be no radioactivity detected at all. The final experiment was again a tagged radioactive carbon-14 experiment. In this case, however, a Martian soil sample was exposed to tagged carbon monoxide (CO) and carbon dioxide (CO_2) brought from the Earth. The aim of this experiment was to see if any of the CO or CO_2 would become incorporated into the soil as biomass.

Well, to cut a long (and complex) story short, the only experiment that produced consistent results that satisfied the control

criteria for the detection of Martian microbes was the Labeled Release experiment (number three in our list). The other three experiments either gave null results (i.e., no organic molecules were detected with the first experiment at either Lander site) or inconsistent results. So, the NASA researchers were left with a confusion of findings, some consistent with the detection of life, others not. The conclusions drawn, therefore, correctly aired on the side of caution, and it was announced that no Martian microbial life had been found at either of the Viking Lander sites. The positive results, from both the Landers, in the Labeled Release experiments were interpreted as being due to some unexpected (and still unexplained) nonbiotic chemical reaction.

Given the spread of results between the various experiments, it is hardly surprising that there were dissenters who rejected the NASA panel's conclusion that no Martian life had been detected. Sir Fred Hoyle and Chandra Wickramasinghe, whose panspermia ideas we described at the end of Chapter 3, have, for example, openly rejected the NASA panel findings. They argue that the experimental results can be made consistent if the Martian microbes have a thermophilic (heat-loving) physiology and a highly efficient free-organic molecule-scavenging system. Other researchers have focused on conducting laboratory experiments to show how the Viking Lander results are consistent with the presence of Martian microbial life.

Gilbert Levin, a Viking scientist team member who helped design the Labeled Release experiment, has long been a strong advocate for the positive detection of life on Mars, and at a recent seminar presented at the Carnegie Institution in May of 2007 he argued that researchers "should re-focus the analysis of the Viking mission results to working out the broadest physiological details required by the organisms in Marciana."⁶ By using the term *Marciana*, Levin is, in fact, arguing that a new biosphere has been discovered, that is, that of Mars, and he is also adopting the nomenclature recently proposed by Argentinean neurobiologist Mario Crocco (Hospital Borda, Buenos Aires). Indeed, following a reappraisal of the Viking data,⁷ Crocco has argued that by any reasonable standards, life on Mars has most definitely been detected, and accordingly he has proposed the new domain Jakobia (named in honor of German-born neurobiologist Christfried Jakob (1866–1956) who

Table 4.4. The division of organic life within the Solar System as suggested by Mario Crocco.

Biosphere	Domain(s)	Genera/species
Terrestria	Bacteria, Archaea, and Eukaria (see Figure 3.12)	Many millions known
Marciana	Jakobia	<i>Gillevinia straata</i>

worked for much of his life in Buenos Aires, Argentina) to complement the three domains (Bacteria, Archaea, and Eukaria; see Figure 3.12 and Table 4.4) that codify all life on Earth. Crocco has also proposed the name *Gillevinia straata* (in honor of Gilbert Levin and co-experimenter Patricia Straat) for the microorganisms purportedly detected by the Viking Lander Labeled Release experiment.

Adding a twist to the Viking Lander story, researchers Joop Houtkooper (Justus-Liebig University of Giessen, Germany) and Dirk Schulz-Makuch (Washington State University, US) have recently suggested that Martian extremophiles might have evolved to use a hydrogen peroxide/water ($\text{H}_2\text{O}_2/\text{H}_2\text{O}$) mixture instead of salty water as their intercellular fluid.⁸ The advantage of this mixture is that it only freezes at temperatures well below -50°C , which is a definite advantage on the freeze-dried surface of Mars. Houtkooper and Schulz-Makuch also suggest that the hydrogen peroxide/water mixture can explain the otherwise anomalous results recorded by the Viking biology experiments.

So the debate continues. Needless to say, and in spite of Crocco's recent positive reevaluation of the Viking data, not everyone is convinced. Indeed, it will probably require new and overwhelming results before the majority of researchers are convinced of the presence of contemporary life on Mars. One of the key experiments that will be carried aboard the recently launched Phoenix mission (see Figure 3.3), which touched down on Mars in mid-2008, is the thermal and evolved gas analyzer (TEGA), which is a modern-day, more sensitive version of the first experiment carried aboard the Viking Landers. This new instrument will provide data concerning the detailed chemical makeup of the Martian soil, and it will also test for the presence of organic molecules within the soil at levels as small as ten parts per billion.

Notes and References

1. In this calculation it has been assumed that water ice accounts for two-thirds of the volume and that there are 5×10^{12} cometary nuclei in the Oort Cloud.
2. To achieve planetary status an object must satisfy three conditions. First, it must orbit the Sun; second, it should be spherical due to its own self-gravity; and third, it should have cleared the immediate neighborhood of its orbit of smaller objects. If an object only satisfies the first two conditions, then it is designated a dwarf planet. All other objects are collectively considered to be small Solar System bodies.
3. It should be noted, however, that there are many factors involved in sea-level rise and island-land loss, not all of which are directly related to global warming.
4. The history of the Tikopia is discussed in detail by Jared Diamond in his book *Collapse: How Societies Choose to Fail or Succeed* [Penguin Books, New York (2005)]. Photographs of the island of Tikopia and its people can be found at <http://home.netcom.com/~yellowrose/tikopia/index.html> and http://janesoceania.com/solomons_tikopia/index.htm. Many further web links can be found at <http://en.wikipedia.org/wiki/Tikopia>.
5. The critical component deciding the Earth's fate is how much mass the Sun loses during its red giant phase. A recent set of solar model calculations published by Klaus-Peter Schröder (Universidad de Guanajuato, Mexico) and Robert Smith (University of Sussex, UK) in January of 2008 [Distant future of the Sun and Earth revisited, available at <http://arXiv.org/abs/0801.4031>] suggests that the Earth will be consumed during the Sun's asymptotic giant branch phase, when it undergoes thermal pulsations just prior to forming a planetary nebula. These authors also note that while the mass loss from the Sun will result in the Earth acquiring a larger orbit, tidal interactions between the Earth and the Sun's extended outer envelope will tend to make its orbital radius smaller. Exactly which mechanism will dominate is partly dependent upon what assumptions go into the calculations, and accordingly there is still a good deal of uncertainty as to whether the Earth will survive or not. Schröder and Smith do note, however, that the greater the Sun's mass loss rate the more likely it is that the Earth will survive. Large-scale mining to reduce the Sun's mass is therefore one possible operation that our distant descendants might wisely initiate. Such a process also ties in well with the rejuvenating scenario described by Beech [see Chapter 2, Note 3].
6. A transcript of Levin's talk can be found at <http://arxiv.org/abs/0705.3176>.

7. Carocco's detailed re-analysis of the Viking Lander data can be downloaded at http://electroneubio.secyt.gov.ar/First_biological_classification_Martian_organism.pdf.
8. The abstract to Houtkooper and Schulze-Makuch's paper is available at <http://www.cosis.net/abstracts/EPSC2007/00439/EPSC2007-J-00439.pdf>.

5. In the Right Place at the Right Time

The coming together of two hydrogen (H) atoms and one oxygen (O) atom produces something that is both marvelous and altogether greater than the sum of its parts: water (Figure 5.1). Symbolically written as H_2O , water is the medium of life as we know it. Without water there is no life—end of story. A liter of pure water contains an incredible 3×10^{28} H_2O molecules, and while this seems (and is) an astronomically large number, we are fortunate to live in a universe that is predominantly composed of hydrogen (to the level of about 75% by mass fraction), with oxygen coming in as the third most-abundant element, after helium (He), which accounts for about 24% by mass fraction of the universe.

Water is the most-abundant molecule on the Earth's surface, and although predominantly found in its liquid form, it is also



FIGURE 5.1. A typical view of the Earth's surface. Since some 70% of the Earth's surface is covered by oceans (recall Figure 4.12), the most typical vista that might be seen if placed at random on the Earth is that viewed from a boat. The tsunami-warning buoy, however, is not a typical foreground object. Image courtesy of NOAA.

present as a gas and a solid. This remarkable ability of water to exist on the Earth's surface in three distinctly different phases has immensely important consequences for our very existence and for the long-term stability of the biosphere.

Water is indeed a very special substance, and human survival is entirely dependent upon there being a ready supply of it to drink. The existence of and access to a supply of liquid water is often taken to be a minimum requirement for any terraforming program; so in the sections below, we look at some of the many remarkable properties of H_2O and determine the physical properties required of an atmosphere such that liquid water can exist on the surface of a planet.

Planetary Temperatures

Key to the existence of liquid water is the temperature. On Earth, as all introductory physics books explain, the Celsius temperature scale is defined according to the freezing point (0°C) and boiling point (100°C) of distilled water. As we shall see in more detail below, there is also another very important part of the temperature scale definition, and that is that the freezing and boiling points are determined at sea level. This latter condition, in fact, relates to the atmospheric pressure, and this will vary according to the characteristics of the atmosphere surrounding the planet. The Celsius temperature scale is very much an Earth-based temperature scale, certainly useful (on Earth) but not universal.

Rather than taking the zero temperature point to be that of freezing water, astronomers and physicists make use of the Kelvin temperature scale, which starts at absolute zero. Named in honor of William Thompson (who adopted the honoree title of Lord Kelvin), the absolute zero point is, as its name implies, the lowest-possible temperature that any substance can have in our universe. The existence of this absolute minimum comes about because of a quantum mechanical effect that dictates no atom can have an energy state less than a finite, so-called, zero point energy. On the Celsius scale, the absolute zero temperature occurs at $-273.15^\circ\text{C} = 0\text{ K}$ (the convention is to say Kelvin, rather than degrees Kelvin). On the Kelvin scale, water freezes at 273.15 K , and it boils at 373.15 K .

Accordingly, a 1-degree Centigrade change in temperature is identical to a 1-degree change in temperature on the Kelvin scale.

The ultimate energy source for heating the surface of any planet or moon within the Solar System is the Sun's luminosity. Measured in watts (or joules per second) the Sun radiates a total of $L_{\odot} = 3.85 \times 10^{26}$ joules of energy into space per second. At a distance D from the Sun, this energy is spread over the entire surface area of a sphere of radius D , and this provides the energy per second per unit area (the so-called energy flux F) for heating a planet. Accordingly, the flux can be expressed as the ratio $F = L_{\odot} / 4 \pi D^2$, and since the Sun's luminosity is constant over a timescale smaller than a few millions of years, we see that the energy flux for heating a planet decreases with increasing distance from the Sun. This is the key reason why the planets in the outer Solar System are much cooler than their companions closer toward the Sun—there is literally less energy available per unit area per second to produce any heating effect in the outer Solar System.

In addition to its distance from the Sun, the temperature of a planet also depends upon whether it has an atmosphere, what the atmosphere is composed of, and how the surface layers of the planet re-radiate energy back into space. In general terms, the surface temperature T_p (Kelvin) of a planet with no atmospheric backheating (or greenhouse effect) can be expressed according to the formula:

$$T_p = 279 \left(\frac{L}{D^2} \right)^{1/4} \left(\frac{(1 - A)}{\varepsilon} \right)^{1/4} \quad (5.1)$$

The above equation looks a little complicated, but it is worth writing down once since it illustrates how much of the Sun's energy, at a distance D away from the Sun, is used in the heating of a planet's surface. The terms in the first bracket describe how much of the Sun's energy is available per square meter for heating the planet. The second bracket describes, through the albedo (A) term, how much of the Sun's incident energy is potentially available for surface heating. The albedo is defined as the ratio of the reflected sunlight to the incident sunlight, with $A = 1$ corresponding to complete reflection.¹ The second bracket also includes a term that describes how efficient the planet is at re-radiating energy back

into space once it has been heated; this is the ϵ term. We should also note that in Equation (5.1) the luminosity L and distance D are respectively cast in units of the Sun's luminosity and the Earth's orbital radius.

The atmosphere will also absorb (rather than reflect) some of the Sun's energy, leading to a further reduction in the energy flux reaching the planet's surface. In the case of the Earth, about 30% of the Sun's incident radiation is reflected straight back into space, indicating that the atmosphere has an albedo of $A \approx 1/3$. At a distance of 1 AU from the Sun, the energy flux above the Earth's atmosphere is measured to be $F_{\odot} = 1,370 \text{ W/m}^2$, and the corresponding flux that enters the Earth's atmosphere will be $(1-1/3) F_{\odot} = 913.3 \text{ W/m}^2$. The atmosphere absorbs about 20% of the incident flux, leaving some $F_{\text{surface}} = 730.6 \text{ W/m}^2$ for heating the surface of the Earth on its sunlit hemisphere. Taking the Earth's radius to be 6,371 km (see Table 4.2), then the total amount of solar energy absorbed at the Earth's surface on its sunlit hemisphere amounts to $4 \pi R_{\oplus}^2 F_{\text{surface}} / 2 = 1.86 \times 10^{17}$ joules per second. Figure 5.2 illustrates the flow of solar energy as it first encounters and then eventually leaves a planet and its associated atmosphere.

Equation (5.1) is derived according to the fundamental idea of the conservation of energy. If all that a planet did was absorb energy

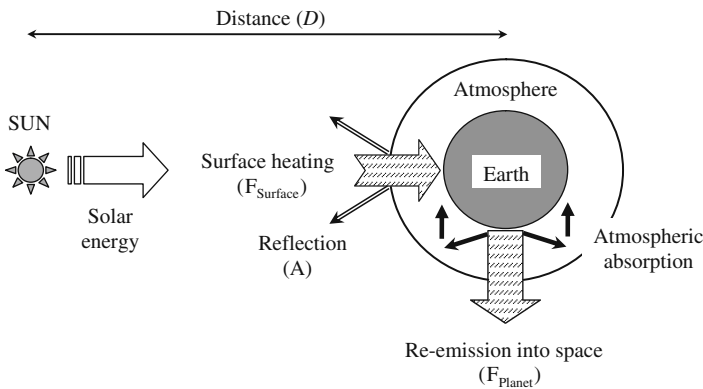


FIGURE 5.2. Schematic energy flow diagram for planetary heating. The small arrows next to the large surface heating arrow account for reflection of energy back into space (the albedo term A). The small solid arrows associated with the larger reemission into space arrow indicate the process of atmospheric infrared heat absorption, which in turn leads to the greenhouse heating effect.

from the Sun, then it would simply get hotter and hotter. The fact that this doesn't happen indicates that energy must be re-radiated back into space at a rate that maintains the constant temperature T_P . Accordingly, the energy radiated back into space per second per square meter at the surface of the planet (see Figure 5.2) is given by the expression $F_{\text{planet}} = \epsilon \sigma T_P^4$, where σ is the Stefan–Boltzmann constant (see Appendix A) and ϵ is the emissivity. The emissivity term accounts for the incoming energy that ends up heating the oceans and land, and being conducted into the Earth's interior; typically, however, it is not unreasonable to take $\epsilon \approx 1.0$, which simplifies our calculations.

If a planet is surrounded by an atmosphere, then not all of the energy radiated from its surface ends up traveling straight back into space. Indeed, the longer wavelength infrared radiation is absorbed by atmospheric molecules, such as the carbon dioxide molecule, which is made up of one carbon atom and two oxygen atoms: CO_2 . This absorption of infrared radiation results in the atmosphere becoming heated. The warmed atmosphere then backheats the planet's surface, and the so-called greenhouse heating effect is produced (this effect will be described in more detail later).

In general terms, the actual surface temperature of a planet T_A is a combination of the solar heating temperature T_P , the greenhouse effect heating T_{GH} , and a small contribution due to the energy flow from the planet's (or moon's) interior T_{IN} . Combining all the various terms, the actual surface temperature of a planet (or moon) can be written as the sum $T_A = T_P + T_{GH} + T_{IN}$. Table 5.1

Table 5.1. Planetary and moon surface temperatures. The planet or moon is identified in column 1, and its distance (D) from the Sun in astronomical units (AU) and the adopted albedo (A) are given in columns 2 and 3. Column 4 is the surface temperature as determined by Equation (5.1), while the greenhouse gas and internal heating effects are given in columns 5 and 6. Column 7 provides the measured surface temperature.

Object	D (AU)	A	T_P	T_{GH}	T_{IN}	T_A (K)
Mercury	0.387	0.14	432	0.0	0.0	100–725
Venus	0.723	0.84	208	525	0.0	733
Earth	1.000	0.37	249	39	0.0	288
Moon	1.000	0.11	271	0.0	0.0	100–390
Europa	5.202	0.64	95	0.0	8.0	103
Titan	9.558	0.21	85	8.0	0.0	93

shows the relative contributions of the three temperature terms for a selection of planets and moons within the Solar System. The temperature increase due to internal heating is typically small for the terrestrial planets. On Earth, the average outward flow of energy due to its hot interior amounts to about 0.06 W/m^2 ; this is about 1/12,000 of the energy flux reaching the Earth from the Sun.

In a number of the larger satellites that orbit the Jovian planets, a periodic stretching and relaxing effect due to gravitational tides and noncircular orbits can result in significant internal heating. The Jovian moons Io and Europa are the extreme examples of this heating-by-flexing effect. In the case of Io, the interior of the moon is kept molten, and accordingly, this moon is the most geologically active place in the entire Solar System. In the situation of Europa, the internal heating has enabled a near-surface global ocean to remain liquid, and this is certainly one location where terraforming and ice mining operations will take place in the future (as will be discussed in Chapter 8).

The temperature contribution due to the greenhouse effect also varies dramatically from one planet (and the moon Titan) to the next. The extreme example is the planet Venus, where T_{GH} contributes over 500° of additional surface heating. The Earth's atmosphere is warmed by some $35\text{--}40^\circ$ by the greenhouse effect, while the surface of the Saturnian moon Triton is heated by nearly 10° by its dense methane- and nitrogen-rich atmosphere.

The Earth's Moon and the planet Mercury have no significant amounts of residual internal heat, nor do they have any atmosphere. The surface temperature of Mercury is an oddity, however, in that it ranges from a bone-chilling 100 K to a scorching 725 K. This wide variation in the temperature relates to its very slow rotation (88 days), and at any one moment, one hemisphere is essentially being baked by the Sun and the other is simply radiating surface heat into the coldness of space.

The Moon shows a similar slow rotation-induced variation in surface temperature, but the range is smaller than that recorded on Mercury because of the Moon's greater distance from the Sun and because of its more rapid rotation rate (29.5 days). The planet Venus is also a very slow rotator, with a Venusian day lasting some 224.7 Earth days, but there is no appreciable variation in its surface temperature because of the efficient transport of heat within its

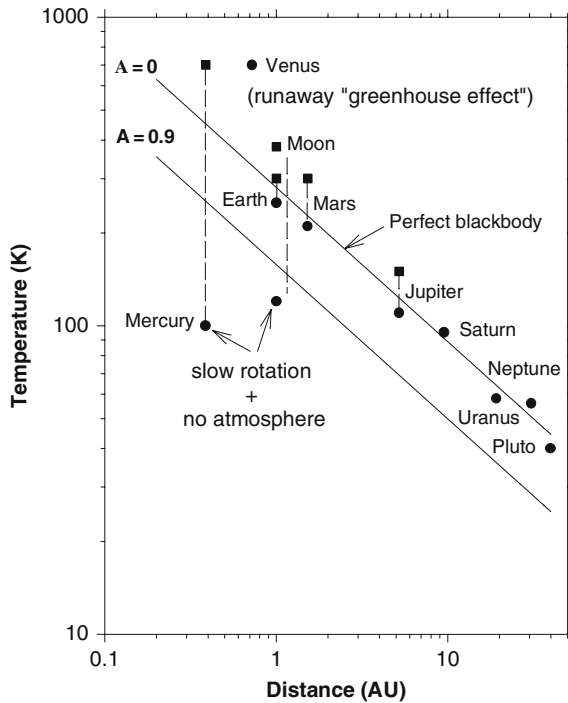


FIGURE 5.3. Temperature versus heliocentric distance diagram for the planets. The two diagonal lines correspond to Equation (5.1) for the situation of perfect absorption ($A = 0$) and near-total reflection of solar radiation ($A = 0.9$). That some planets have extreme temperatures that plot above the $A = 0$ line indicates that they are either slow rotators, that they have a significant internal heat source, or that their atmosphere supports an appreciable greenhouse heating effect.

dense atmosphere. The range of temperatures exhibited by the Moon and the planets in the Solar System is shown in Figure 5.3.

With respect to terraforming operations, there are a number of options available when it comes to modulating planetary temperature. The key factors that control the temperature of a planet or moon are its distance from the Sun, the Sun's luminosity, the albedo, the emissivity, and the composition of any surrounding atmosphere. If we use an up arrow ($\uparrow$) to indicate that a quantity is increasing and down arrow ($\downarrow$) to indicate a decrease, then the actual surface temperature of a planet will increase if any or all of the following effects occur: $D \downarrow$, $A \downarrow$, $\epsilon \downarrow$, and the greenhouse gas concentration in the atmosphere $\uparrow$. In contrast, $T_A \downarrow$ if any or all of the

following effects occur: $D \uparrow$, $A \uparrow$, $\epsilon \uparrow$, and the greenhouse gas concentration in the atmosphere $\downarrow$. All of these options and their potential impact upon terraforming operations will be considered as we move through the remainder of this book.

Atmospheric Temperature and Pressure

In addition to providing an albedo and a greenhouse warming effect, an atmosphere also exerts a downward-directed pressure onto the surface of a planet. Pressure is defined as the force divided by the area over which the force is applied. In the case of a planetary atmosphere, the force term will be determined by the gravitational interaction between the atmosphere and the planet itself, and the area will be the surface area of the planet.

On Earth, the atmospheric pressure at sea level is 1.013×10^5 Pa, and the density of the atmosphere, defined as the total mass of atmospheric gas per cubic meter, at sea level is 1.217 kg/m^3 . Now, it turns out that neither the atmospheric density nor atmospheric pressure is constant with height above the Earth's surface. In terms of the arrow symbols, as the atmospheric height $\uparrow$, so both the atmospheric density and atmospheric pressure $\downarrow$. The atmospheric temperature varies in a rather complex manner with height above the Earth's surface, but at altitudes below 15 km (in the so-called troposphere region), $T_{atm} \downarrow$ as $h \uparrow$.

Mountaineers often use a rule-of-thumb calculation that the temperature drops by about 2° for every 300 m increase in altitude.² The highest point on the Earth's surface is the top of Chomolungma (Mt. Everest), and with an altitude of 8.48 km, the ambient temperature at its summit will be around -40°C . The atmospheric pressure and the atmospheric density will also have dropped by about one-third of their sea-level values at Everest's peak. At 100 km altitude, the temperature has dropped to about -60°C (or 210 K), the pressure is 3.5 million times smaller than its sea-level value, and the density is 2.5 million times smaller than its sea-level value.

A visual demonstration of the change in temperature with height can be seen in many mountain valleys, where there is often a distinct change in the vegetation that can grow at a given elevation (Figure 5.4). Low on the valley floor, the temperature is

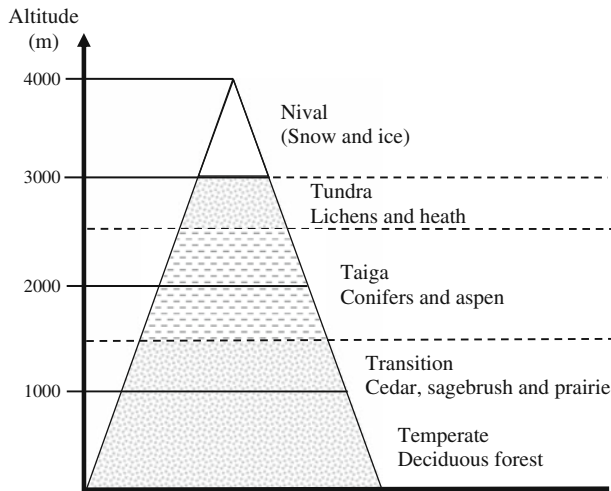


FIGURE 5.4. Variation of vegetative ecosystems with height. The same general variation is also seen according to latitude on the Earth, with the Polar region ecosystems being similar to those of the highest mountains, and the equatorial regions being rich in temperate deciduous forests.

warmer and one might find a mixture of deciduous trees, flowering plants, and grasses growing. Higher up the valley walls, the ecosystem changes to one dominated by conifers, sagebrush, and hardy alpine plants. Higher up still one only finds low-lying and sparse vegetative growth and lichens. Above 3,000 m altitude, however, virtually no plant life can survive, and the highest mountain peaks are barren and snow capped. We come back to discuss this essentially temperature-driven diversity of ecosystems later since it will be a useful guide to the evolutionary changes that terraforming might produce on Mars.

For a low-density gas in which the constituent particles rarely interact, there is a relatively straightforward equation that links together the pressure, temperature, and density. It is worth looking briefly at this equation, since it tells us what happens to the pressure if the density or temperature of a gas changes. Accordingly, the ideal gas law equation is written as: Pressure (P) = Constant $\times$ Density (ρ) $\times$ Temperature (T). We see from this relationship that if the density stays the same but the temperature increases, so the pressure must increase. Using our arrow notation to indicate an increase or decrease in a quantity, the ideal gas equation informs us

that $P \uparrow$ if both ρ and $T \uparrow$; $P \downarrow$ if both ρ and $T \downarrow$. The variation in the pressure if $\rho \downarrow$, but $T \uparrow$ (or vice versa) is a little more complicated, since P will remain constant, for example, if the decrease in the density is counter-balanced by the increase in temperature—that is, if the density is halved but the temperature doubled, the pressure remains the same.

In general, therefore, we will have to look carefully at any density and temperature changes that terraforming might introduce in order to determine if the atmospheric pressure is increasing or decreasing. How the relevance of such atmospheric pressure changes, with respect to the possible existence of liquid water, will be seen shortly.

The constant in the ideal gas equation varies according to the mean molecular weight of the atoms or molecules that characterize the gas under investigation. The mean molecular weight is a relative term that expresses the mass of an atom in terms of its atomic mass and the mass of the hydrogen atom. The atomic mass relates to the number of protons and neutrons in the nucleus of the specific atom, and accordingly the atomic mass of hydrogen is 1, while that of carbon is 12, and that for oxygen is 16. Since water is composed of one O atom and two H atoms, its atomic mass is 18. Carbon dioxide, CO_2 , on the other hand, being made of one carbon atom and two O atoms, has an atomic mass of 44.

Planetary atmospheres are usually composed of a mixture of ideal gases, and it is therefore convenient to express the total pressure in terms of the partial pressures due to each molecular species. This is generally known as Dalton's law, after the British chemist John Dalton. For an atmosphere composed of, say, molecular nitrogen (N_2), molecular oxygen (O_2), and water vapor (H_2O), the total pressure can be expressed as $P_{\text{total}} = P(\text{N}_2) + P(\text{O}_2) + P(\text{H}_2\text{O})$, where the partial pressures $P(\text{N}_2)$, $P(\text{O}_2)$, and $P(\text{H}_2\text{O})$ are each described by the ideal gas equation with the appropriately substituted constant (which, recall, varies according to the mean molecular weight) and density. See Appendix C at the end of this book for further details on this topic.

For a gas held inside a small container, on, say, a laboratory bench, the effects of gravity will be entirely negligible, but for an atmosphere surrounding a planet the pull of gravity becomes important, and the gas density decreases with increasing altitude.

In response to the density and temperature decrease with height, the gas pressure also decreases with altitude. The variation in pressure is characteristically described by the so-called pressure scale height, which corresponds to the distance over which the pressure drops by a factor of about one-third. The pressure scale height decreases as the mean molecular weight of the atmospheric gas increases, and the smaller the pressure scale height so the more rapidly the pressure decreases with altitude. In the Earth's lower atmosphere the pressure scale height corresponds to a distance of about 8 km.

As we shall see in the section that follows, water can exist on the surface of a planet under a range of pressures and temperatures. However, since terraforming will, in general, aim to produce the conditions suitable for liquid water to exist on the surface of a planet, it is the surface pressure produced by an atmosphere of some specific total mass that is of interest to us here. It is common to characterize an atmosphere according to its so-called column mass, which is the total atmospheric mass divided by the surface area of the planet. The surface pressure is then simply the column mass multiplied by the planet's surface gravity. Figure 5.5 shows the location of the terrestrial planets and a few of the larger

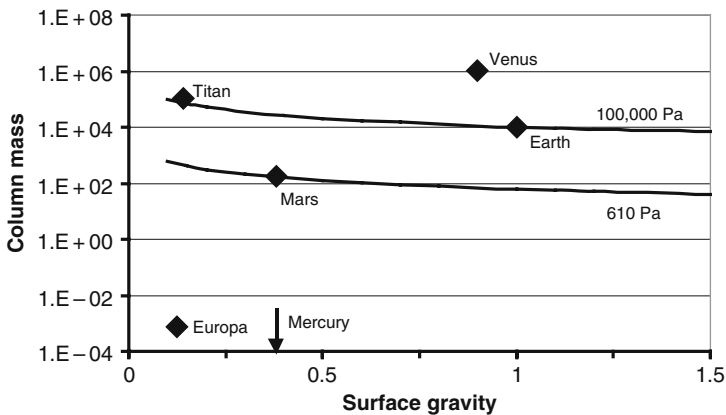


FIGURE 5.5. Atmospheric column mass plotted against surface gravity. The upper solid line corresponds to a surface pressure of 10^5 Pa (i.e., that of the Earth), while the lower solid line corresponds to a surface pressure of 610 Pa, which is the lowest-possible pressure under which liquid water can exist. The data points for the terrestrial planets, Titan, and Europa are also shown in the diagram. A downward pointing arrow is used for Mercury (which has the same surface gravity as Mars), since it has no atmosphere at all.

planetary moons in the atmospheric column mass versus surface gravity diagram. This diagram is useful in that it tells us how the atmospheric mass must be changed (if indeed, it needs changing) so that liquid water might exist on the surface of a specific planet or moon.

Figure 5.5 indicates that in principle the column mass of the Titan's atmosphere is already high enough for liquid water to exist on its surface; the only reason that it currently does not exist there is because the temperature is far too low, $T_a(\text{Titan}) = 93 \text{ K}$ (see Table 5.1). Although water cannot be in its liquid state on the surface of Titan, methane (CH_4) and ethane (NH_3) can exist in their liquid states, and the highly successful ESA Huygens mission to the moon was able to photograph dendritic channels produced by the flow of such liquids (see Figure 5.6). Likewise, the surface pressure on Venus is certainly high enough for liquid water to exist there, but it currently does not because the temperature is far too high

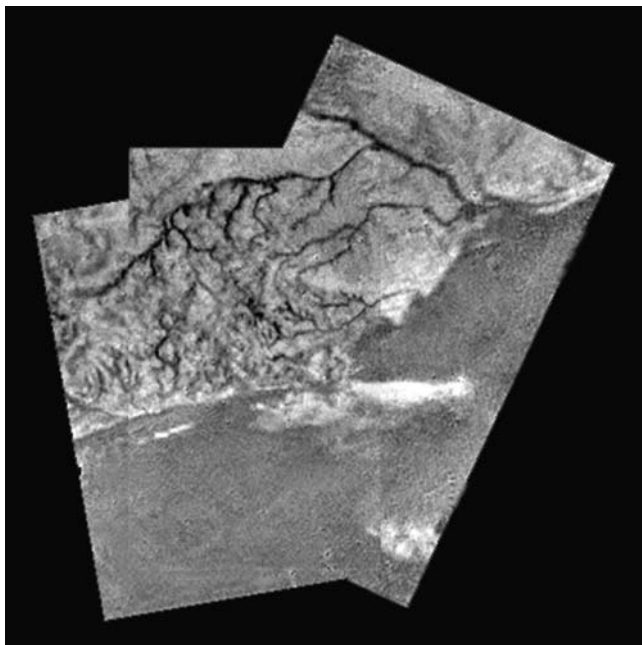


FIGURE 5.6. Flow channels probably produced by liquid ammonia or possibly a liquid water-ammonia mixture on the surface of Titan. Image courtesy of ESA/NASA.

[$T_A(\text{Venus}) = 733 \text{ K}$]. The surface pressure on Mars is not quite high enough for liquid water to exist there permanently at the present time. Interestingly, there is a high probability that liquid water exists in the form of aquifers under the surface of Mars, where the pressure is increased by the weight of overlying rock layers.

The pressure and temperature on Jupiter's moon Europa are both far too low for liquid water to exist at its surface. Below the surface, however, the weight of overlying ice layers will add to the pressure and combining this effect with the internal heat source that Europa is able to tap (see Table 5.1) liquid water most probably exists within its interior. Clearly, from the foregoing discussion and comments, the existence of liquid water is determined according to both pressure and temperature, and the combined effects of these two terms are usually discussed in terms of the phase diagram.

Phase Diagram of Water

The characteristic properties of any substance, not just those of water, are determined according to the prevailing pressure, temperature, as well as the volume and amount of material present. Indeed, physicists say that these latter quantities determine the state of the material. In a few cases the relationship between the pressure, temperature, and volume can be written down as a simple formula, and the ideal gas equation is one such example.

Now, while the properties of a warm water-vapor gas can be determined according to a specific equation, the properties of water ice and liquid water cannot; indeed, they have their own distinct equations of state. Rather than write down the formulae for H_2O in its various states, it is more convenient to look at the so-called phase diagram. Within such a diagram one can draw three loci: the fusion locus, which indicates where the phase transition from a solid to a liquid occurs; the vaporization locus, which shows where the phase transition from a liquid to a gas takes place; and finally the sublimation locus, which indicates the conditions under which a solid undergoes a phase transition straight to a gas with no intervening liquid phase. Figure 5.7 shows the phase diagram for water.

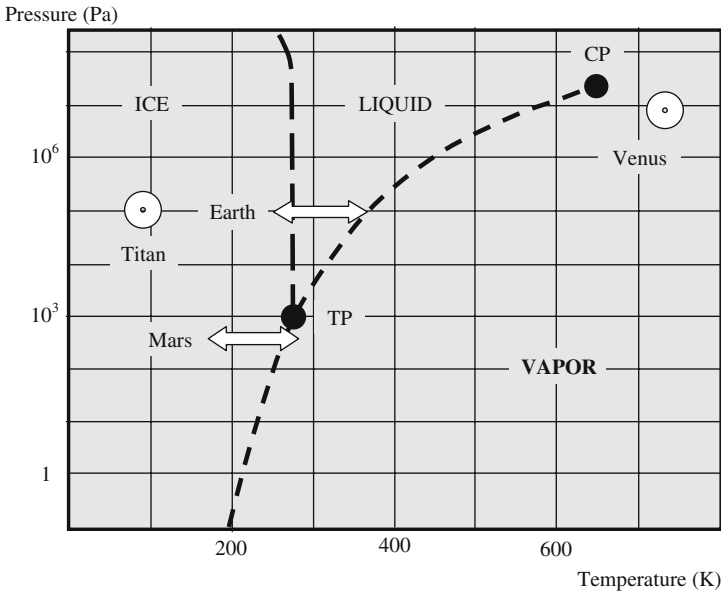


FIGURE 5.7. The pressure–temperature phase diagram for water. The sublimation, fusion, and vaporization curves indicate where phase changes occur. The location corresponding to the surface pressure and temperature of Earth, Mars, and Venus are indicated.

The three-phase change loci meet at the triple point, and this indicates the temperature and pressure at which liquid water, water ice, and water vapor can exist simultaneously. For H_2O , the triple point occurs at a temperature of 273.16 K (or, 0.01°C) and a pressure of 611.73 Pa. The critical point (see Figure 5.7) corresponds to the end point of the vaporization curve, and for temperatures and pressures beyond this point, H_2O vapor will change (upon cooling) into a liquid gradually, without an abrupt phase change. The critical point for water is located at a temperature of 647.4 K (or 374.3°C) and a pressure of 2.21×10^7 Pa.

The great utility of the phase diagram for water is that it provides a clear indication of what must be achieved through terraforming so that liquid water can exist on the surface of a planet or a moon. As indicated schematically in Figure 5.8, the atmosphere of Mars must be increased in mass (since this will increase the surface pressure; see also Figure 5.5), and it must also be warmed. The increase in the surface pressure that might be aimed for on Mars

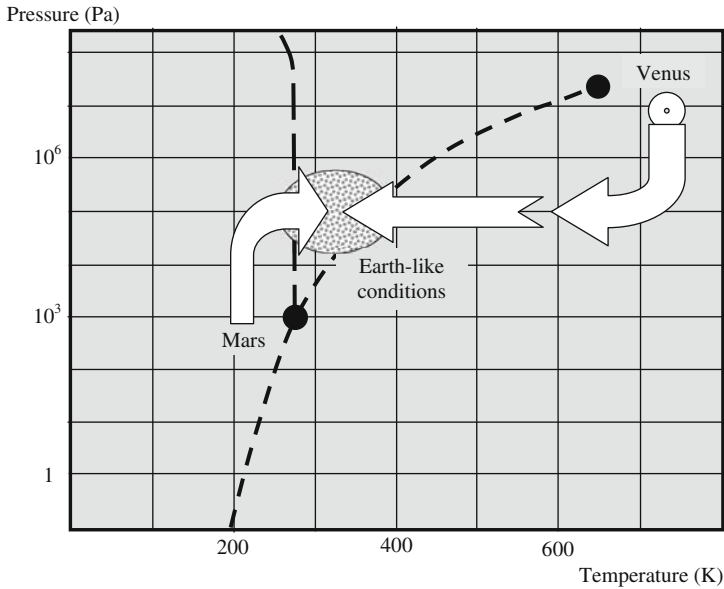


FIGURE 5.8. Schematic phase diagram for water, indicating possible paths by which the atmospheres of Venus and Mars might be changed so that liquid water can exist upon their surfaces.

through terraforming corresponds to about a factor of 10–100 times greater than its present value. In addition, the average surface temperature will have to be warmed by perhaps as much as 15–20 K through terraforming.

For Venus, the problem is almost the exact reverse to that of the Martian situation, with both the atmospheric mass and the surface temperature requiring reduction. To make the surface conditions similar to that of the Earth, the surface pressure will have to be reduced by a factor of about 100, and the surface temperature will have to be reduced by some 440 K. To allow liquid water to exist on the surface of Titan, its surface temperature will have to be increased by about 200 K by terraforming.

The phase diagram for water shows that terraforming must typically control or modify both the surface pressure and the surface temperature of a planet or moon. Before we move on to consider how these two ends might be achieved, let us have a brief look at the circumstances under which a range of doppelgänger Earths might allow liquid water to exist upon their surfaces.

The Habitable Zone

Imagine that it is possible to make multiple copies of the Earth and then place them at random in circular orbits around the stars of one's choice. Presuming further that we wish to have liquid water available on the surface of each new Earth, the question is, given the parent stars luminosity, what range of orbital radii will satisfy the surface water existence condition? This question has, in fact, long ago been addressed by James Kasting (Pennsylvania State University) and co-workers, and the term "habitable zone" has been coined to describe the region in which liquid water might exist on the surface of an Earth-like planet.

The width of the habitable zone is bounded according to the distances at which water boils (the inner boundary) and freezes (the outer boundary), and these distances will change according to the star's luminosity.³ The lower the luminosity, the closer the habitability zone resides to the parent star; the higher the luminosity, the further it is away.

Kasting and co-workers have refined the determination of the habitability zone by studying detailed climate models. The inner edge of the habitability zone in such detailed models is set according to the rapid loss of water vapor (actually, its constituent hydrogen atoms) by photodissociation in the upper atmosphere. The outer edge is set according to the formation of CO₂ clouds that, being highly reflective, dramatically increases the albedo and the planet is thereby cooled off. The variation of the width and radial location of the habitable zone, according to the calculations of Kasting and co-workers, is illustrated in Figure 5.9.

As one would expect for our Solar System (Figure 5.9), the Earth is situated within the habitability zone for a solar-mass star of age 4.5 billion years. Similar such diagrams for different-mass stars of other ages can also be constructed to gauge the location of the habitability zones for exoplanet-supporting stars (a topic we return to in Chapter 8). For the present, however, we note that terraforming might, in some sense, be described as the vertical shifting of a planet within the habitability zone diagram. The present orbit occupied by Venus, for example, would fall within the habitability

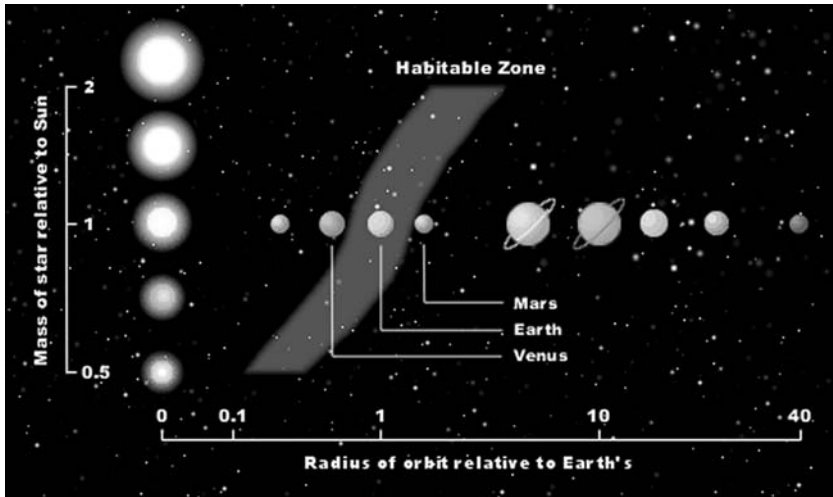


FIGURE 5.9. The location of the habitability zone (shown by the diagonal gray band) for a range of parent star stellar masses. Image courtesy of NASA.

zone if it orbited a $0.75 M_{\odot}$ star. Likewise, the current orbit of Mars would place it in the habitability zone if it orbited a $1.5 M_{\odot}$ star.

Although not necessarily beyond the realms of possibility, we are not advocating changing the Sun's mass in order to make the planets Venus or Mars habitable (there are easier ways of achieving the same ends), but as the Sun ages there are, in fact, sound reasons for attempting to reduce its mass, as briefly described at the end of Chapter 4.

Atmospheric Retention

One of the greatest achievements of nineteenth-century physics was the development of a statistical theory to describe the behavior of gases. Scottish-born physicist James Clerk Maxwell was one of the pioneers in this new field of study, and he developed an important series of equations to describe the distribution of gas-particle speeds. In a Maxwellian gas, the particles move around at a variety of different speeds, some moving very slowly, others moving about very rapidly.

What Maxwell was able to do was determine a mathematical expression for the most probable speed V_P of a particle within a gas of temperature T . Indeed, the most probable speed varies according to the temperature and the mean molecular weight of the molecules that constitute the gas. Now, although the most probable speed can be determined, some (a minority of gas particles) will move much more rapidly, while others (again a minority) will move much more slowly (Figure 5.10).

Where all this becomes important for the planetary engineer and would-be terraformer is that an atmosphere is held in place by the gravitational attraction of the planet around which it revolves, and this sets a definite upper limit to the speed that a gas particle can have and still remain bound to the planet, or else, it will escape into space. This upper speed limit is set by the escape velocity V_{esc} which depends upon the planet's surface gravity and size. For Earth, the escape velocity is 11.2 km/s (see Table 4.2); for Mars, the escape velocity is 5.0 km/s (Table 6.1).

We now have two velocities, one for the typical speed of the molecules within an atmosphere and one for the escape velocity of the planet about which the atmosphere is located. Clearly, if the typical velocity of the molecules within an atmosphere is much greater than the escape velocity for the planet ($V_P > V_{esc}$), then the atmosphere will soon be lost into space. Conversely, if the typical

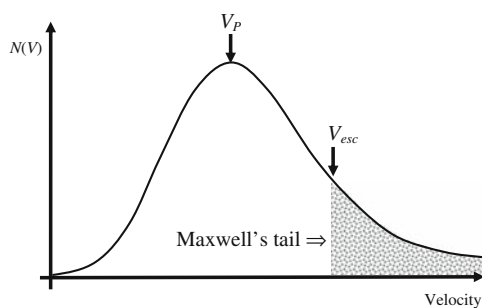


FIGURE 5.10. The distribution of particle speeds in a Maxwellian gas. V_P is the most probable speed, and assuming that we are dealing with an atmosphere, then V_{esc} corresponds to the escape speed of the planet about which the atmosphere resides. The retention of an atmosphere over billion-year time-scales is based upon the magnitude of the escape velocity and its location with respect to the tail of high-velocity gas particles (the so-called Maxwell's tail).

velocity of the molecules in the atmosphere is much less than the escape velocity ($V_P < V_{esc}$), then we would expect the atmosphere to remain in place for an extended period of time.

However, in any Maxwellian gas, there are always some molecules that will have speeds greater than any specific escape velocity. This is Maxwell's tail, as illustrated in Figure 5.10. What this means is that we can think of an atmosphere as being comparable to a gas contained within a leaky box, and the closer the typical speed of the molecules in the atmosphere is to the escape velocity of the planet, so the larger the leak in the container and the more rapidly will the atmosphere be lost into space. The lifetime of an atmosphere is essentially determined by difference between V_P and V_{esc} , and detailed studies have found that for an atmosphere to be retained over extended time periods, say the current age of the Solar System (4.56 billion years), the typical speed of atmospheric molecules must be less than about one-tenth that of the planet's escape velocity.

Now, while the escape velocity is set by the physical properties of the planet or moon (specifically the mass and radius), the typical velocity of the atmospheric molecules is determined by the temperature of the atmosphere and the mean molecular mass of the specific molecule being considered. The more massive molecules move more slowly than the less massive ones, and consequently we would anticipate that the lighter atoms and molecules in any atmosphere will be the most rapidly lost. Indeed, although the Earth's atmosphere is rich in heavy molecules, such as nitrogen (N_2) and oxygen (O_2), it retains only very small amounts of hydrogen (H) and helium (He), the two most abundant but least massive atomic species in the universe.

Now, a quick glance back at Equation (5.1) will remind us that the characteristic temperature of an atmosphere is determined according to the distance of the planet from the Sun, with temperature decreasing as distance increase. The long-term survival of an atmosphere, therefore, is determined by the size and mass of the planet or moon (which determine escape velocity) and the distance of the planet or moon from the Sun.

The gases that should be retained over the age of the Solar System in the temperature versus speed diagram are shown in Figure 5.11. In that figure, the Earth plots below the diagonal lines

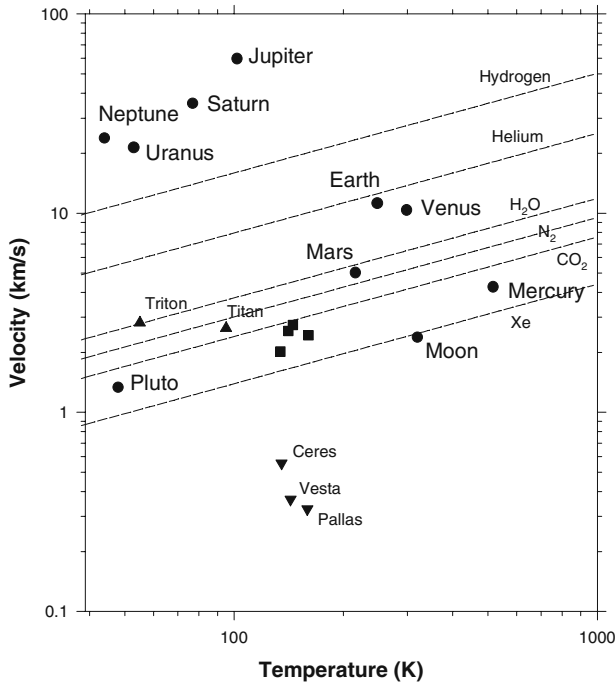


FIGURE 5.11. Retention of atmospheric gases. The diagonal lines indicate the most probable molecular speed divided by ten ($V_P / 10$) for various atomic and molecular species. The data points for the planets and moons are plotted according to escape speed (V_{esc}). According to the condition for the long time-scale retention of an atmosphere, if a planet data point plots above a particular diagonal line then that molecule will not be present in the atmosphere. On the Moon, for example, we see that only xenon might be present over the age of the Solar System, all other original atmospheric molecules having been rapidly lost into space. In the case of the Moon it is its low surface gravity ($g = 1.66 \text{ m/s}^2$) and low escape speed (2.4 km/s) that stops it from holding onto a long-lived atmosphere. In contrast, the Jovian planets can retain all of their original atmospheric atoms and molecules because of their very high escape velocities and low atmospheric temperatures. None of the asteroids (nor the dwarf planet Ceres) is massive enough to retain an atmosphere over long periods of time.

for hydrogen and helium but above those of water vapor and nitrogen, which indicates that the latter two molecules will be found in its atmosphere over geologically long timescales, while the former two will not. Mars plots just below the water vapor line, which indicates that this molecule will be scarce, but it plots above the line for carbon dioxide, indicating that this molecule can reside in its atmosphere for long intervals of time. The large Jovian planets

(Jupiter, Saturn, Uranus, and Neptune) plot above the line for hydrogen, indicating that they will retain all of their atmospheric constituents, even hydrogen finding it difficult to escape into space. Indeed, these planets have massive hydrogen and helium envelopes.

The key lesson to be learned from a terraforming perspective at this stage is that there are natural limits to what kinds of gases can remain over the long term in an atmosphere. One might spend a great deal of effort in producing, say, a breathable nitrogen and oxygen atmosphere on the Moon, but any such atmosphere, as Figure 5.11 indicates, will be rapidly lost into space because of the Moon's low escape velocity. In this respect one has to be resigned to either building large habitable structures on the Moon (see Chapter 8) or of finding a means of continuously re-creating the atmosphere.

The Greenhouse Effect

A partial breakdown for the composition of the Earth's atmosphere is given in Table 5.2. The major components, as already seen in Chapter 4, are nitrogen and oxygen. Although these two molecules account for 99.03% of the atmosphere's total volume, they are mostly irrelevant with respect to the greenhouse-heating phenomenon. It is, in fact, the minor constituents, such as water vapor,

Table 5.2. Composition and abundance of selected elements in the Earth's atmosphere.

Component	Symbol	Volume percentage
Nitrogen	N ₂	78.08
Oxygen	O ₂	20.95
Argon	Ar	0.93
Water vapor	H ₂ O	< 4.0
Carbon dioxide	CO ₂	353 ppm ⁽¹⁾
Methane	CH ₄	1.7 ppm
Ozone	O ₃	< 50 ppb ⁽²⁾
Hydrogen	H ₂	0.4–1 ppm
Helium	He	5.2 ppm

⁽¹⁾The abbreviation *ppm* stands for parts per million.

⁽²⁾The abbreviation *ppb* stands for parts per billion.

carbon dioxide, and methane, in the Earth's atmosphere that drive the all-important greenhouse forcing effect.

The atmospheric greenhouse effect acts in the same fashion as a fisherman's lobster pot: the lobsters can get in easily enough, but they have great difficulty in getting out. For the atmospheric greenhouse heating effect, the key issue is that the incoming radiation from the Sun has a much shorter wavelength than the outgoing radiation from the Earth. Most of the energy received from the Sun (see Figure 5.2) is in the form of visible light (with wavelengths $\lambda \sim 10^{-7}$ m) because the Sun has a surface temperature of 5,780 K. The Earth, on the other hand, radiates energy back into space, mostly in the form of far infrared radiation (at wavelengths $\lambda \sim 10^{-5}$ m) because it is a relatively cool object of 291 K.

All this is a consequence of what is known as Wien's law, which states that the wavelength at which the greatest amount of energy is radiated into space per second per unit area is related to the temperature. (See the Appendix in this book for more details.) The greenhouse effect comes about because of a change in the predominant wavelength of the incoming and outgoing radiation (Figure 5.13) and, to use our fishing analogy, the Earth's atmosphere is the lobster pot. The short wavelength visible light from the Sun can penetrate through the atmosphere to heat the ground with little absorption. The longer wavelength radiation emitted by the warmed Earth, however, can and indeed is absorbed by molecules such as carbon dioxide, water vapor, and methane (to mention just three), and this warms the atmosphere. The warmed atmospheric gas then radiates long wavelength radiation both into space and back toward the Earth's surface. It is this latter backheating component that is called the greenhouse effect. (It is perhaps worth pointing out, just for the record, that the way in which the atmospheric greenhouse effect works is not the same process that causes an actual greenhouse to become heated.)

There is no simple formula to describe the greenhouse heating effect, but put simply, if the greenhouse gas abundance is decreased, then the surface temperature will fall. Alternatively, the temperature will rise if the greenhouse gas abundance is increased. Modulating the greenhouse gas abundances of an atmosphere, therefore, provides a whole new suite of possibilities for future terraforming engineers.

The Tail Wagging the Dog

Before moving on to consider how the atmosphere interacts with the Earth's surface, we should make a few additional comments about several of the remarkable numbers displayed in Table 5.2. On the low-abundance side, the last two entries in the table for hydrogen and helium are not a particular surprise, since we have already seen that these light elements are easily lost from the atmosphere (see Figure 5.11).

The ozone (O_3) abundance is even smaller than those of hydrogen and helium, and yet its presence is absolutely vital to the Earth's surface life. Figure 5.12 (lower panel) shows that it is the tenuous stratospheric ozone layer that straddles Earth at altitudes between 15 and 50 km, which absorbs the potentially lethal-to-life solar UV radiation. The ozone layer is dynamic in the sense that ozone is continuously created and destroyed. Ozone is produced through a three-component recombination reaction in which $\text{O} + \text{O}_2 + \text{M} \Rightarrow \text{O}_3 + \text{M}$, where M is an atmospheric molecule that takes away the excess energy liberated during the reaction. In contrast, ozone can be destroyed by a whole host of processes. Photodissociation will destroy ozone through the reaction $\text{O}_3 + \text{E}(\text{photon}) \Rightarrow \text{O}_2 + \text{O}$, where $\text{E}(\text{photon})$ corresponds to the energy carried by a short-wavelength photon (i.e., those corresponding to UV radiation). It is also destroyed by reactions with, for example, free hydrogen, nitrogen oxide (NO_2), chlorine (Cl), and bromine (Br).

One particularly tenacious group of ozone-destroying agents are the chlorofluorocarbon (CFC) compounds. Invented by American engineer and chemist Thomas Midgley in 1928, CFCs were initially hailed as a significant and versatile industrial product—which, it must be said, they are. Their legacy, however, has been a near-environmental disaster. Not produced in nature, all of the ozone-destroying CFC compounds that permeate the Earth's atmosphere have been placed there by human industrial activity since the 1930s. Incredibly, in less than 60 years after their invention, the global effects of CFC emissions were measurable.

The first indications that something had gone badly awry was the discovery of a hole in the ozone layer over Antarctica in 1985; a corresponding ozone hole over the Arctic was soon thereafter

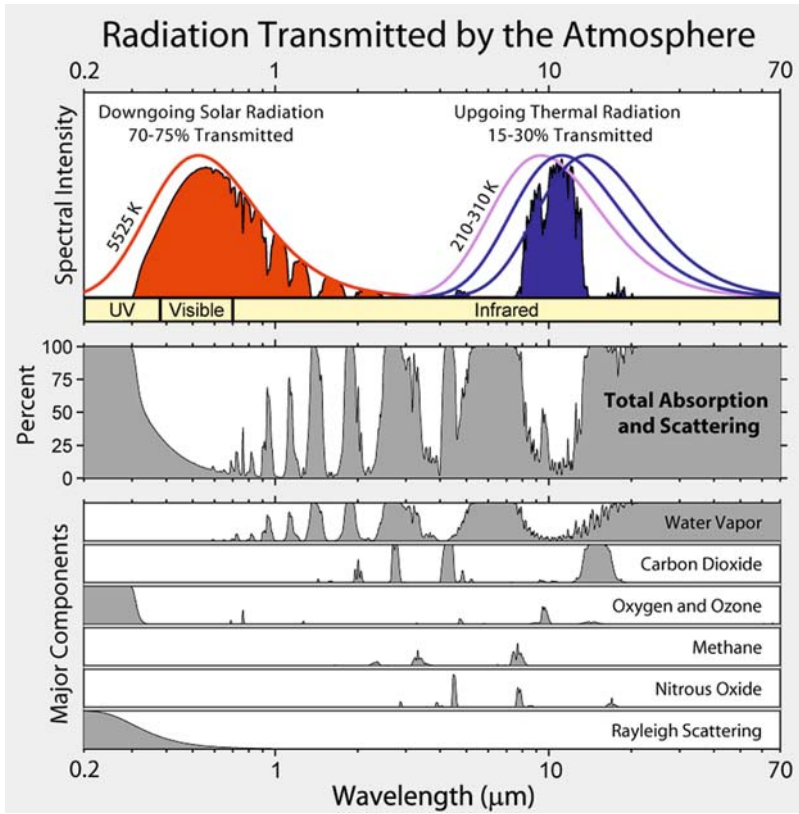


FIGURE 5.12. The top panel shows the energy flux of the Sun and Earth as a function of wavelength. Since the Sun has an effective temperature of 5,780 K, most of its energy is radiated in visual wavelengths. The Earth, in contrast, has an effective temperature of about 300 K, and it radiates most of its energy into space at infrared wavelengths. The middle panel shows the effect of the Earth's atmosphere. Although visible light can pass unhindered through the atmosphere, short-wavelength ultraviolet and long-wavelength infrared radiation are either completely or selectively absorbed. The lower panel shows the major atmospheric-absorbing components. Water vapor is the strongest absorber at infrared wavelengths, followed by carbon dioxide and methane. Oxygen and ozone (O_3) are the main absorbing components at ultraviolet wavelengths. Figure prepared by Robert A. Rohde for the Global Warming Art Project (www.globalwarmingart.com).

discovered as well. All of a sudden, the free UV protection provided by the ozone layer was in doubt. In a rare coming together of nations, the Montreal Protocol was established in 1987 to curb CFC production and emissions, and it has been (well, mostly)

successfully held to. Detailed numerical model calculations, however, suggest that the Antarctic ozone hole won't fully recover until 2050 or even later.

In the case of the Earth's ozone layer, it is clear that a little goes a long way, and the lesson for the would-be terraformer is that it is not always necessary to build elaborate protective structures when the careful regulation of relatively minor atmospheric gas components can do the same job in a much more efficient way. The other lesson, of course, is that atmospheric chemistry is far from simple and that important atmospheric components can be altered, for good or ill, on timescales of just a few decades. This lesson is also double edged in the situation of CFCs, since they are also highly efficient greenhouse gases and may well have an important atmospheric warming role to play when terraforming Mars.

Feedback Cycles and Stability

It was noted in Chapter 4 that the Earth has an active and ever-changing outer layer. The tectonic plates that crisscross its surface slowly slide and grind past each other, while seafloor spreading pushes other plate boundaries outward and eventually below neighboring ones (Figure 5.6). In those regions where one plate is pushed below another a chain of volcanoes will emerge, and these billowing vents enable the completion of a long and remarkable journey undertaken by the Earth's carbon dioxide (Figure 5.13).

Since carbon dioxide is a greenhouse gas, if it were able to accumulate in the atmosphere, global temperatures would soon soar to an uncomfortably high level, resulting in the melting of ice caps and heat stress on the biosphere. In contrast, if carbon dioxide were not present in the atmosphere, then the oceans would freeze out, and the mass extinction of numerous life forms would take place. Clearly, there is an optimum abundance for carbon dioxide such that life on Earth can thrive. It is the classic Goldilocks effect: there can't be too much and there can't be too little. The Earth (some would say Gaia; see Vignette D at the end of Chapter 6) has managed to solve this problem by establishing a remarkably temperature-sensitive feedback cycle in which carbon

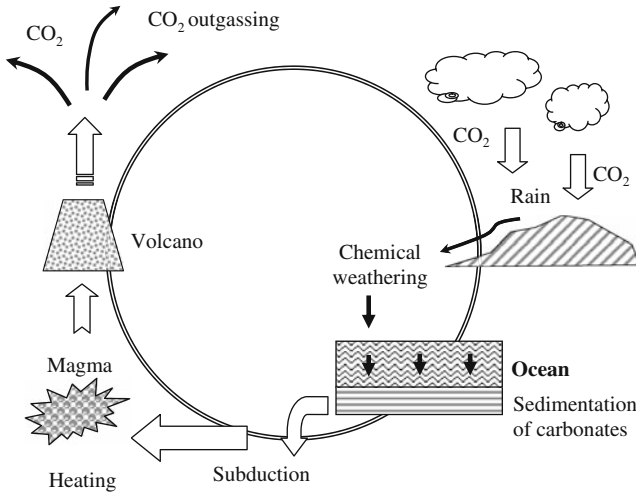


FIGURE 5.13. The great terrestrial circulation of CO₂. The cycle begins with the release of CO₂ into the atmosphere as a result of volcanic outgassing. The CO₂ then interacts with surface rocks, and through weathering and sedimentation layers of carbonate rock are deposited. Seafloor spreading and tectonic activity eventually result in the carbonate rocks being heated, with their CO₂ component being vented back into the atmosphere through volcanic outbursts.

dioxide cycles between the atmosphere, the oceans, fossil fuels, and rock as well as living organisms.

Following the cycle shown in Figure 5.13, the story begins with the outgassing of carbon dioxide from the deep magma chasms tapped by active volcanoes. Thus released into the atmosphere, the carbon dioxide gas will eventually fall to the ground as carbonic acid, enabling the chemical weathering of surface rocks to take place. Symbolically, the weathering reaction runs as $\text{CaSiO}_3 + \text{CO}_2 \Rightarrow \text{CaCO}_3 + \text{SiO}_2$, and the original carbon, and two oxygen atoms are now contained within solid carbonate and silicate phases. This chemical weathering process is temperature sensitive, running more rapidly (that is, taking more CO₂ out of the atmosphere) at higher temperatures. Eventually the carbonate and silicate phases will form bedrock sediments.

The process now slows down to the pace of continental drift. Eventually, after many eons of gradual seafloor spreading, the bedrock is forced beneath an abutting tectonic plate and driven deep into the Earth's lower mantle, where it becomes heated. The

oppressive heat and pressure beneath the Earth's surface results in a complex alchemy, but the key end result is that amid the formation of the volcanic magma is the re forging of carbon dioxide, which is then released through outgassing back into the atmosphere. The whole grand cycle then starts again.

The fact that the weathering cycle and the oceanic sedimentation phases are temperature sensitive has important consequences for the long-term temperature regulation of the Earth's atmosphere. If the atmosphere warms, then more carbon dioxide is consumed through weathering, and this reduces its greenhouse heating effect, which in turn cools the atmosphere. If the atmosphere cools, then less carbon dioxide is extracted from the atmosphere by weathering, and its greenhouse contribution has the effect of warming the atmosphere.

The carbon dioxide cycle is an example of a negative feedback mechanism. Such mechanisms counteract any perturbations away from an equilibrium state. That is, they work in such a way as to keep a system fixed at some stable level. It is this environmental stability over geological timescales that has enabled life to thrive on Earth.

In contrast to the stability-maintaining negative feedback cycles, other systems have what is known as positive feedback. These latter systems are highly unstable, and rather than any perturbations being damped out, they are actively magnified. Positive feedback systems behave in such a way that the perturbation is continuously magnified, becoming larger and larger (or smaller and smaller) until the system fails.

The schematic diagram of a typical feedback system is shown in Figure 5.14. The signal input (In) goes to the amplifier A, and the output from the amplifier is sampled by a control device B, whose response is added back to the input channel at the point marked " $\oplus$ ". If control device B reduces the amplified signal, then a negative feedback system is formed, and the output signal (Out) will tend to remain constant with time. On the other hand, if control device B is additive, then a positive feedback system is formed, and the output signal (Out) will increase indefinitely with time.

There will most certainly be times when the terraforming engineer will want to exploit the characteristics of both positive and negative feedback systems. When attempting to warm the

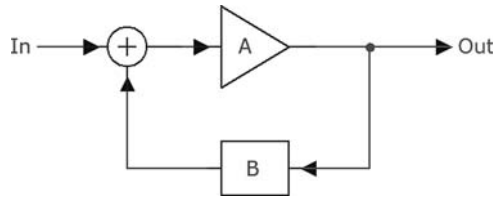


FIGURE 5.14. A schematic feedback system diagram. If control device B acts in an additive fashion, then positive feedback will occur, and the output signal will become larger and larger. If, in contrast, control device B acts in an inverse fashion, then a negative feedback system results, and the output remains stable against perturbations.

atmosphere of Mars, for example, it would be desirable to begin the process with a positive feedback approach. In this manner the initial warming of the atmosphere would proceed rapidly, with only modest amounts of additional external input. Once the atmosphere has attained its desired end state, however, a negative feedback response would become desirable, since then the system would automatically maintain its own equilibrium. In the case of Mars, there are few geological feedback mechanisms that can be exploited, and some human control over the atmosphere will always be required (see Chapter 6). The greater the amount of the equilibrium end state that can be controlled by negative feedback processes, however, the simpler (in relative terms) the task for the terraformer.

In addition to the feedback cycle that helps to modulate the Earth's atmospheric CO₂ abundance, there are similar grand cycles that control the atmospheric quantities of elements such as nitrogen, oxygen, and sulfur. Perhaps the most remarkable, and important, control system is that which regulates the atmosphere's oxygen abundance. As we saw in Chapter 3, the Earth's original atmosphere was poor in free oxygen (recall the Miller–Urey experiment—Figure 5.8). Indeed, what little initial oxygen there was in the Earth's prepubescent atmosphere reacted actively with various “sinks” and was typically buried with organic compounds, or bonded with elements such as methane, sulfur, and iron.

Table 5.2 indicates, however, that free oxygen (O₂) is the second most common molecule in the Earth's atmosphere at the present time, and the questions now are, “Where did all this free

oxygen come from, and is its abundance still increasing?" The answer to the first question is that the free oxygen in the Earth's atmosphere is mostly derived from plant photosynthesis. The reaction proceeds by several steps, but the basic result is six carbon dioxide and six water vapor molecules are converted into glucose and six oxygen molecules. Symbolically, the process can be written as $6\text{CO}_2 + 6\text{H}_2\text{O} \Rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$. By the process of photosynthesis, the plant gains energy from the glucose (the $\text{C}_6\text{H}_{12}\text{O}_6$ term) and the Earth gains six O_2 molecules. The first cyanobacteria that utilized photosynthesis appeared about 3 billion years ago (when the Earth was already 1.5 billion years old), and since about 2.3 billion years ago Earth's atmosphere has been nonoxidizing—that is, free oxygen has been able to accumulate in the atmosphere.

The oxygen abundance in Earth's atmosphere has varied during the past several billions of years, but it has never become greater than about 35% of the atmospheric total. This result is remarkable, and James Lovelock has interpreted it as an indicator that there are processes at work (described under the rubric of Gaia theory; see Vignette D at the end of Chapter 6) that keep the atmospheric-oxygen level at about its present value of 21% most of the time.

It turns out that there is a Goldilocks process at work again. If the oxygen abundance drops below about 13%, then it would be impossible for forest fires, for example, to burn; if, on the other hand, the oxygen abundance were to exceed about 25%, then great conflagrations would rage, with all forests being rapidly destroyed. Lovelock also notes that the major constituent of the Earth's atmosphere is nitrogen (N_2), and this gas is a fire suppressant. Indeed, combustion is controlled not just by the amount of oxygen present but also by its relative abundance compared to nitrogen. At the times when the oxygen abundance has been elevated (such as in the Carboniferous period 300 million years ago), so too, Lovelock argues, must the nitrogen levels have been higher in order to prevent the Earth from burning uncontrollably.

Give and take, move and counter-move, negative feedback and recycling systems: these are the processes that control the habitability of our world, and the would-be terraformers of the future will need to understand how they operate in much greater detail than we do at present.

Even if the same geological processes that help nurture life on Earth do not operate on other worlds, the message is still the same. Terraforming will proceed best when a system is left to find its own equilibrium level, with the terraforming being applied to adjust the equilibrium level to that which will support life.

The End of the Biosphere

At the end of Chapter 4 we cast our gaze billions of years into the future and looked at the effects of an aging Sun upon the Earth. The prognosis was not good. As the Sun ages, so its luminosity will increase, and this will drive up the effective temperature term T_p [given by Equation (5.1)], and the Earth's surface temperature will rise. However, since the weathering of silicate rocks proceeds more rapidly at higher temperatures, so the atmospheric CO_2 concentration will be drawn down via, for example, the $\text{CaSiO}_3 + \text{CO}_2 \Rightarrow \text{CaCO}_3 + \text{SiO}_2$ reaction. The reduced CO_2 concentration will in turn lower the greenhouse heating effect, and this will tend to buffer the temperature change, with the net result that, at least initially, the Earth's surface temperature will remain nearly constant. This is the negative feedback phase described earlier.

After a while, however, the temperature will increase to a level at which the loss of atmospheric CO_2 through weathering will exceed its volcanic replenishment rate, and the buffering effect will no longer be able to offset the temperature forcing due to the Sun's increasing luminosity. At this point, the Earth will start to warm rapidly, and it will essentially enter a positive feedback mode. As the Earth continues to warm, so its surface waters will begin to evaporate, placing large quantities of water vapor into the atmosphere, a process that will enhance the atmospheric greenhouse heating effect.

Life on Earth is thus marked for death. More water evaporation results in more H_2O greenhouse gas in the atmosphere, which leads to more warming, which then leads to more evaporation, and so on, with the end result being that a lethal runaway greenhouse cycle is established. Eventually the oceans will have completely evaporated away, and with the drying of the oceans so life on Earth will decline to total extinction.

When might the deadly runaway greenhouse effect begin to come into play? Detailed computer models constructed by James Kasting (Pennsylvania State University) and co-workers⁴ find that the runaway greenhouse phase might begin as early as 1.5–2 billion years from now, with the oceans being lost some 1 billion years later. The demise of the Earth's biosphere will begin when the Sun is about 10% more luminous than it is at the present time.

Such disastrous and inevitable results prompt a number of responses. The first might be, "Well, the demise of the biosphere is so far into the future that we needn't worry about it." On the practical side this, for us, is absolutely true. That being said, and provided the human race actually survives beyond the next several centuries, such a response will not always be true. Someday our very distant descendants will have to face the consequences of an ever-more luminous Sun and the forced warming it will drive on Earth. This situation correspondingly begs the question, "Are our ancestors irrevocably doomed?" Of course, no one alive today knows. It is certainly the case, however, that alternative future scenarios can be envisioned, and the runaway greenhouse effect and the death of the Earth's biosphere may be avoidable.

One alternative scenario for the future is that in which terraforming is combined with solar engineering. There are, it turns out, a number of ways that the Sun's aging effects might be combated. These ideas have been discussed in the author's book *Rejuvenating the Sun and Avoiding Other Global Catastrophes*. The details of the solar rejuvenation process need not be recounted here, but in many ways they are the logical, albeit scaled-up, continuation of the skills that will have been developed and honed for the terraforming of planets and moons within the Solar System. The long-term future, provided humanity can survive until then, need not be one of doom and desolation. Indeed, there are absolutely no reasons to force us to conclude that the deep future won't be one of great growth and prosperity. The Solar System provides the potential, while terraforming and solar engineering the methods, for an incredibly prosperous future for humanity. We can make no predictions about what will come to pass in the deep future. It probably won't be a utopia that evolves, but neither must it necessarily be a dystopia, either.

The Formation of Terrestrial Planets

The planet Earth was born amid the clash and turmoil of colliding planetesimals. In its final stages of growth, it even suffered gargantuan collisions with multiple 1,000-km-sized assemblages, objects that astronomers describe as planetary embryos. Imagine the chaos and drama as two Mars-sized objects collided in a hail of fragments and pulverizing energy. The mind reels at the thought of the indomitable processes at work.

The origins of the Solar System date back some 4.56 billion years. This age is derived from the study of meteorites,⁵ and since meteorites are derived from the very first multi-kilometer-sized solid objects that formed within the solar nebula, their formation time sets the moment at which the Earth itself began to assemble, thunderous collision followed by thunderous collision.

There was nothing inevitable about the appearance of the Earth in our Solar System, and if the whole process of planetary assembly were to be run over again, an entirely different set of planets would probably emerge. Perhaps there would be no Mercury-like planet close in toward the Sun, and maybe a three Earth-mass planet might form at a distance of 2 AUs, and a 2 Jupiter-mass gas giant planet might form at 7 AUs. There would be some similarities between the planets produced in our rerun solar nebulae, but the appearance of an Earth-mass planet in the Solar System's habitable zone has been our great and good fortune.

Astronomers now believe that planet formation is ubiquitous; whenever and wherever solar mass stars form, so, too, do planets. The process begins with the gravitational collapse of a dense core of interstellar gas and dust. Star-forming cores are perhaps a few light years across, and they are invariably located within a much larger molecular cloud complex. Indeed, stars are not loners by nature, and they tend to form in great numbers over an extended region of space. Once gravity has sunk its teeth into the star-forming cloud, however, there is no going back, and the material falls ever inward, leading to an increase in both the central density and central temperature.

Combined with the initial gravitational collapse, however, is the faint whisper of the gas clouds initial slow rotation; this

whisper, however, is soon amplified by the conservation of angular momentum into a vigorously rotating maelstrom, and this turns the collapse away from being purely spherical into one that is shaped like a flattened disk. Rather than the material from the outer reaches of the star-forming cloud falling straight onto the central proto-star, it settles onto an extended disk, and once in the disk it slowly spirals inward.

Swirling accretion disks have been observed around many young stars, and so, too, have the spin-axis-aligned jets that squirt away excess material (and angular momentum) in order to stop the disk from flying apart (Figure 5.15). The Sun took perhaps 10 million years to form in this fashion. Where planets enter into the picture is in the relatively short interval between the accretion onto the proto-star essentially stopping and the disruption of the disk through the strong wind and highly ionizing radiation produced by a newly forming low-mass star.

Disks are ideal places to build planets. Within a disk, there is a large quantity of gas and dust that has conveniently all been brought together in close proximity, and under these conditions

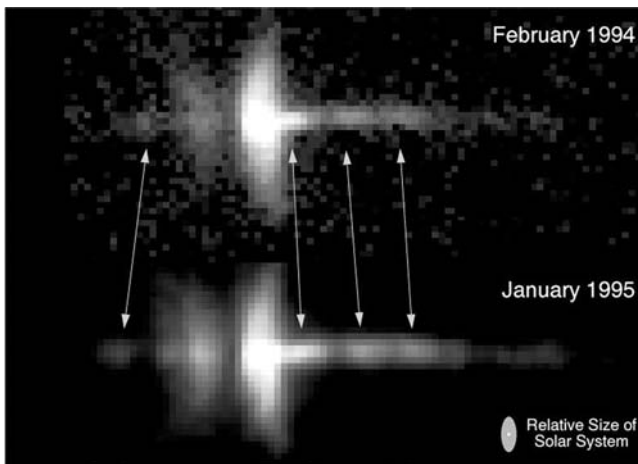


FIGURE 5.15. The accretion disk (seen edge on) and spin-axis-aligned jets (displayed horizontally in the image) associated with the newly forming star cataloged as Herbig-Harrow 30. By taking multiple images of the system over time, material is observed to move outward along the jets. The size of the Solar System out to the orbit of Pluto is shown for scale. Hubble Space Telescope image.

collisions begin. Once the collisions start, the process starts to build according to the well-known aphorism, "From little acorns do mighty oak trees grow." Small grains and molecules collide with other small grains and molecules in an intricate dance of hit and miss, but the end result is that after a few hundred thousand years the small grains will have clumped together and grown into large grains; large grains accrete smaller grains to become even larger ones, and so on. The process speeds along, and after a few millions of years there are kilometer-sized and then tens of kilometer-sized planetesimals, all colliding, fragmenting, sticking together, and rebuilding.

As in any competition there are always winners, and slowly and surely a few larger, dominating structures begin to form. These are the hundred to thousand kilometer-sized planetary embryos. The main chemical makeup of the planetesimals is determined according to where they formed in the planetary disk. Close in toward the proto-star the temperature in the disk is very high, so only high-melting-point silicates and nickel-iron alloys can survive. Further out in the disk, where the temperature drops below 273 K, water ice can form, and still further out carbon monoxide (CO) ice can exist, and so on. This temperature (and hence location in disk)-dependent chemistry dictates that the innermost planets will form from material that is predominantly rich in silicates and iron, while further out water ice is a dominant ingredient. This split in the basic chemical makeup of the planetesimals is revealed in our Solar System in the internal structure and composition of the terrestrial and Jovian planets.

Beyond about 3 AU in the solar nebula, ices were able to form, and this resulted in the rapid formation of Jupiter (at 5.2 AU from the Sun), which has a silicate ice-rich core perhaps some 30 times more massive than the Earth; a further 300 Earth masses of hydrogen and helium surrounds this core. Further inward than Jupiter the planetesimals were predominantly silicate and nickel-iron rich, and this is reflected in the basic makeup of the planets Mercury through to Mars. We still see this basic chemical dichotomy of the planetesimal building blocks in the Solar System to this very day, with the main-belt asteroids being leftover silicates and nickel-iron rich planetesimals, and cometary nuclei being the leftover ice planetesimals.

Since ices are very efficient at growing large structures (during accretion they basically hit and stick with little fragmentation taking place), astronomers now believe that Jupiter and Saturn grew to their final masses very rapidly. Indeed, Jupiter may have formed within just a few tens of thousands of years, according to some calculations. This short growth time for Jupiter has important consequences for the formation of the terrestrial planets, which developed over a much longer timescale, perhaps a few hundred million years in the case of the Earth. A series of detailed numerical simulations⁶ produced by John Chambers (Carnegie Institution of Washington) nicely illustrates the perturbative effects of Jupiter and Saturn on the dynamics of planetary embryos. The simulation starts (Figure 5.16, top left-hand panel) with all the embryos, each having a mass of $0.0167 M_{\oplus}$, orbiting the Sun along nearly circular orbits, with orbital radii between 0.5 and 2 AU. Over time, and taking into account the gravitational effects of Jupiter and Saturn, the planetary embryos becoming dynamically excited, specifically resulting in their orbits becoming more and more eccentric. This increased orbital eccentricity of the embryos results in there being a greater chance of collisions, and the simulations show that over time a few dominant planetary-mass objects appear (Figure 5.16, lower right-hand panel).

The simulation shown in Figure 5.16 resulted in three planets appearing after several hundred million years: an Earth-mass planet developed at about 0.8 AU, a one-half Earth-mass planet formed at 1.4 AU, and a planet with a few tenths the mass of Earth formed in a quite eccentric orbit at about 0.5 AU. Other runs of the computer simulation produced a distribution of planets similar to that seen in our Solar System today.

The vestiges of the blunt-force trauma that shaped the early Solar System are still visible, in some cases, to this very day. Venus, for example, has a very slow 224 (Earth) day retrograde spin, while Mercury has an unusually large nickel-iron core that occupies some 75% of its interior. It is generally believed that in the case of Venus, it was a glancing blow from a Mars-sized planetary embryo that slowed its spin rate down and at the same time tipped over its spin axis by nearly 180° . For Mercury the general interpretation is that a large fraction of its outer rocky mantle was lost through one or more planetary embryo collisions; its core only appears large now

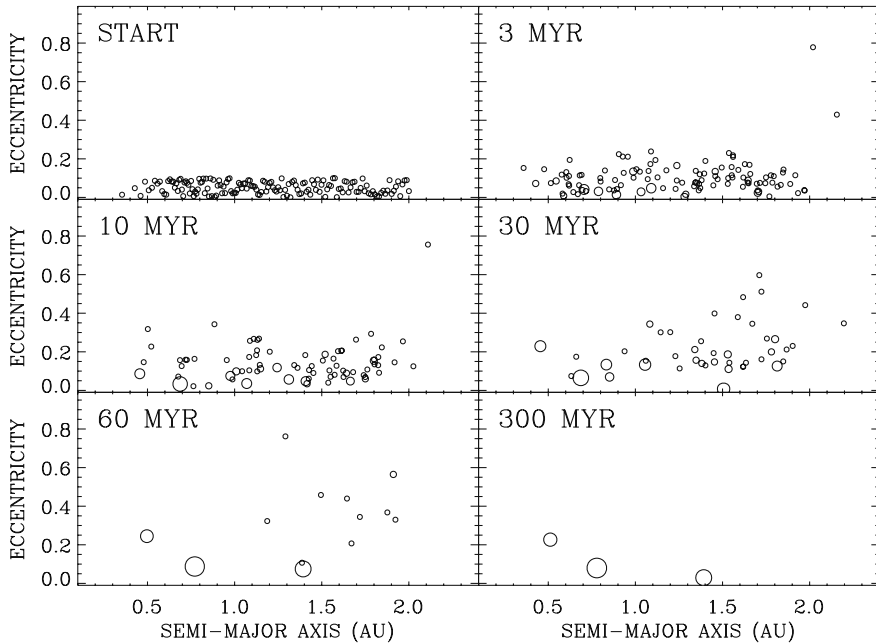


FIGURE 5.16. The growth of terrestrial planets from accreting planetary embryos. Each panel shows the orbital eccentricity and semimajor axis at a specific time of the computer simulation. Panel A (top left corner) is the assumed starting time, when the planetary embryos have nearly circular orbits and semimajor axes between 0.5 and 2 AU. After a few million years, the orbital eccentricities have been “pumped” upward through gravitational perturbations from Jupiter and Saturn. As the time of the simulation lengthens, the more collisions occur, with a few dominant mass proto-planets appearing after about 30 million years. At the end of the simulation, some 300 million years on from the start time, four planets moving in nearly circular orbits have been produced. Figure courtesy of Dr. John Chambers.

because much of its original overlaying rocky mantle has been blasted into space (see Figure 5.17). In addition to explaining these broad terrestrial planet features, it is also believed that our Moon was formed by a giant impact at some time shortly after the Earth’s formation.

Fortuna also smiled upon our Earth when the otherwise devastating Moon-producing impact occurred. It was a eucatastrophy. Indeed, the Moon is very much more than the silvered muse of love-torn poets; it is one of the contributing reasons why life on Earth has managed to survive for so long.

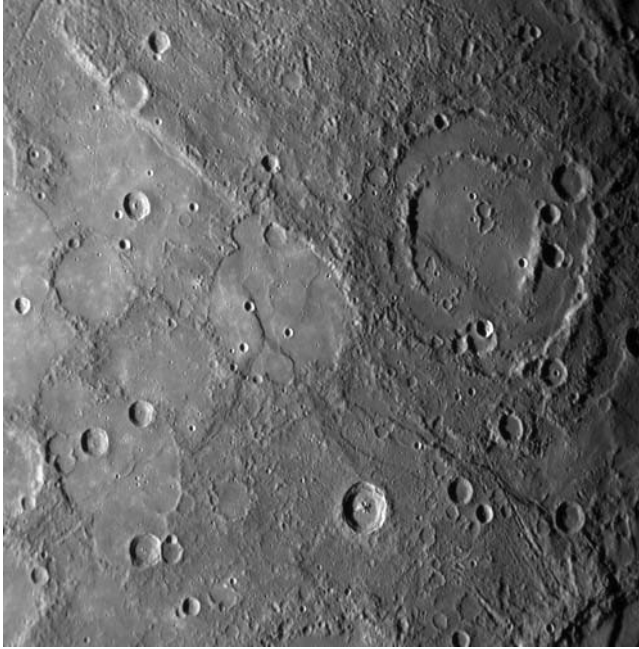


FIGURE 5.17. A detailed image of the surface of Mercury as recorded by the camera system aboard the Messenger spacecraft in January 2008. The double-ringed crater in the upper right is filled with a smooth lava-produced plain. The crater was subsequently disrupted, however, by the formation of a prominent cliff (called a lobate scarp), which is the surface expression of a major crustal fault. This fault may have produced the uplift seen across the crater's floor. A smaller crater in the upper left of the image has also been cut by the cliff, showing that the fault beneath the cliff was active after both of these craters had formed. Image courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

In spite of its tradition of inciting lunacy in humans, the Moon actually plays a vital role in stabilizing Earth. The Moon-to-Earth mass ratio is larger than that of any other planet-moon combination within the Solar System, and consequently the Moon has a strong influence on the dynamics of Earth, and, of course, upon the tides of our oceans.

Most importantly, however, the Moon helps stabilize the direction of tilt of the Earth's spin axis. Since the spin-axis tilt (the so-called obliquity of the ecliptic) is the main driver of seasonal weather variations, its stability means that the seasons (and on longer timescales, the climate) do not change too rapidly. Without

the Moon's moderating influence, the tilt of Earth's spin axis could vary widely and change rapidly. Such flipping would cause climatic chaos, and, of course this would result in the mass extinction of animal and plant species previously adapted to different weather conditions. There is absolutely no reason to believe that moons won't exist around both terrestrial and Jovian exoplanets in other planetary systems, but it is far from guaranteed that all of the Earth-mass planets situated within the habitability zones about other Sun-like stars will have a similar moon.

Super-Earths

Given that terrestrial planets are produced through random collisions, we might reasonably ask, "How massive can they become?" First, this will depend upon the amount of material that resides in the disk, and second, it will depend upon where the Jovian planets form and how rapidly their orbits evolve inward toward the central proto-star.

Planetary migration is certainly an important effect in planetary formation, since many of the newly found exoplanets contain "hot Jupiters," an expression invented to encapsulate the observation that they are found very close in toward the parent star, often with orbital radii of just a few tenths of an astronomical unit. The problem with hot Jupiters is that they could not possibly have formed where they are found, and hence it is now clear that they formed deeper within the disk, in the region where water ice is stable, and then migrated inward as a result of gravitational interactions with the disk itself.

This inward movement of the massive Jupiter planets will have tended to scatter any terrestrial planets that might have formed closer in. At first it was thought that this would mean that Earth-like planets must be very rare, but more recent detailed calculations by, for example, Martyn Fogg and Richard Nelson (Queen Mary, University of London, UK) have shown⁶ that terrestrial planets can survive the gravitational stirring effects produced by a migrating Jupiter, and there are, in fact, no longer any specific reasons to believe that terrestrial planets are uncommon objects. Fogg and Nelson also find from their numerical models that the inward

migration of a Jovian planet might also result in the formation of hot super-Earths.

The key factor that shapes the final appearance of a terrestrial planet is whether it grows too rapidly and thus acquires sufficient mass that it begins to accrete a hydrogen and helium gas envelope. If a terrestrial planet begins to acquire a massive hydrogen envelope a runaway accretion effect comes into play, and the planet becomes heavier and heavier, eventually becoming a Jovian-type planet. The limit at which this runaway accretion effect begins seems to be at about 10 times the mass of the Earth. Hence, the largest Earth-like exoplanets that might be found in orbit around other stars will have masses no greater than about 6×10^{25} kg.

Super-Earths will be quite different in some important ways to the one-Earth mass planet that we evolved upon. First, a $10 M_{\oplus}$ super-Earth planet will be about 85% larger than Earth,⁷ and it may well have a global ocean. A planet-covering ocean is likely to arise because a massive planet will have a higher surface gravity and a less ridged crust than a low-mass planet, resulting in it having a more stunted topography. It will also experience a much higher atmospheric pressure at its surface than that found on a low-mass planet. All these effects, although the exact details are still far from clear, are likely to combine to produce a deep, planet-covering ocean. We come back to look at the potential habitability of super-Earth and ocean-world exoplanets in Chapter 8, since in principle they would make ideal sites for interstellar terraforming projects (should that day ever arrive).

Vignette C: Kepler's *Somnium*

To dream and to imagine ourselves in faraway places and different times is one of the great gifts of being human. Johannes Kepler, although highly schooled in mathematics and philosophy, was also a dreamer, and he took his fantasies to the Moon. He also took the additional step of writing down his make-believe dream in a work called *Somnium* (literally, *The Dream*).

Kepler began to write his *Somnium* as a university student at Tübingen in 1593. It was a brave and daring term paper that his course tutor, Professor Veit Müller, in fact, refused to accept.



FIGURE 5.18. Earthrise over the Moon. The image was taken by William Anders of the Apollo 8 astronaut crew in December of 1968. Image courtesy of NASA.

Undeterred, however, Kepler kept his rejected term paper safe and sound, and every now and then, throughout the remainder of his life, he would dust it off and add some additional thoughts and footnotes—a lot of footnotes. Kepler was seeing the final version of *Somnium* go to press when he died in 1630, and it was only through the efforts of his son Ludwig Kepler that the story finally appeared in print in 1634.

What was this work? It was a short story that challenged the established astronomical authority and defiantly praised the Copernican cosmological model. This was why Professor Müller so vehemently objected to it. It was also a story that even though not publicly available at the time the events took place was partially responsible, much to Kepler's great regret, for his mother being put on trial for witchcraft.

Kepler's *Somnium* represents a giant leap of the imagination, as it describes a journey to the Moon and the Earthly adventures of Duracotus, a native of Iceland, who at one stage in the dialog is sold

by his mother, Fiolxhilde, to a sea captain, who then takes him to Tycho Brahe's island of Hven to be schooled in the art of astronomy. Kepler's *Somnium* is more than a simple fantasy story, however, and he takes great pains to describe exactly what an observer on the Moon would see—or, more to the point, a narrator referred to as Daemon provides the details.

The Dream begins wonderfully, and Kepler writes,⁸ "It happened one night after watching the stars and the moon, I went to bed and fell in a very deep sleep. In my sleep I seemed to be reading a book brought from the [Frankfurt book] fair." Following the opening adventures of Duracotus in Hven, Kepler eventually sets about the process of getting to the Moon, a journey that takes just 4 hours to complete.

Once on the Moon (or Levania, as the Daemon calls it) the narrator describes the scene of the heavens, including a daily-spinning Earth (or Volva, as it is called by the Levanians) that undergoes a periodic change in its degrees of illumination over the course of 1 month for observers on one hemisphere (this is where the subvolva live). On the Moon's other hemisphere, where the Privolvas live, Earth is never seen at all. For those subvolvae that chance to live close to the boundary between the two hemispheres the Daemon comments, "Volva always clings to the horizon, giving the appearance of a mountain on fire far away." The Daemon further explains that, "whatever is born on the land or moves about on the land attains a monstrous size. Growth is very rapid. Everything has a short life, since it develops such an immensely massive body". Some of the creatures have wings and fly about Levania, and others use boats to navigate Levania's water systems. Daemon continues, "Things born in the ground—they are sparse on the ridges of the mountains—generally begin and end their lives on the same day, with new generations springing up daily."

The Dream ends rather abruptly: "A wind arose with the rattle of rain, disturbing my sleep, and at the same time wiping out the end of the book acquired at Frankfurt."

Although the story may have not received critical acclaim, its enduring memory lives on. Begun during the halcyon days of his early adulthood, but not published until after his death, Kepler's *Somnium* is a wonderfully imaginative work, and it is an early attempt to describe the environment and life, both animate and

inanimate, that might be encountered on another world. The story also explores the manner in which the geography of a world, along with its spin-rate and day-to-night cycle, shapes the lives of the creatures that dwell upon and in it. Indeed, Kepler's *Somnium* is a marvelous early work on explorative astrobiology.

We do not know where Johannes Kepler, the first person to truly understand the orbital motions of the planets and who made the Copernican theory practicable, is buried; the Protestant cemetery of St. Peter's where he was laid to rest was destroyed during the many religious skirmishes that swept over Regensburg in the mid-1630s. It is said, however, that on the night following Kepler's commitment to the grave that a multitude of fiery lights (shooting stars) fell from the sky.⁹ Even the mighty heavens, for so we may imagine, wept at the passing of this great astronomer.

Notes and References

1. The albedo is also a complex function of wavelength, but this effect will not be considered in our discussion.
2. The lapse rate for the Earth's lower atmosphere is actually about 0.65° decrease in temperature per 100-m gain in altitude.
3. Although the width of the habitable zone (ΔHZ) doesn't vary very much, the radial location varies significantly with the mass of the parent star. This result reflects the mass–luminosity relationship for stars that are converting hydrogen into helium within their cores (the so-called main sequence stars), with the luminosity (L) increasing with the mass (M) of the star raised to the power 3.5 ($L \sim M^{3.5}$). Accordingly, a two-solar mass star is about 11 times more luminous than our Sun, and as Equation (5.1) indicates the temperature of a planet varies according to the one-fourth power of the parent star's luminosity, from which we deduce that the boundaries of the habitability zone will be shifted outward by about a factor of $11^{0.25} \approx 1.8$; in this manner, the inner edge of the habitability zone therefore begins at about 2 AU from a $2 M_\odot$ parent mass star. A star having half of the Sun's mass will have a luminosity $0.5^3 = 0.125$ times smaller than that of the present Sun, and accordingly the inner boundary of the habitability zone must move inward to about 0.5 AU—a distance interior to the orbit of Venus around our Sun.

4. The moist greenhouse effect is a little controversial at the present time, since Kasting, quite deliberately and reasonably, didn't include the effect of cloud production in his initial set of models [Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. *Icarus* **74**, 472–494 (1988)]. A moist atmosphere will most likely have a large percentage of cloud coverage, and this will increase the albedo, thus reducing the solar insolation. This accordingly will drive the atmospheric temperature downward.
5. The standard technique for determining the formation age of meteorites is to study the parent-to-daughter abundances ratio of radionuclides. The decay of rubidium (the parent) into strontium (the daughter) is one such nuclear decay clock that runs at a half-lifetime 'tick' of 48.8 billion years.
6. See, for example, John Chambers, Making more terrestrial planets. *Icarus* **152**, 205–224 (2001). Calculations leading to the simulations described in Figure 4.15 assume the orbital radius of Jupiter has not changed since it formed—a result that is increasingly in question. More recent calculations in which terrestrial planet accretion occurs in the presence of an inwardly migrating Jupiter have been published by Martyn Fogg and Richard Nelson [The effect of type I migration on the formation of terrestrial planets in hot-Jupiter systems. *Astron. Astrophys.* **472**, 1003–1015 (2007). See also the archive preprint at <http://arxiv.org/abs/0707.2674>]. Even when migration is included Fogg and Nelson find that terrestrial planet formation can still take place.
7. If the radius of a planet was simply described by its mass and bulk density, then it would be expected that the radius would increase as the mass to the one-third power. In this case, the radius of a 10 Earth-mass planet should be $10^{1/3} \approx 2.15$ times larger than a 1 Earth-mass planet. Detailed calculations by Diana Valencia and co-workers [Detailed models of super-Earths: how well can we infer bulk properties? *Astrophys. J.* **665**, 1413–1420 (2007)], however, indicate that compression effects due to the weight of overlying layers results in the radius of the super-Earth's varying as the mass to the power 0.262 rather than 0.333. This relationship means that a 10 Earth-mass planet will be just $10^{0.262} \approx 1.83$ times larger than a 1 Earth-mass planet.
8. Quotations are from Edward Rosen's commentary and translation of Kepler's *Somnium*. The University of Wisconsin Press, Madison, 1967.
9. See *Johannes Kepler and the New Astronomy* by James Voelkel. Oxford University Press Inc., Oxford (1999).

6. The Terraforming of Mars

Mars, the Red Planet, is a desolate world, and it is completely unsuited to human habitation at the present time (see Figure 6.1). Yet, while incapable of sustaining human life, it is a planet that has provided humanity with a rich and fertile muse for the imagination.

Johannes Kepler (see Vignette C at the end of Chapter 5) often wrote of his war with Mars, and indeed, he spent many years of his life studying the observations of the planet gathered by Tycho Brahe, the noble Dane, and his assistants. Kepler knew that if he could only understand the motion of Mars then he could unravel the true workings of the Sun-centered Copernican theory, and



FIGURE 6.1. Full-disk profile of planet Mars indicating surface albedo variations, but no indication of intelligent life. Image courtesy of NASA.

accordingly his three famous laws of planetary motion have their origins in his detailed study of the Red Planet's motion.

Kepler's battle with Mars was won in 1605, when he finally realized that the orbit of the planet was elliptical and that it moved about the Sun, sweeping out equal areas in equal intervals of time. These first two laws of planetary motion were described by Kepler in his *Astronomia Nova* (literally, *The New Astronomy*) published in 1609, and although astronomers were suspicious for many decades of his second and third laws [the latter presented as the eighth item in a list of 13 planetary attributes in his *Harmoni Mundi* (The Harmony of the World) published in 1618] these, too, were eventually explained as natural laws by the great Isaac Newton with the publication of his *Principia Mathematica Naturalis* in 1687.

Some two centuries after Kepler, in 1820, the "prince of mathematicians," Karl Friedrich Gauss, suggested that a signal of humanity's intelligence might be sent to Mars by cutting a massive Pythagorean triangle into the forests of Siberia. He also reasoned that by growing giant square-shaped fields of wheat along each side of the triangle for contrast, the message would be easily visible to alien telescopes. Any observant Martian would then know, albeit several thousand years after the fact, that humanity had at least discovered the rule that the square of the hypotenuse is equal to the sum of the squares of the other two sides of a right-angles triangle.

In 1898, some 80 years after Gauss suggested that we send a sign of our mathematical prowess to the Martians, writer Herbert George Wells cast our erstwhile neighbors in a more menacing light with the publication of his *The War of the Worlds*. The story begins with an apparent straightforward statement of fact: "No one would have believed, in the last years of the nineteenth century, that human affairs were watched keenly and closely by intelligences greater than man's and yet as mortal as his own," and everyone who read this opening paragraph knew that it carried the ring of truth. Indeed, the same story, broadcast by radio under the directorship of Orson Welles in 1938, could frighten an all-too-gullible public into believing that a real Martian invasion was actually taking place.

Mars—it grips us and pulls at our imagination. History, for so it seems, suggests that humanity has long believed that it would travel there, one day, to settle and to prosper. That day, incredibly, is nearly upon us. Indeed, it does not overstretch the limits of

credibility to suggest that there are people alive today that might actually walk on the surface of Mars. Even if the current generation of human beings doesn't make it to Mars, then the next generation surely will. Not only is the possibility of this remarkable journey in sight, but also the first humans to explore Mars will probably know and recognize as familiar much of what will surround them.

Although some 38 spacecraft missions have set out for planet Mars since 1960, less than 50% of them have achieved their mission objectives. Although the Red Planet has not yielded up its secrets without great hardship, in recent decades a number of highly successful missions have mapped its surface in exquisite detail, studied its surface composition, measured and probed its atmosphere, and moved upon its surface to "sniff," grind, and analyze its rocks. Its subsurface layers have been scanned with ground-penetrating radar, and skittering whirlwinds have been captured in time-lapse video sequences to dance, ghost-like, across its open plains. Mars is both familiar and distant, comfortingly like Earth in some aspects and yet grandiose and overwhelming in others. In many ways, Mars is a Frankenstein world: some parts we can recognize, but other parts are alien to us. Indeed, they are very much Martian.

The Spirit and Opportunity rovers deployed so successfully by NASA in January of 2004 have returned incredible and yet disconcerting images of the Martian panorama (Figure 6.2). The pictures



FIGURE 6.2. Sunset over Gusev crater, a scene that is both familiar and yet totally alien to us. Spirit rover image captured on 19 May 2005. Image courtesy of NASA.

look as though we could literally walk into them, and that once within we might expect to find desert plants, scuttling insects, and myriad exotic birds swooping through the pinkish Martian sky. Yet in reality, the ground is barren, maybe even totally lifeless (but check out Vignette B at the end of Chapter 4 in this book), and the sky is devoid of any animate motion.

The Mars we see by spacecraft proxy today runs counter to our expectations, but 3 billion years ago it was an entirely different place. Let us piece together the past and present Mars in anticipation of what our terraforming descendants might make of its future.

The Measure of Mars

Table 6.1 presents the tabulated data for planet Mars and compares its characteristics to those of the Earth. There are very few physical similarities between the worlds; Mars is about one-tenth the mass of the Earth, about half its size, takes nearly twice as long to orbit the Sun, but rotates at nearly the same rate as the Earth. The surface area of Mars is nearly identical to the landmass area of the Earth, but its average surface temperature is nearly four times cooler. Mars currently has no large-scale, organized magnetic field, no oceans, no active volcanoes, and no tectonic activity. Indeed, Mars is a geologically inactive world at the present time, and the main agents behind surface alteration are impacts from cometary nuclei and asteroids.

Interestingly, however, a recent study by Tomasz Stepinski (Lunar and Planetary Institute, Houston) and co-workers, on the fractal characteristics of sinuous drainage channels, have revealed that the roughness of ancient surface terrains on Mars is consistent with an origin that included impact cratering and rainfall-fed erosion, a result that reminds us that Mars was once indeed wet and had an active hydrosphere. While geologically inactive now, Mars does show climatic activity; the seasonal growth and recession of its polar ice caps, for example, which were first noticed well over a century ago. Likewise, seasonally active ice geysers have been observed, as dark fans, in the southern polar regions of Mars (Figure 6.3). There are also some indications that small-scale

Table 6.1. The physical measure of Mars. Column 3 compares the Martian value to that of the Earth's.

Property	Value	Mars/Earth
Total mass (kg)	6.4185×10^{23}	0.107448
Average radius (km)	3389.9	0.5319
Polar [Equatorial] radius (km)	3377.4 [3402.5]	0.53 [0.53]
Surface area (km ²)	1.448×10^8	0.284
Bulk density (kg/m ³)	3933	0.7131
Average surface temperature (°C)	−55	−3.7
Escape velocity (km/s)	5.027	0.449
Surface gravity (m/s ²)	3.690	0.38
Sidereal spin rate (hr)	24.622962	1.0288
Spin velocity (at equator, km/s)	0.241	0.519
Obliquity (°)	25.19	1.074
Magnetic field (Tesla)	(*)	—
Sidereal (orbital) period (years)	1.8807	1.8807
Average distance from Sun (km)	2.274×10^8 km	1.52
Average orbital speed (km/s)	24.13	0.81

(*) Although there is no large-scale, organized magnetic field, localized auroral activity has been detected in the Martian atmosphere, indicating that there must be some remnant surface magnetism.

alterations of Martin terrain can take place due to the intermittent exposure of surface water (Figure 6.4).

It has been clear for many decades that large quantities of liquid water must have existed on the surface of Mars in the distant past.



FIGURE 6.3. Artistic impression of Martian ice and dust jets. During spring warming, jets of carbon dioxide gas escape through cracks in the surface ice, carrying with them, small dust and sand grains. Image Credit: Arizona State University/Ron Miller.

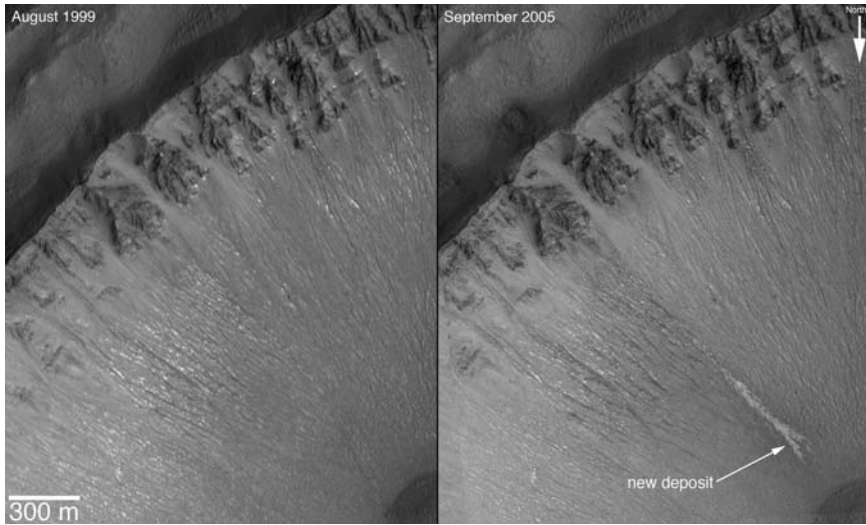


FIGURE 6.4. A frozen trail of ice reveals a recent outflow of water down the interior rim of an unnamed Martian crater. The two images were taken 6 years (August 1999 and September 2005) apart, and the run-off event must have occurred at some moment during this time interval. Image courtesy of NASA.

The evidence for this is literally everywhere to be seen. Orbital spacecraft images reveal long, sinuous, flowing channels; water-scoured flood plains; and water-shaped teardrop islands (Figure 6.5). Spacecraft analysis of surface terrains has also revealed the presence of aqueous altered minerals, such as the hematite-bearing regions of Sinus Meridiani and Aram Chaos. High-resolution images of complex surface terrain, such as is seen in the southwestern Candor Chasma region, reveal a clear sedimentation origin (Figure 6.6). Surface robotic missions have further revealed the presence of water-altered mineralogy, such as the goethite deposits identified by the Spirit rover in the Columbia Hills, and the jarosite found by the Opportunity rover in Meridiani Planum. In addition, both Mars rovers have found great numbers of “blueberry” spherules (Figure 6.7) scattered across the Martian surface, and these betray the past presence of enduring pools of standing water.

Figure 6.8 shows two topographic views of the Martian surface as interpreted by Mars Global Surveyor data. In each view, north is toward the top, and it is clear from the images that the southern hemisphere of Mars is more heavily cratered than the northern one.



FIGURE 6.5. Mars Global Surveyor image of a streamlined landform in the Mangala Valles region of Mars. The teardrop-shaped feature was sculpted by an ancient catastrophic flood (the flow direction is from the bottom of the image toward the top). The region shown in the image covers an area about 3 km wide. Image courtesy of NASA.

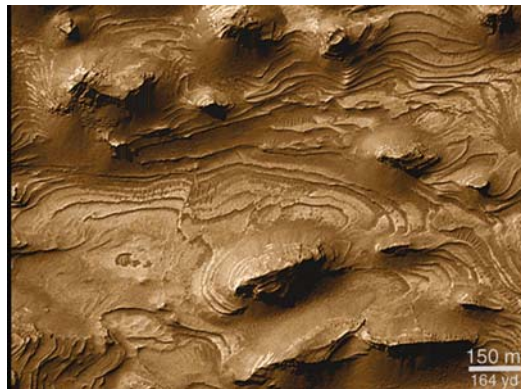


FIGURE 6.6. Mars Global Surveyor image showing layered sedimentary rock on Mars. The picture shows part of the southwestern Candor Chasma region and reveals extensive outcroppings of layers with regular thickness. Each layer is about 10-m thick and suggests a dynamic depositional environment as might be found in a standing body of water. Image courtesy of NASA.

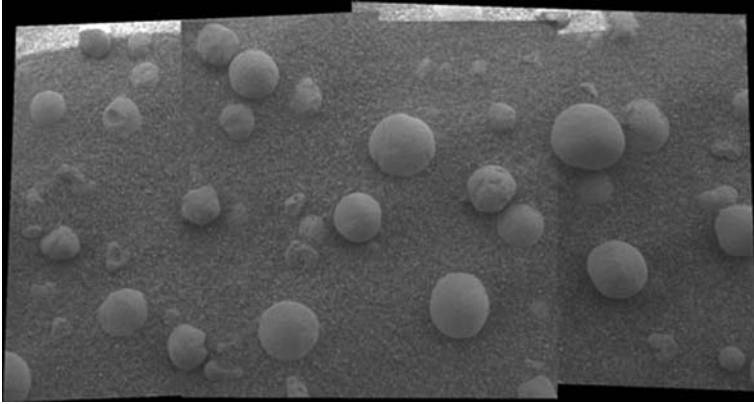


FIGURE 6.7. Martian “blueberry” spherules. The spherules, which are typically a few millimeters in diameter, contain hematite and formed under standing water conditions. The image scale is 5 cm across. Image courtesy of NASA.

The greater number of craters observed in the southern hemisphere is not due to some quirk of the impact process avoiding the northern hemisphere; rather, it indicates that the northern hemisphere must have a younger surface. Laser altimetry studies by in situ spacecraft also show that the northern hemisphere is systematically lower, by about 5 km, than the southern hemisphere. Crater counts per unit area can be used to gauge the relative ages of any planetary surface, and the ages of Mars have accordingly been divided into the Noachian, Hesperian, and the Amazonian (Figure 6.9).

The youngest large-scale surface features on Mars are the Tharsis and Elysium regions, where huge volcanoes rise above the surrounding plains. Crater counts indicate that the impressive chain of Tharsis volcanoes have probably been active during the past 1 billion years, and the least cratered flanks of the mighty Olympus Mons (the largest volcano in the entire Solar System) have an estimated age of just 30 million years, suggesting that perhaps the volcano is presently dormant rather than extinct.

The northern lowlands occupy about one-third of the surface of Mars, and as can be seen in Figure 6.8, numerous outflow channels empty into it. The lack of impact craters and the smooth appearance of the northern lowlands have long been interpreted as constituting an ancient, but now remnant, seabed. Indeed, several possible paleoshorelines have been identified¹ (Figure 6.10), and these are commonly

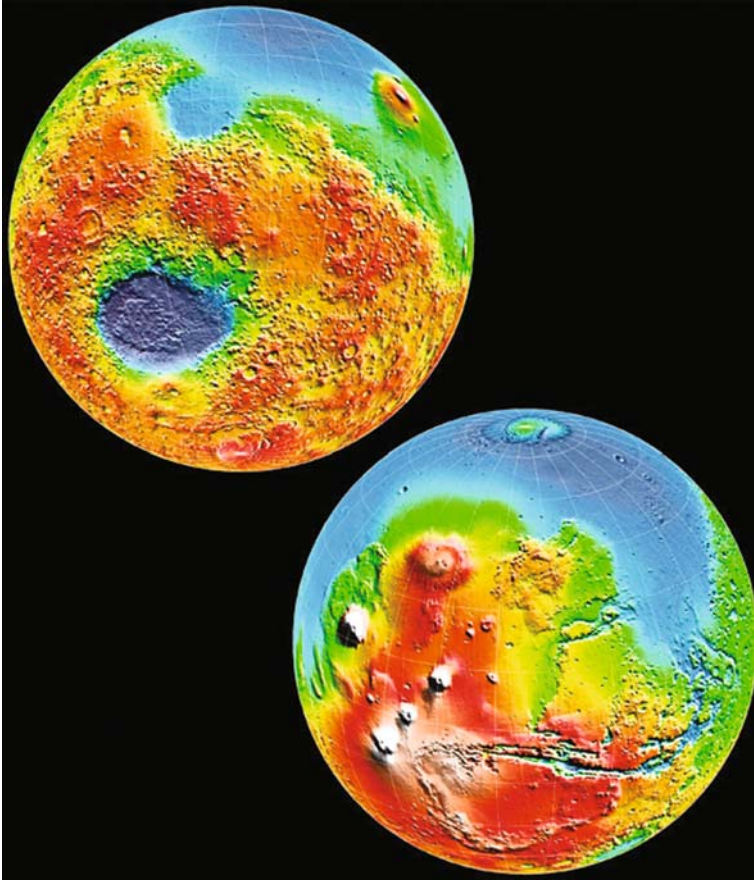


FIGURE 6.8. Two hemispheric views of the Martian surface. In the upper left hand image the highly cratered, older surface regions of Mars's southern hemisphere are portrayed. The large circular feature to the lower left in this image is the 5-km-deep Hellas Planitia impact structure. This feature is some 2,300 km across and was formed during late heavy bombardment some 3.8–4 billion years ago. The Elysium volcano complex is located in the upper-right-hand region of the projection. The image to the lower right is centered on the Tharsis bulge and reveals the massive 2,000-km-long scar of the Valles Marineris. The upper-left region of this projection shows the distinctive chain of volcanoes in the Tharsis region. The 25-km high, 550-km wide Olympus Mons volcano is located at the far left and center of the projection. Note that the northern hemisphere shows many fewer craters than the southern hemisphere. Image courtesy of NASA.

called, somewhat unceremoniously, contact 1 and contact 2. Contact 1 is the longer "Arabia shoreline," while contact 2, which lies inside contact 1, is known as the "Deuteronilus shoreline."

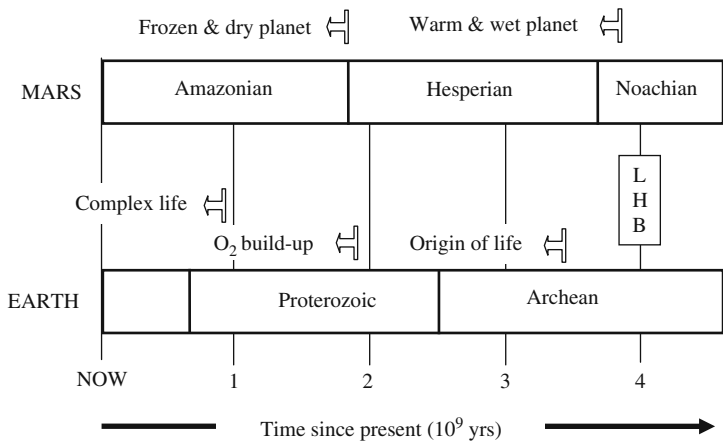


FIGURE 6.9. The comparative ages of the Earth and Mars. The timescale covers the 4.5 billion years since the planets formed, and each bar indicates the major time periods that have been described on each planet. LHB indicates the estimated time of the late heavy bombardment, a time of intensive, large-scale cratering. At about the same time that oxygen-producing bacteria evolved on the Earth, Mars was rapidly cooling, and its surface waters were drying up.

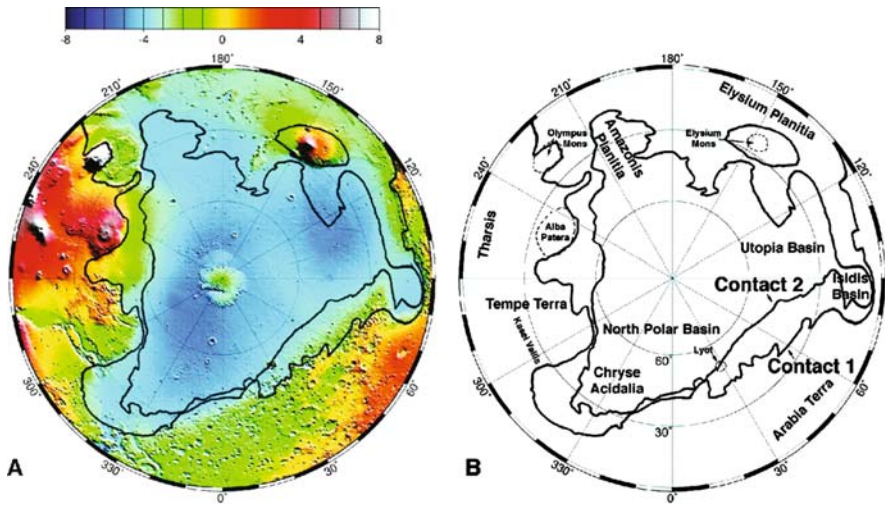


FIGURE 6.10. (A) North pole to equator projection of Mars showing the positions of the contact 1 and 2 shorelines. (B) Major features map corresponding to Figure (A). Image courtesy of NASA.

From the mapped contact levels, the ocean-filling factor can be determined, and the Arabia shoreline would constrain an ocean volume of some 10^8 km^3 . The smaller Deuteronilius shoreline would constrain an ocean averaging some 560 m deep and a volume of 10^7 km^3 . The ocean bounded by the Deuteronilius shoreline dates from the mid-Noachian to mid-Hesperian, a timespan covering perhaps 500 million years. The longer Arabia shoreline is believed to be younger, dating from the late Hesperian to the early Amazonian, representing a time span of about 1.5 billion years.

A long-running problem associated with the identification of the paelaeoshorelines on Mars has only recently been resolved in light of a detailed mathematical study by Taylor Perron (University of California) and co-workers.² It was noticed soon after the two shorelines were first mapped out using visual analysis that they did not actually follow a contour of constant gravitational potential. In other words, the seas would not have been level, which, of course, is not physically possible.

What Perron and co-workers have shown, however, is that the shorelines are consistent with a constant gravitational potential if the spin axis of Mars has shifted from 30° to 60° over the past 2 billion years. That is, the current Martian north pole location was not the same as the north pole position when the oceans existed. The mechanism invoked by Perron et al. to account for this change is known as true polar wander (TPW), which is a spin-axis reorientation effect that comes into play whenever a significant mass redistribution takes place on and in a planet. It is not exactly clear what might have produced the TPW on Mars, however, but Perron and colleagues suggest it might have been the formation of the Elysium volcanic region (see Figure 6.8, at the two o'clock position in the upper diagram).

Another issue that has puzzled researchers, and may have recently been solved, relates to the predominance of sulfur-rich minerals on the Martian surface. Both orbital spacecraft and the Martian rovers Spirit and Opportunity have found that there are almost no calcium carbonate (limestone) deposits on Mars but that there are plenty of sulfur-rich ones. On the Earth, silicate rocks remove carbon dioxide from the atmosphere and in the presence of water produce limestone. On Mars, however, although there is abundant evidence for past surface water, there is very little surface

limestone. The solution to this puzzle may reside in the Red Planet's past volcanic activity. Writing in the journal *Science*, for 21 December 2007, Itay Halevy (Harvard University) and co-workers suggested that on Mars volcanically outgassed sulfur dioxide substituted for carbon dioxide in the weathering process to produce sulfates rather than limestone. Not only this, while on the Earth, sulfur dioxide is quickly destroyed by oxidization, on Mars it would have served as a long-lived, atmosphere-warming greenhouse gas.

Figure 6.9 indicates that since about 2.5 billion years ago Mars has been an essentially dry and frozen world; small, high-salinity, and isolated lake systems may have existed near the pole in the northern lowland region for an additional billion years, but even these would have frozen over by the mid-Amazonian epoch. The questions that we need to ask now are, "How did this change of state come about, and what happened to all the water?" The point of these questions, of course, from the terraforming perspective, is to ask if large water-ice reserves exist on Mars, and might the heating of its atmosphere result in the reappearance of its long-lost oceans?

Whither the Water?

Figure 5.7 in the last chapter provides us with an understanding of why liquid water cannot exist for long periods of time on the surface of Mars at the present time. The surface pressure is too low and the surface temperature is not high enough for the liquid phase to be stable. We have already seen, however, that in the distant past the higher density of the Martian atmosphere did allow liquid water to pool and flow on the planet's surface. This atmospheric support no longer exists, and much of the ocean water will have turned to surface ice and seeped into the deep interior of the Martian crust.

It is likely that since the Martian oceans disappeared, intermittent large-scale volcanic activity—such as that recorded in the relatively recent appearance of the Tharsis magmatic complex—enabled temporary greenhouse gas-heated atmospheres to form, triggering, in the process, flood inundations.

We are left with the understanding, therefore, that large quantities of water have, without doubt, flowed on Mars in the distant past, but that in the present only highly localized and very short-duration

flows are possible (see Figure 6.4). These surface observations, however, do not exclude the possibility that large reserves of liquid water exist within the Martian crust, and this, of course, has great implications for the possible existence to this day of indigenous Martian life.

In terms of the water phase diagram, two important things will happen as deeper regions of the Martian crust are encountered. First, the pressure will increase due to the weight of overlying rock layers, and second the temperature will increase, since the Martian core is still warmed somewhat by the decay of long-lived radioactive isotopes. Eventually, indeed inevitably, the ambient temperature and pressure will enable liquid water to exist. At what depth this ice-to-liquid water transition occurs will depend upon the specific rock structure of the Martian crust. Estimates for the depth at which liquid water might be stable on Mars have recently been made by Michael Mellon (University of Colorado) and Roger Phillips (Washington University, St. Louis), who found that in regions with a low thermal conductivity, such as those associated with a dry, porous regolith might allow liquid water to exist just a few hundred meters below the Martian surface. In regions where the thermal conductivity is very high, such as those associated with ice-cemented regolith and ice-free sandstone, liquid water can only exist at much greater depths, between 3 and 7 km. There is great uncertainty, therefore, at what depth liquid water might generally be found in the Martian crust. In regions where there is rock stratification, liquid water may exist near the Martian surface, at depths of perhaps just a few hundred meters. In this situation, the liquid water is sandwiched between a lower impermeable rock layer and a topping made of dry, low conductivity regolith. Such aquifer confinement models offer one possible explanation for the many gullies and recent water run-off flows observed by the Mars Global Surveyor spacecraft (see Figure 6.4).

Ground-penetrating radar studies carried out from the ESA Mars Express spacecraft have found and analyzed water-ice deposits to a depth of about 4 km at Mars' southern polar cap and deposits to a depth of about 2 km at the northern polar cap (Figure 6.11). The radargrams produced from the spacecraft surveys indicate a clean transition between the water-ice cap and the underlying bedrock, so there doesn't appear to be any substantial liquid water region underneath the polar caps of Mars.

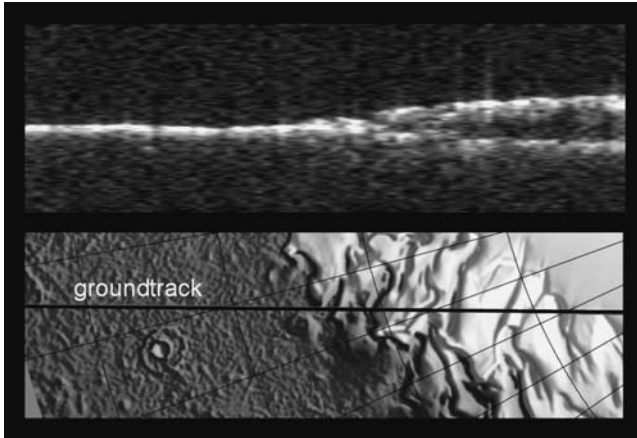


FIGURE 6.11. ESA's Mars Express advanced radar (MARSIS experiment) radargram (*top image*) showing the subsurface of the layered deposits at Mars's northern polar cap. The lower image shows the groundtrack superimposed upon a topographic map of the north polar region studied. The bright reflection (*top image*) from the water-ice deposits splits into two once the groundtrack crosses from the smooth plain to the layered region. The upper bright trace corresponds to the echo from the surface deposits, while the lower trace is the echo from the lower surface of the ice cap. The echo indicates that the water-ice layer reaches to a depth of some 1.8 km. Image courtesy of ESA.

While the ice-to-liquid water transition boundary has not been directly observed on Mars to date, the ground-penetrating radar studies of the water-ice contained in the southern polar cap indicate that it alone could produce an 11-m deep global ocean if it was melted. Importantly, therefore, from a terraforming perspective there appears to be an abundant supply of Martian water-ice that can be transformed, through atmospheric warming, into extensive regions of deep-standing surface water.

The Opening Salvo

The ever-enthusiastic, and ever-inspirational, planetary astronomer Carl Sagan (late of Cornell University) was a key figure in the initiation of the modern-day search for extraterrestrial intelligence (SETI) program, and he was one of the first scientists to seriously study the idea of terraforming planets. With respect to Mars, the

story begins in late 1971. It was in that year that Sagan published a short research paper in the then relatively new planetary astronomy journal *Icarus*. Entitled *The Long Winter Model of Martian Biology: A Speculation*, Sagan's paper was mostly concerned with the possibility of life having evolved on Mars (and how the Viking Landers might verify this possibility), but it also included some discussion on the idea that Mars might, once again, be made habitable.

Sagan built his argument upon the assumption that the northern polar cap of Mars was composed entirely of carbon dioxide ice, and that while seasonal changes in the relative sizes of both polar caps were known to have taken place, the northern polar cap had never been observed to fully disappear, not even during the northern summer. However, if all the ice in the northern polar cap could be devolatilized then Mars, Sagan realized, would rapidly develop a much denser and warmer atmosphere, and the conditions for liquid water to exist on the planet's surface might be achieved. The final step in Sagan's argument then linked the freezing out of the atmosphere and the devolatilization of the northern polar ice cap to a periodic cycle controlled by Mars' equinoctial precession rate.

Figure 6.12 shows a schematic illustration of the orbit of Mars and indicates the direction in which the planet's spin axis presently points (dashed line with arrows). Although the alignment direction

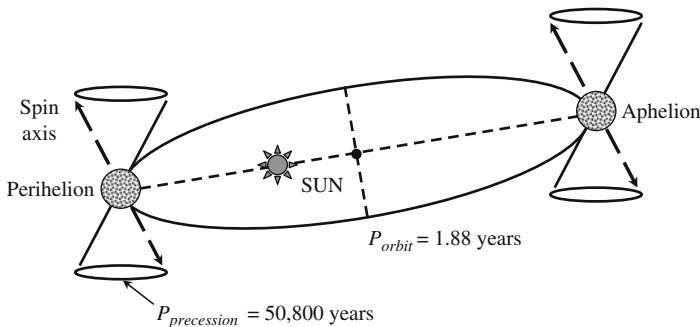


FIGURE 6.12. Schematic illustration of the Martian orbit and spin-axis orientation. Since the orbit of Mars is appreciably eccentric, it receives a slightly greater solar energy flux when it is at perihelion. The northern winter currently takes place, however, at this time. The dashed, arrowed line shows the present orientation of Mars' spin axis. Some 25,000 years from the present, the northern summer will take place when the planet is at perihelion, and this is the time and spin-axis orientation, Sagan argued, when the northern polar cap will melt.

of the spin axis does not noticeably change from one orbit of Mars about the Sun to the next (over a period of 1.88 Earth years), it does slowly change due to gravitational interactions on a precession cycle timescale of 50,800 years. At the present time, the Martian north polar cap is directed away from the Sun when the planet is at perihelion, its closest point to the Sun, and this, Sagan reasoned, is why it never quite manages to melt. The northern summer on Mars occurs, in fact, when the planet is at aphelion, its greatest distance from the Sun, and at this time the solar energy flux is at its lowest level.

Having made these observations about the present status of the northern winter on Mars, with wonderful foresight Sagan asked, "What will happen 25,400 years from now?" The answer, of course, is that at perihelion the northern polar cap will be pointed toward the Sun (i.e., it will be northern summer), and accordingly Sagan suggested it might well be expected that as a result of the enhanced solar heating at perihelion, the northern polar cap will be devolatilized. The hot, perihelion-located, northern summer conditions will prevail for a few thousands of years, but after this time the precessional cycle will begin to carry the northern summer location back toward the aphelion point, and the atmosphere will begin to freeze out at the northern pole.

Based on this reasoning, Sagan suggested that the Martian atmosphere undergoes a 25,000-year or so periodic freeze out during the precessional winter. Any life forms that might have evolved on Mars, Sagan further reasoned, might also undergo a similar hibernation cycle, sleeping as it were through the cold of atmospheric freeze out and rising from dormancy during the precessional summer.

Sagan's long-winter model for Mars was a bold and exciting idea, and it mirrors the Kroll-Melankovich cycle that is known to control the glaciation cycle on Earth. Perhaps Sagan's greatest leap of the imagination, however, was contained within the penultimate paragraph of his 1971 paper: "It is just conceivable that, in time, human endeavors could, by volatilizing the present NPC [northern polar cap] remnant, and taking advantage of the hypothesized instabilities, introduce much more clement conditions on Mars, in times considerably shorter than the precession cycle." Here, in all its bravado, is the rallying call to terraform Mars.

Almost exactly a year to the day after Sagan submitted his long-winter model paper to the journal *Icarus*, two of his Cornell University colleagues, Joseph Burns and Martin Harwit, submitted to the journal editors a research article illustrating how the Martian precession cycle might be modified. Burns and Harwit suggested that the Martian precession cycle could be altered by either modifying the orbit of its largest moon, Phobos, or by introducing material mined from the main-belt asteroid region to form a ring around the planet (similar to that presently seen around Saturn).

The Burns–Harwit maneuver, as their method is now often called, would no doubt work if the physical engineering could be achieved, but it is interesting to read the authors concluding statements. They make two points. First, the authors raise the point that their proposed method does the least damage to Mars, since no “foreign matter” is introduced to its surface. They even comment, “There is always something a little repugnant about man pushing his own interests and fixing nature.” This latter comment is rather astounding in that it either fully misses the point about why Mars should be terraformed, or it is an early admission that humanity has much to learn, both about itself and its interaction with nature (i.e., on Earth) before it might reasonably contemplate terraforming Mars. The second point made by Burns and Harwit is that, “The proposal is, perhaps, a fantastic one to contemporary minds. However, it seems to us that the required technology will not be wanting if man is alive 10,000 years from now.” This final paragraph is remarkable from our contemporary perspective in that there is now absolutely nothing surprising about the possibility of terraforming Mars—we expect it to happen—and it also completely underappreciates the likely timescale upon which Mars might be terraformed by a factor somewhere between 10 and 100. Such comments, however, are small quibbles over arguable details and personal opinions.

Again, almost exactly a year to the day after Burns and Harwit submitted their paper to *Icarus*, Sagan came back with a second research article; this time, perhaps rather provocatively, the article was entitled *Planetary Engineering on Mars*. Sagan outlined three possible methods by which Mars might be terraformed (which will be discussed later), and concluded in contrast to Burns and Harwit that, “It will be possible, in a short period of time, to reengineer

Mars into a world with much higher pressure and temperature, and much larger abundances of surface liquid water than are now present on the planet." Sagan also uses the expression "reengineering Mars for human purposes" in his paper, making it clear that his motivations are not simply ones of pure scientific interest.

The initial salvo of Martian terraforming papers were published over a time span of 2 years (from mid-1971 to mid-1973), and the three publications essentially constitute a public debate between three researchers located at the same institution. In 1976, however, two NASA Landers successfully touched down on the surface of Mars (see Vignette B at the end of Chapter 4), and Sagan's terraforming model was found to be wanting.

Sagan's elegantly argued long-winter model for Mars was simply not true. Not only was the northern polar cap of Mars not made entirely of carbon dioxide ice, but there was absolutely no evidence from the surface geology to support the idea of periodic liquid water inundations. The long-winter model for Mars was dead within 5 years of being formulated. This, of course, is exactly what science is all about, and it is by no means an indictment of Sagan's thinking, and indeed, some aspects of his long-winter model are at the core of present-day terraforming models. In the wake of the highly successful Viking Lander missions, the stage was set for a new beginning, and in relatively short order the first NASA report on the possible habitability of Mars was published, and the first conference dedicated to terraforming was convened.

Altered States: The Means of Terraforming Mars

Earlier we discussed the essential changes in surface pressure and temperature that must be brought about to make Mars habitable. Two specific initial issues dominate:

1. The atmospheric pressure must be increased by at least a factor of 100.
2. The mean global temperature must be increased by at least 60 K. Additional, longer-term requirements for habitability will also require the following:

3. The establishment of standing liquid-water reserves on the Martian surface.
4. A change in the chemical composition of the Martian atmosphere.
5. A reduction in the surface UV flux.

Exactly how these basic goals might be achieved is still unclear, but what is known at the present time is that there are a number of options open to the future terraformers of Mars. A list of possibilities follows. Some of these ideas are certainly more exotic than others, but the truly exciting point is that there are options:

1. Change the orbital eccentricity of Mars's orbit about the Sun.
2. Change the obliquity of Mars's spin axis.
3. Change the Martian precession cycle.
4. Spread dark, heat-absorbing dust grains over the polar ice caps.
5. Degas the carbon dioxide within the Martian regolith.
6. Add super-greenhouse gases to the Martian atmosphere.
7. Seed the Martian atmosphere with heat-absorbing, cloud-forming particles.
8. Devolatilize carbonates within the Martian crust.
9. Heat the polar ice caps by large statite (solar sail) mirrors.
10. Channel volatile-rich cometary nuclei into the Martian atmosphere.
11. Induce large-scale drainage of Martian aquifers.
12. Introduce bioengineered microbes to alter the atmospheric composition.
13. Introduce bioengineered plants to change the planet's surface albedo.

Options 1, 2, and 3 are the most drastic and perhaps the least desirable methods by which Mars might be terraformed, but there is no reason to suppose that in the deep future such terraforming tools won't become available, as Burns and Harwit argued in 1973. Option 1 essentially aims to reduce the perihelion distance of Mars (see Figure 6.12) while keeping the aphelion distance at about its current value. The reduced perihelion distance will result in periodic bouts of more intensive solar heating [the distance D term in Equation (5.1) is being periodically reduced in this process], and this, over time, will result in the degassing of the polar ice caps and the Martian regolith, producing a denser and warmer

atmosphere. The aphelion distance must be kept near its current value, since if Mars moves much further away from the Sun, then it will begin to strongly interact with the inner regions of the asteroid belt, a process that will likely result in an increased number of asteroid impacts on all of the inner Solar System planets.

Option 2 is also rather drastic, but in this case the idea is to tip the Martian spin axis over by perhaps as much as 65° so that in the extreme case it lies along the orbital plane, similar to the spin-axis orientation of Uranus. In this state, each polar cap will be directly heated for half of each orbit of Mars around the Sun. This extended seasonal heating might then result in the degassing of the polar ices, producing, eventually, the desired denser, warmer atmosphere. Sagan and co-workers first described this scenario in 1973, and later investigations found that an additional tilt of just 6° (to an obliquity of 31°) would suffice to devolatilize the polar caps and trigger a climatic runaway to higher global temperatures.

Both orbit change and the tilt adjustment of the Martian spin axis can be achieved through the application of controlled close-gravitational encounters. In this process, the orbit of a large main-belt asteroid, or Kuiper Belt object (KBO), is altered in such a manner that a close flyby or, more likely, multiple close flybys, with Mars is achieved. Such encounters can be repeated until the desired change occurs.

Certainly the process of altering the orbit of a large asteroid or KBO are beyond our current technological capabilities, but the dynamics of the process and the means of calculating the required close encounter conditions are fully understood. There are no physical reasons to suppose, therefore, that options 1, 2, and 3 will never be utilized. Indeed, a variant of the Barns-Harwit maneuver, proposed as a means of effecting option 3, must ultimately be implemented, since the orbit of Phobos (Figure 6.13) is slowly decreasing.

Detailed model calculations indicate that Phobos will impact the Martian surface in about 100 million years, an epoch well beyond the stage when Mars will have been fully terraformed and inhabited. Either the orbit of Phobos will have to be changed so that it maintains a stable orbit around Mars, or it could be mined for mineral resources and then ejected from Mars orbit. The latter option might, in fact, be modified with Phobos being mined

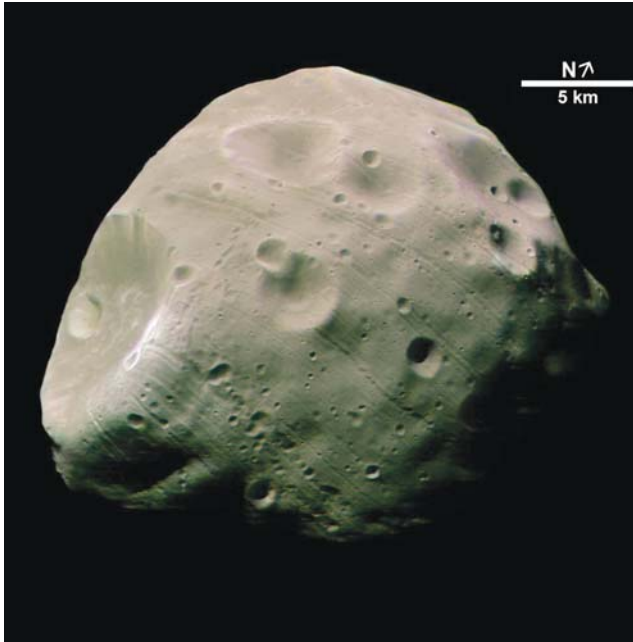


FIGURE 6.13. Phobos, the largest and innermost of the two Martian moons discovered by Asaph Hall in 1877. It has an average radius of 11.1 km, weighs in at 1.07×10^{16} kg, and has an orbital period of 7 h 39.2 min. The 10-km-wide crater Stickney can be seen to the middle-left of the view. Image courtesy of ESA/Mars Express.

very early on in the terraforming process and then, once exhausted of useful minerals, made to impact the Martian surface. This early prehuman colonization and destruction of Phobos option has the added advantage of supplementing terraforming options 4, 8, and 11.

Options 4, 7, and 13 are aimed at decreasing the Martian albedo. A reduced albedo, as indicated by Equation (5.1), will result in an enhanced heating of the planet. Sagan favored the application of option 4 and suggested that the polar caps might be devolatilized by the deposition of 1-mm layer of carbon-rich material over just 6% of the exposed surface. Pulverizing a 300-m diameter asteroid could produce the material required to generate the thin carbon-rich coating. Option 13 is a Mars-specific variant of the Daisy World model described in Vignette D at the end of in this chapter. Detailed calculations suggest that darkening the polar caps from their

present $A = 0.77$ to an albedo of about $A = 0.73$ (a 5% reduction in reflectivity) would be sufficient to initiate complete devolatilization.

Options 5, 8, 9, and 11 are all concerned with the introduction of greater amounts of carbon dioxide or water vapor into the Martian atmosphere. Option 5 essentially aims to amplify the seasonal ice-dust jet effect illustrated in Figure 6.3, while option 11 aims to greatly enhance the natural water leakage effect recorded in Figure 6.4. Likewise, options 6, 10, and 12 aim to alter the Martian atmosphere in such a way that its greenhouse-heating effect is increased. The details and reasons behind the various options are discussed below. The atmosphere and greenhouse-heating effect model that we shall see in the sections below is described in the Appendix of this book, and readers with an interest in the mathematical details are directed there.

Increased CO₂ Abundance

As described in Chapter 5 (see also the Appendix of this book), carbon dioxide is a greenhouse gas. This, we recall, means that it has absorption bands situated in the infrared part of the electromagnetic spectrum. These absorption bands will intercept the energy radiated into space from the surface of Mars, and accordingly the planet's CO₂-rich atmosphere is warmed. As we shall see later, CO₂ is neither the only nor the strongest greenhouse gas of interest when it comes to terraforming the Red Planet, but for the moment the effect of simply increasing the carbon dioxide abundance in the Martian atmosphere is illustrated in Figure 6.14. The increasing abundance of CO₂ in the atmosphere is expressed in terms of the pressure that it provides at the planet's surface (recall Chapter 5). The present surface pressure due to CO₂ on Mars is about 6 microbars (600 Pa), and this provides about 4° worth of greenhouse heating. At surface pressures of 10, 100, and 200 millibars, the greenhouse-heating effect amounts to 3°, 33°, and 51°, respectively.

Clearly, it can be seen from Figure 6.14 that the surface temperature of Mars increases quite dramatically as the CO₂ pressure increases, and this is exactly what the terraforming process is all about. Indeed, this is also exactly the effect that Carl Sagan had in mind when he developed his long-winter model. Although Sagan's

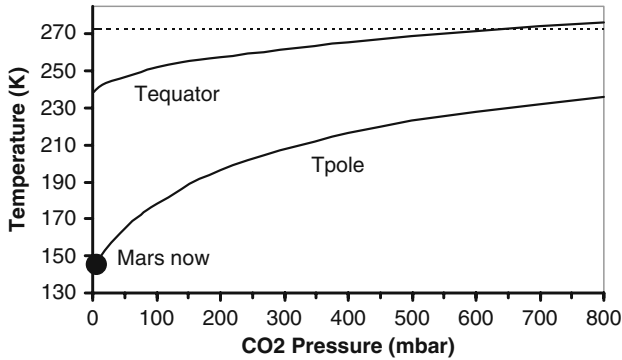


FIGURE 6.14. Martian surface temperature versus carbon dioxide pressure. The equatorial temperature as well as the polar temperature is shown in the diagram. The dashed horizontal line corresponds to a temperature of 273 K—the freezing point of water.

scenario of periodic warm and wet periods on Mars is no longer held to be valid, the basic warming mechanism (the release of additional CO₂ into the Martian atmosphere) is still the end result being sought in terraforming. Once the partial pressure of CO₂ exceeds about 700 millibars the equatorial temperature rises above the freezing point of water. With a partial CO₂ pressure of 800 millibars, a 22° swath, centered on the equator, will experience a temperature that is greater than the freezing point of water.

In principle, increasing the abundance of any one of the many greenhouse gases that are known to exist will warm the Martian surface, and as we shall see below there are, in fact, good reasons for attempting to seed the Martian atmosphere with additional methane, ammonia, and specially manufactured super-greenhouse gases.

The CO₂ Runaway

There are basically two CO₂ reservoirs on Mars that the terraforming engineer can attempt to access. The main reserve of CO₂ is that trapped within the surface regolith, with smaller reserves being contained within the polar caps. In terms of surface pressure increase, if all of the CO₂ in the Martian regolith were released

into the atmosphere, it would contribute an additional 400 millibars. If all the CO_2 in the polar caps were to be released into the Martian atmosphere, some 100 millibars of additional surface pressure would be realized. Figure 6.14 indicates that a 500-millibar increase in the CO_2 surface pressure will produce a maximum equatorial heating of about 268 K—a temperature still 5° below the freezing point of water.

There is an oft-quoted saying attributed to the Greek philosopher Archimedes that runs along the lines, “Give me a big enough lever, a place to stand, and I can move the world.” With respect to releasing all, or as much as possible, of its CO_2 reserve into the Martian atmosphere a lever that produces an additional 5° increase in the polar temperature is all that is required for terraforming to begin. Here the trick is to establish a positive feedback mechanism (recall the discussion in Chapter 5 and see Figure 6.14) such that Mars essentially warms itself, each increment of heating resulting in more CO_2 being placed in the atmosphere, which then results in more heating, and so on. This recipe cooks itself. Under this philosophy, the hardest part of the terraforming process will be to get the runaway process started. Once going, however, the process could run automatically, and the role of the engineer is accordingly minimized.

Stalwart terraforming proponent and researcher David McKay (NASA Ames Research Center) along with a number of co-workers has outlined the basic problem at hand.³ Mars is currently in a stable state, in that moderate changes in surface temperature or atmospheric pressure are self-correcting. In other words, there is a negative feedback mechanism at play, which keeps the polar temperature at about 147 K and the CO_2 surface pressure at about 6 microbars. The situation is illustrated in Figure 6.15, where the polar temperature as a function of surface pressure is displayed (this is essentially a repeat of Figure 6.14), along with the curve representing the CO_2 vapor pressure as a function of polar temperature. The vapor pressure for carbon dioxide is described by the Clausius–Clapeyron equation with $P_{\text{vap}} = 1.23 \times 10^7 \exp(-3168 / T_{\text{pole}})$. It can be seen that the two curves in Figure 6.15 intersect at two points, labeled A and B. The temperature and pressure conditions that presently prevail on Mars correspond to point A.

The stability of this point is illustrated by thinking about what happens when one curve plots above the other. Whenever the polar

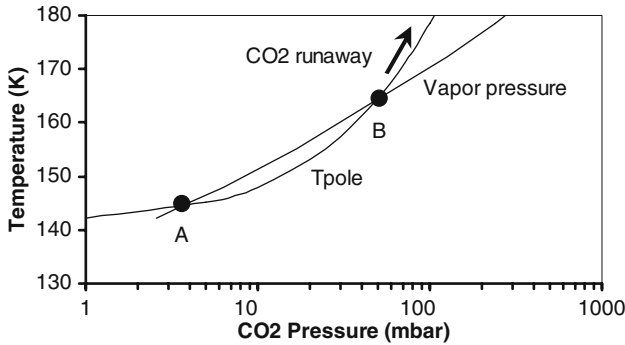


FIGURE 6.15. Atmospheric dynamics of the Martian atmosphere. Intersection point A corresponds to the conditions that presently prevail on Mars, and is stable, that is self-correcting, to small perturbations. Intersection point B is unstable in that once past this point a runaway devolatilization of the polar cap will proceed.

temperature curve falls above the vapor pressure curve, then the ice caps will sublime, releasing more CO_2 with a resultant increase in both temperature and atmospheric pressure. If, on the other hand, the vapor pressure curve lies below the polar temperature curve (as it does between points A and B), then carbon dioxide will condense out of the atmosphere at the polar caps (locking away the CO_2 as ice), and this will result in a lower polar temperature and a lower surface pressure.

So, the problem with attempting to terraform Mars by simply adding additional CO_2 to its atmosphere is that it will redistribute the CO_2 as polar ice and thereby maintain its current equilibrium state (point A in Figure 6.15). McKay and co-workers realized, however, that if some additional polar heating, not directly dependent upon an increase in atmospheric CO_2 , could be found, then this would be equivalent to shifting the locus of the polar temperature curve (as shown in Figure 6.15) upward, with the effect that the intersection points A and B would be brought closer and closer together. With enough additional heating, the polar temperature curve could be made to lie entirely above the vapor pressure curve, and consequently a runaway effect would be produced. The temperature and pressure would increase until all of the CO_2 in the polar ice caps had sublimated away. In this manner, the entire

additional 100 millibar CO₂ pressure could be realized and the polar temperature increased to about 180 K.

The question at this stage is how much of an additional heating effect is required to achieve the runaway state? Well, not much is the short answer. Indeed, just an additional 5° will suffice to trigger the desired effect. This relatively modest additional heating effect might be achieved in a number of ways, such as reducing the polar cap albedo (option 4 listed above), by adding super-greenhouse gases to the Martian atmosphere (option 5), or by heating the polar caps with a large, reflecting, space mirror (option 9; see below). Since the southern polar cap has a much greater reserve of CO₂ ice than the northern cap, the additional heating effect need only be applied to the southern hemisphere.

The devolatilization of the Martian regolith will proceed in a manner similar to that described for the polar caps, although there are more uncertainties in exactly what conditions must prevail for the regolith devolatilization to take place. The main uncertainty with the regolith calculation is exactly how much energy (that is heat) must be put into the surface for it to begin releasing its CO₂ burthen. If the carbon dioxide reservoir is only loosely bound to the regolith, then a relatively small amount of heat energy is required to release it; if the CO₂ is more tightly bound, then a greater heat rise is required to begin liberating it.

Robert Zubrin and Chris McKay have investigated several models for regolith devolatilization and find that perhaps of order half of the regolith CO₂ reservoir might be released as a consequence of inducing the polar cap runaway process. This suggests, therefore, that a Martian CO₂ atmosphere providing somewhere between 300 and 600 millibars of surface pressure might be realized as a result of engineering a 5° temperature rise in the polar cap temperature. With this amount of CO₂ in the atmosphere, the resultant equatorial temperature on Mars would fall somewhere between 262 K and 271 K. Although this is an impressive amount of warming, it is still not enough to allow liquid water to exist on the surface of Mars. In order to push the temperatures higher, additional terraforming agents will need to be employed.

A more direct but perhaps rather extreme process of regolith devolatilization has been proposed by British physicist Paul Birch. His suggestion is to build a mirror system in orbit around Mars that

will act as a giant lens. This aerial lens will then be used to direct a narrow beam of intense solar radiation onto a small region of the Martian surface, thereby raising the temperature to several thousand degrees. At such temperatures, the surface rock will undergo thermal decomposition, and carbonate rocks in particular will evolve CO_2 and H_2O , both gases of which will act to warm the atmosphere.

Birch notes that the deep, glass-lined scars gouged-out by the devolatilization beam could act as liquid-water-bearing canals (an idea that Percival Lowell would presumably like⁴) and, if appropriately roofed, regions of early settlement. British astronomer Martyn Fogg has also outlined a high-energy approach to regolith devolatilization through the application of thermonuclear mining. This approach essentially mimics the asteroid-impact scenario but acts internally rather than externally, with the regolith material being vaporized through the detonation of deeply buried, high-yield thermonuclear bombs. In principle, there are no physical reasons why such dramatic regolith devolatilization mechanisms shouldn't be used in the early stages of Martian terraforming. Each of the methods, of course, has its associated set of technical difficulties and challenges, but they do broaden the horizon of possible approaches to the initial warming of Mars.

Super-Greenhouse Gases

So far, we have only considered the warming effects from an increase in the CO_2 abundance in the Martian atmosphere. Other greenhouse gases, however, may be employed to raise the planet's temperature still higher. Zubrin and Mckay, for example, have noted that cometary nuclei and possibly some asteroids contain ammonia (NH_3) ice, which in its gaseous phase is a strong greenhouse gas, and they suggest that such cometary nuclei and asteroids might have their orbits altered in order to impact upon the surface of Mars (option 10).

Ammonia ice is generally estimated to make up something like 1% of the mass of a cometary nucleus, and to produce a partial pressure of 0.1 Pa (1 microbar) of order 4×10^{12} kg of ammonia gas would need to be imported to Mars.⁵ This amount of ammonia

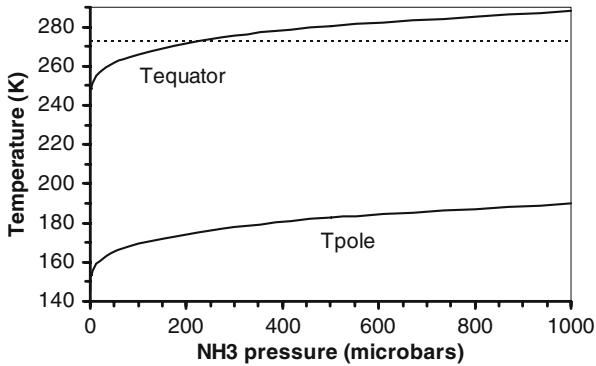


FIGURE 6.16. Greenhouse-heating effect due to the addition of ammonia into the Martian atmosphere. A CO_2 partial pressure of 6 millibars has been assumed in the calculations, and note that the partial pressure of ammonia is given in microbars. The horizontal dashed line indicates a temperature of 273 K (See the Appendix in this book for calculation details).

might be delivered by a single impact from a cometary nucleus with a diameter of about 10 km across.

Figure 6.16 shows the greenhouse-heating effect that will result due to increasing the ammonia content of the Martian atmosphere. An additional 10° of heating over that provided by CO_2 is realized when the partial pressure of ammonia is increased to 0.5 Pa (5 microbars). The equatorial temperature exceeds the freezing point of water once the partial pressure of ammonia is greater than 250 microbars.

Provided that the technological infrastructure can be put in place, and there are no physical reasons why they cannot be, there is a vast reserve of water and ammonia ice within the KBO and the Oort Cloud (see Figure 4.3) that might be utilized in option 10. Not only will the atmospheric and ground disruption of cometary nuclei in the early stages of terraforming Mars provide ammonia, but such actions will also provide additional water vapor, itself a strong greenhouse agent, additional CO_2 , and, important for eventual human habitability, atmospheric nitrogen, and oxygen.

In principle, strong greenhouse gases such as ammonia and methane⁶ might be mined from the atmospheres of the Jovian planets. This option, however, is (from all appearances) likely to be dependent upon technologies that won't be available for many centuries beyond the present, a time frame beyond which the

terraforming of Mars is likely to begin. Robotic spacecraft with the capability of altering the paths of cometary nuclei, on the other hand, are not only being contemplated at this very time, but there are no specific reasons (other than political and funding intransigence) to believe that multiple spacecraft missions couldn't be in place to begin the terraforming of Mars within the next several centuries.

Although the ability to extract large quantities of basic greenhouse gases from the atmospheres of the Jovian planets will probably not be in place by the time Martian terraforming begins, large-volume mining may well play a role in the terraforming of Venus.⁷ It has also been suggested that atmospheric mining might play an important role in the final stages of producing a breathable Martian atmosphere. In this latter case, it is the importation of nitrogen that will need to be performed, and at least one published paper suggests that the nitrogen might be extracted from the atmosphere of Titan, Saturn's largest moon (see Figure 3.6). This latter possibility reminds us of the fact that the Solar System is literally full of resources and that there are no reasons to suppose that terraforming can't proceed for the want of basic raw materials and chemical components. The problem for humanity, of course, is exactly how to perform the large-scale extraction and transportation of the resources from one location in the Solar System to another.

Staggeringly large amounts of ammonia would need to be added to the Martian atmosphere in order to push its equatorial temperature above the freezing point of water. Indeed, a partial pressure of some 250 microbars (= 25 Pa) would be required (Figure 6.16), corresponding to an imported mass of some 10^{15} kg of ammonia (see Note 5). Rather than use gases such as ammonia, therefore, James Lovelock and Michael Allaby realized in the early 1980s that it would make much more sense to utilize super-greenhouse gases such as the chlorofluorocarbons (CFCs) and perfluorocarbons (PFCs) to warm Mars. In the case of CFCs, a partial pressure of order 0.25 microbars, corresponding to an atmospheric mass of about 10^{12} kg, would produce an equatorial temperature above the freezing point of water.⁸ During the peak production time, in the mid-1980s, worldwide production of CFCs amounted to some 1 billion kilograms per year. With a relatively modest increase in

this production rate it would be possible, therefore, to substantially warm Mars via CFC greenhouse gases alone within a few hundred years.

As briefly noted in Chapter 5, there are several serious side effects associated with the introduction of large quantities of CFC gases into a planetary atmosphere. The most important issue (on the Earth currently) concerns ozone depletion through CFC chemistry. Although there is no ozone in the Martian atmosphere at the present time, it is certainly a gas that will warrant eventual accumulation. The key point about the Earth's ozone layer (and eventually that surrounding the Martian surface) is that it is highly efficient at absorbing the potentially deadly solar UV radiation. In contrast to the CFCs, the various PFC gases do not destroy ozone, since they lack the chlorine (and bromine) that catalytically destroys the O_3 , and their atmospheric lifetime against destruction is much longer than those of the CFCs. The fluorine-based gas C_3F_8 is one atmospheric-heating agent that shows particular promise with respect to the warming of Mars, since it is a strong absorber over a large fraction of the infrared spectrum (see Figure B.1). A 1 microbar partial pressure of C_3F_8 alone will produce a 12° temperature increase in the equatorial temperature on Mars, while a 10-microbar pressure would push the equatorial temperature to 6° above the freezing point of water.

Albedo Change and Increased Insolation

The amount of solar energy absorbed by Mars is determined according to the albedo of its atmosphere and surface. As indicated by Equation (5.1), the smaller the albedo term, the greater the amount of solar heating that takes place. Table 6.2 below indicates the effect of varying the atmospheric albedo of Mars.

It is highly likely that solar shades will play an important role in future attempts to moderate the increases in the Earth's temperature as a result of natural warming cycles, the Sun's increasing luminosity, and, on the more immediate timescale, industrial pollution. Such solar shades, however, can relatively easily be turned into solar mirrors capable of enhancing a planet's insolation.

Table 6.2. Equatorial temperatures resulting from various combinations of solar insolation (S , first column) and atmospheric albedo (A , first row). An atmosphere having partial pressures of 10 millibars CO_2 , 1 microbar NH_3 , and microbar CH_4 has been assumed. The calculations are based upon the model described in the Appendix of this book.

$S/A =$	0.1	0.15	0.2	0.25	0.3
0.9	249	246	242	237	233
1.0	257	253	249	244	240
1.05	260	256	252	247	243
1.1	264	259	255	251	246
1.15	267	263	258	254	249
1.20	270	266	261	257	252

The combined effects of artificially altering the insolation and atmospheric albedo are shown in Table 6.2.

Table 6.2 reveals that a 10% increase in the insolation results in an additional 7° of heating, irrespective of the albedo, while halving the current atmospheric albedo to $A = 0.1$ results in a temperature increase of some 9° . A more cloudy Mars will have a larger albedo, and the effect of this is illustrated in the final column, where it is revealed that an increase in the albedo to $A = 0.3$ will cause a 10° reduction in the temperature irrespective of the insolation.

Although the manipulation of the Martian insolation or atmospheric albedo will not be a trivial task, there are potential means of achieving each goal. Carl Sagan, for example, touted the idea of inducing a polar ice-cap albedo change by spreading a thin, dark layer upon the surface ice. This material could be supplied through controlled impacts of asteroids rich in carbonaceous material. The injection of small, dark, energy-absorbing particles into the upper Martian atmosphere might also be a means of reducing the albedo. A Martian analog of Daisy World (see Vignette D at the end of in this chapter) might also be realized through the development of suitably bioengineered dark-colored plants or algae.

In contrast to the surface or atmospheric manipulation of the albedo, the insolation can be increased externally by the means of large space mirrors. Mars intercepts a meager 2×10^{-10} fraction of the total solar energy flux available at a distance of 1.5 AU from the Sun, and the emplacement of large orbital mirrors or solar sails



FIGURE 6.17. L'Garde's 20-m solar sail demonstration model. Similar greatly scaled-up structures placed in orbit around Mars might be used to heat its polar caps. Image courtesy of L'Garde and NASA.

could certainly improve upon this number by reflecting additional sunlight onto the planet's surface.

From a dynamical point of view, the beauty of solar sails (Figure 6.17) is that they can be placed in orbits that are controlled not only by the gravitational force of a specific planet but also the pressure force resulting from an interaction with the Sun's radiation field. Aerospace engineer and science fiction writer Robert Forward realized in the late 1980s that this combination of forces could be balanced one against the other and used to place a solar sail in a fixed position relative to the planet–Sun line. Moving beyond the equatorial geosynchronous location commonly used by Earth-orbiting broadcast satellites today, solar sails can be made to occupy fixed sky positions at any inclination above or below the equatorial plane. Forward has introduced the term “statite” to describe a solar sail occupying a fixed sky position with respect to a planet.

Robert Zubrin and Christopher McKay have argued (see Note 3) that the southern Martian polar cap might be heated by an additional 5° through the use of a 250-km-diameter statite located 214,000 km from the center of Mars in the anti-Sun direction. A 350-km-diameter statite would provide about 10° of additional polar heating. If such solar mirrors could be constructed of material

having a density of $5,000 \text{ kg/m}^3$ and a thickness of 1 micron, then they would weigh in at between 250 and 500 million kg.

Solar sail technology is presently in its infancy, but missions supporting the deployment of small such structures (Figure 6.20) will likely take place within the next few years. Solar sails as large as a Mars-heating statite, however, will need to be constructed in a low-gravity environment, and this will require the continued industrialization of low-Earth orbit and the development of Moon-base colonies. Although certainly beyond our current construction capabilities, there are no physical reasons to suppose that large, multi-kilometer-scale solar sails won't become realizable constructs by the beginning of the twenty-second century.

The Phases of New Mars

In his groundbreaking book *Terraforming: Engineering Planetary Environments*, published in 1995, British researcher Martyn Fogg has argued that a synergistic approach will need to be adopted in order to make Mars habitable. In this sense Fogg argues that no one atmospheric heating and thickening process is capable of making Mars fully habitable for free-walking humans, and that multiple processes will have to be run either in parallel or in appropriate order. To date, no detailed synergistic program has been developed for Mars, but Fogg, for example, suggests that a three-phase approach might be followed, with each phase having its own distinct set of goals, the completion of which could be achieved on various long and short timescales. The three main phases for making Mars habitable are:

1. a nonbiological (anaerobic) warming phase
2. a habitability-making phase
3. a stewardship phase.

Phase 1 will see the initiation of all, or a selection of, the processes already described in this chapter: polar heating with a statite, *in situ* production of super-greenhouse gases, comet/asteroid impact delivery of greenhouse gas, albedo reduction, and so on. The expression *ecopoiesis*, meaning the generation of an open, anaerobic biosphere, is often used to describe these first steps of

terraforming. The aim of this ecopoiesis phase is to create the atmospheric conditions that provide a surface temperature greater than 273 K over a sizable fraction of the Martian surface, and a surface pressure that will allow liquid water to be stable and, indeed, will foster the growth of a northern hemisphere ocean.

Opinions differ as to whether a full CO₂ runaway process should be initiated in order to achieve the goals of the ecopoiesis phase. It is certainly the case that if the CO₂ runaway process is allowed to proceed, then with only a small amount of additional heating a warm, wet Mars will be brought about. The problem, however, is that a CO₂-rich atmosphere will have been produced, and while various plants and algae could thrive under such conditions, the atmosphere would be lethal to humans (and any other higher life forms). Fogg suggests that rather than allowing the CO₂ runaway process to dominate the Phase 1 heating phase, an atmosphere with the following partial pressures might be aimed for: $P(\text{CO}_2) = 350$ millibars, $P(\text{N}_2) = 10$ millibars, $P(\text{O}_2) = 20$ millibars, and $P(\text{H}_2\text{O}) = 25$ millibars. Such an atmosphere, while still not breathable by humans, would result in an equatorial temperature of about 275 K and above-freezing temperatures over a 10°-band centered on the Martian equator (based upon the model described in the Appendix of this book). The point that Fogg is making is that eventually, if Mars is ever going to move beyond a cloistered city world (as described in Chapter 2) upon which human beings might freely move about, then the atmospheric CO₂ partial pressure will have to be brought below 10 millibars. It is in this sense that the smaller the quantity of CO₂ that is released in order to achieve the end of Phase 1, the better.

By necessity, the first Martian colonists will be constrained to live in self-contained, self-sufficient, and self-regulating housing (see Figure 6.18). Such quarters, however, will be natural extensions of the systems that already exist on, for example, the International Space Station (ISS). In contrast to living in low-Earth orbit, as the ISS crew do, Martian colonists will need to grow all their own fresh food. Indeed, creating the conditions suitable for a crop management cycle will be of paramount importance during the Phase 1 terraforming process.

Preliminary studies have already been conducted with respect to growing cereal crops in CO₂-rich atmospheres. Indeed,

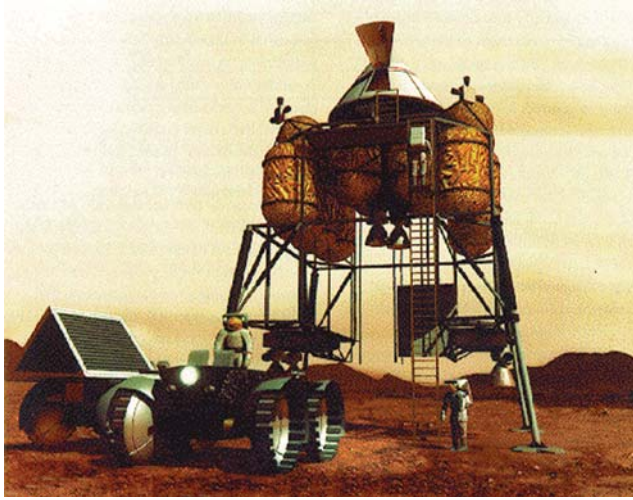


FIGURE 6.18. An artist's impression of possible living quarters and Mars exploration vehicle. Early colonial life on Mars will be confined to atmospherically isolated, self-sufficient structures. Image courtesy of NASA.

researchers at the University of Guelph, in Ontario, Canada, in conjunction with the Canadian Space Agency and NASA, are studying advanced life-support systems and greenhouse technology (these are real greenhouses, not the gases) on Devon Island, a Mars analog site located off the Arctic coast of Canada.

The biological fertility of Martian soil has also been studied, by Michael Mautner (Lincoln University, New Zealand). Mautner finds, in fact, that asparagus and potato tissue cultures can be successfully grown in pulverized Martian meteorite soil. He also finds that the biological fertility of Martian basalts is greater than that of terrestrial basalts. Not only can plants thrive in laboratory analogs of Martian regolith, but so, too, can micro-bacteria, a result that prompted Mautner to write in his 2004 book *Seeding the Universe with Life—Securing our Cosmological Future*, that “Microorganisms pioneered life on Earth, and similarly, they can pioneer life on new planets and establish ecosystems suitable for humans.”

Not only can plant cultures grow in soil composed of Martian meteorites, but they can also grow, although with a lower fertility yield, in soils made from pulverized carbonaceous chondrite

meteorites (see Figure 3.9). This latter result may turn out to be particularly useful, since the two moons of Mars, Phobos (see Figure 6.13) and Deimos, are both rich in carbonaceous material, and this makes them ideal as mining sites to produce a rich fertilizer for the early Martian colonists. Remember also, as discussed earlier, that something will have to be done about Phobos and Deimos anyway, since they are currently destined to crash into the Martian surface in several hundred million years' time. If these moons are not utilized as part of the regolith devolatilization process, then they might usefully produce soils for the first Martian crops. Some crops might also be produced on the moons themselves and then transported to the Martian surface.

The propagation of plant species and the introduction of microorganisms will, with little doubt, play an important role in the Phase 1 (and after) alteration of Mars. With respect to the initial plant colonization phase, the process will mimic that observed in the Earth's mountainous regions. Specifically, as terraforming proceeds, so the Martian regolith will experience a gradual warming and increase in surface pressure; this combined change is similar to that experienced in descending a tall mountain on the Earth (recall Figure 5.4). At the top of a high mountain, the nival region, nothing can grow, but below about 3,000 m a tundra region begins to open up where hardy lichens and a selection of cold-adapted microorganisms can thrive.

As on the Earth, so too on Mars the lichens will be one of the first pioneer species. Importantly, lichens are highly resistant to UV radiation (which on the Phase 1 Mars will be high due to the lack of any ozone layer), and they excrete acids that dissolve rock minerals, an action that will aid in the generation of an organically rich surface soil on Mars. Lower down the mountain slopes, we encounter the analog to the Phase 2 terraforming stage with the appearance of more complex and diverse microorganisms, along with flowering plant and various conifer and deciduous tree species.⁹

Phase 2 is concerned with the process of making Mars habitable for a wide range of biota and free-moving human beings over larger and larger regions of the planet's surface. This will primarily require the production of an atmosphere rich in nitrogen and oxygen. Phase 2 will also see the final generation of two large bodies of standing water: the northern boreal ocean and a near-circular

southern hemispheric ocean located in the mighty Hellas Planitia (see Figure 6.8, top image).

To make the Phase 2 atmosphere of Mars breathable for humans, the Phase 1 abundances will require considerable alteration. The partial pressure of oxygen will need to be increased by a factor of about 5, while those of nitrogen and carbon dioxide will need to be increased and reduced, respectively, by a factor of about 30. The increased oxygen and nitrogen abundances are required for human respiration as well as allowing for the growth of a temperate ecosystem containing flowering plants, grassland regions, forests, multiple microorganisms, and diverse animal life forms. The oxygen increase will be driven by microbial activity, such as that due to cyanobacteria, and through planet photosynthesis. Usefully at this stage of the terraforming process, the oxygen is being produced in a nonreducing environment, and it will therefore go directly into the atmosphere. The generation of oxygen will not only be important for making the atmosphere of Mars breathable, it will also produce an ozone layer that will act to reduce the surface UV flux (just as it does on the Earth).

Mars currently supports a nitrogen partial pressure of 0.15 microbars, and this will have to be significantly increased during the Phase 2 stage of terraforming. It seems highly likely that Mars' initial inventory of atmospheric nitrogen was much higher than it is today, its loss being precipitated through oxidation to produce nitrate (NO_3), which currently resides in the regolith. The denitrification of the regolith can be brought about through bacterial action in an aqueous environment, whereby the nitrate is initially converted into nitrite (NO_2). Other bacteria then reduce the nitrite to nitric oxide (NO) and nitrous oxide (N_2O), with the eventual release of nitrogen gas (N_2). Furthermore, other microorganisms can assimilate nitrate to produce ammonia (NH_3), and then the nitrate in the regolith can be reduced and the partial pressure of nitrogen increased. Importantly, once the partial pressure of nitrogen exceeds 5 microbars, then nitrogen fixation can begin, and a closed biochemical nitrogen cycle will become established.

Although the Phase 2 stage of nitrogen production will most likely proceed through biotic activity, the initial Phase 1 increase might require the direct importation of nitrogen. Usefully, the atmosphere of Saturn's largest moon, Titan (Figure 3.6) is nitrogen

rich, and transport and extraction problems aside, this exotic satellite might play an important role in making Mars habitable. The reduction in atmospheric CO₂, a vital part of the Phase 2 stage, might also proceed biologically through the growth of bryophytes, such as mosses. Indeed, their role will be to sequester carbon dioxide in decay-resistant organic compounds in Martian peat lands. Conditions compatible with the eventual appearance of trees will further enhance the biological reduction of atmospheric CO₂.

Since the CO₂ abundance must be reduced during Phase 2, alternate super-greenhouse gases will need to be added to the atmosphere in order to keep the surface temperatures above the freezing point. It is not beyond the realms of possibility that microorganisms capable of producing the desired greenhouse gases might be genetically engineered and released into the Martian regolith. The insolation might also be increased at this stage by the placement of large or multiple statite mirrors in close Martian proximity, or by the introduction of dark, surface-growing lichens and microbes.

The onset of the stewardship, Phase 3, stage of Martian terraforming will in some sense mark the end of the terraforming process. Once this stage begins, Mars will be fully, or at least mostly, habitable. The planet will be able to support larger and larger numbers of people in step with the large-scale growth and development of surface agriculture and manufacturing industries. A long-lived, zero-maintenance, life-supporting atmosphere on Mars, however, will never be fully realized, and a terraformed Mars will require continuous monitoring and stewardship. We will not acquire the new Eden on Mars for free, and this will place great responsibility upon our descendants. Indeed, they will need to avoid all of the pitfalls and fallacies of the industrio-political ideologies that have dominated the workings of the world in recent (if not historical) times.

The Times of Their Lives

There is a well-known story concerning the construction of a large new college hall at Oxford University many hundreds of years ago. Hopefully it is a true story, and if it isn't, it certainly deserves to be told anyway. The story goes something like this: the new building

was framed with large oak timbers and was consequently a very sturdy structure, and indeed, it held up extremely well under the vagaries of the English climate. After several hundred years, however, it was realized that the oak beams were beginning to fail and that they would need replacing. The college dean at the time was apparently distraught at the news and became almost apoplectic at the thought of the incredibly high costs that would follow as a result of the needed renovations. "We cannot afford to use new oak beams," the dean cried as he passed across the senior common room floor, "and surely, even if we could afford it, there is no supplier capable of delivering the quantities of seasoned oak that we require?" It was at this point that one of the college historians directed the dean's attention to the common room window, through which vista a magnificent stand of mature oak trees could be seen. The white-haired history professor then respectfully explained to the befuddled dean that when the hall was being constructed, the craftsmen planted a new stand of oak trees, ready for the day, which they knew would eventually come many years after their deaths, when their work would need replacing. In short, the moral of this story is that the craftsmen thought ahead, and put into action a plan for future renovations that they would not see in their lifetimes and from which they would not directly profit.

Well, as suggested earlier, this may or may not be a true story, but the forward-looking attitude of the craftsmen portrayed certainly exemplifies the sort of collective outlook that we must adopt before the terraforming of Mars commences. Indeed, on the timescale that a human generation turns over, say an interval of 30 years, the initial terraforming phase of Mars will be a multigenerational project. Estimates vary, but most researchers suggest that the Phase 1 stage of ecopoiesis might take several centuries to complete, which corresponds to a minimum of some six to seven human generations. The completion of Phase 2 will take at least an order of magnitude longer than Phase 1, requiring perhaps 1,000–2,000 years before the beginning of Phase 3, the stewardship stage, is realized.

We are now considering an interval of time that embraces some 60–70 human generations. In some sense, this timescale gives us great hope for the future if we reflect upon the incredible changes, both practical, technical, and philosophical that have taken place over the last 2,000 years of history. In another sense, it also provides



FIGURE 6.19. The Stonehenge monument was occupied, developed, and central to life for a time span in excess of a thousand years. This same mindset of building from the distant past, through the present to a distant future is something that will be required of humanity when the terraforming era finally begins.

us with a real cause for concern, since during that same time interval not one universally binding project has ever been started, let alone completed, by humanity.

It is a sobering thought, for the modernists among us that ancient archaeological history provides us with a number of examples of dedicated, multigenerational, large-scale building projects. The great megalithic encampment of Stonehenge (see Figure 6.19) in Britain, for example, is a structure that was adapted and maintained over a time span of at least a thousand years starting from circa 3,000 B.C. Its true purpose is not readily known to us today, but it was clearly an extremely important object to our distant ancestors, who invested a tremendous amount of time, energy, and no doubt lives into its development. For the many extended family clans that lived upon the downs that surround the Stonehenge structure, it was an ancient object that bound them together. It was also a structure that they communally nurtured in order that it might pass into the “now” of their distant descendants. It is often said that if we don’t remember our history, we are doomed to repeat

its failures. It might also be said that we should remember our ancient history, since it tells us how to live and plan for the sake of future generations.

Worldhouse

It was argued in the Introduction and Chapter 5 that in the future the vast majority of humans will live within domed cities that are integrated into a biosphere where crops can be grown and water resources exist. The extreme of this Martian domed living concept resides in the Worldhouse¹⁰ idea described by Richard Taylor (London University). Under the principle of creating deliberately restricted ecospheric environments (DREE), Taylor suggests that the entire Martian surface might be covered by a transparent dome reaching to perhaps a few kilometers in height. Under this dome, it is envisioned that a breathable atmosphere will be produced and an active, interacting, and diverse biosphere developed. Taylor suggests that either a modular or a global approach can be taken to generating a DREE. The initial phase might, for example, consist of the construction of multiple domed cities at key mineral resource sites on Mars. Each city boundary might then be added to as the Martian population and economy growth rate allows. The Worldhouse idea can, in principle, be extended to any planetary body, and it represents the perfection and technological evolution of pioneering projects such as the Biosphere 2 experiments (see Figure 2.3) carried out in the early 1990 s.

Near-Term Developments

What technology and space-based infrastructure must be put in place in the near-term future, say over the next 100 years, so that the terraforming of Mars might begin within the next several centuries? The generation of industrial pollution is something that humanity is already very good at, and in the case of terraforming Mars this might actually be a useful skill. For example, the technological skills required to produce super-greenhouse gases, such as CF_4 and C_3F_8 , on an industrial scale are already well known, and it

is certainly conceivable, given the right political will and funding, of course, that such robot-run industrial plants could be constructed on Mars within the next several hundred years. The basic materials from which such industrial complexes might be made are available on the Moon as well as Mars, and accordingly the establishment of permanent lunar colonies will be of great initial importance.

The existence of Moon colonies will not only be vital to the establishment of the technologies and infrastructure required for planetary (as well as asteroid, cometary nucleus, and satellite) mining, they will also facilitate the construction of very large space structures. It will be much easier to build large-diameter statites in the low gravitational field of the Moon, for example, than upon the Earth's surface, or even in low-Earth orbit. In addition, the mining technology that will be required for Moon development and Martian terraforming will be based upon the straightforward development of the integrated robotic systems that already exist in Earth mines in the present day. Indeed, in many cases, rather than future engineers having to develop new technologies in order to colonize the Moon or to begin the terraforming of Mars, they will rather find themselves adapting technologies that are already well established on our present home planet.

As outlined earlier in this book, NASA has already announced plans to establish a lunar base by the mid-point of this century. The European Space Agency (ESA) has further plans to mine, albeit at a very low level, the nucleus of Comet Churyumov-Gerasimenko in 2014 with the Lander currently attached to their Rosetta spacecraft. The Japanese Space Agency has possibly mined, again through a very small mass extraction sample, asteroid (25143) Itokawa during its 2005 Hayabusa mission. ESA has also drawn up plans for, but has not yet funded, a near-Earth asteroid orbit-altering mission. Mining upon Mars, again at a very low level, has already taken place during the Viking Lander missions (see Vignette B at the end of Chapter 4 in this book), and surface material has been sampled and returned from the Moon by both astronauts and landers (i.e., through the Soviet Lunokhod missions). Further, future NASA mission plans call for the return to the Earth of Martian-sampled surface material by the mid-2020s. We truly live in exciting times!

Humanity already has the basic skills, as well as an understanding of the processes involved, to begin the terraforming of Mars. What is most needed over the next century, however, is the development of a clear and strong commitment to fund and perform the action. In the immediate future, a continued commitment is also required to fund those projects that will enable the development of the basic technological skills and infrastructures required to work in both alien and extremely unforgiving environments. Once humanity has learned to live within the Earth's carrying capacity and after a truly global society has committed itself to fostering a distant future for its far-off descendants, and when we have gained a clearer understanding of how to engineer planetary atmospheres effectively and safely, then the time for the direct action of terraforming Mars will have arrived.

Vignette D: Daisy World

As described earlier, the atmosphere and all life on and in Earth interact in numerous feedback cycles. The feedback cycles are in some cases almost literal and animal populations are controlled by predator/prey dynamics. The interconnectedness is profound and fully invasive: herbivores, by their grazing, control certain types of vegetation growth; the vegetation interacts with the atmosphere through photosynthesis; the atmosphere interacts through wind, rain, and weathering with the Earth's surface rocks, which in turn regulate the abundance of atmospheric gases (i.e., the CO₂ cycle; see Figure 5.13); and finally predators hunt, eat, and control the population of herbivores.

There is no real beginning or end to this chain of interconnectedness, and in some sense one could argue that the population level of Serengeti lions is partially controlled by seafloor spreading, since the latter is part of the great CO₂ cycle and the photosynthesis essential to plant life. The chain can only proceed if the atmospheric CO₂ abundance¹¹ is greater than about 150 p.p.m., and finally, the wildebeest that roam the Serengeti Plain, the lions prey, can only survive if they have grasses to eat. There are, of course, many other local factors that determine lion populations, but the notion that the Earth is a vast self-regulating system in

which the biota has the ability to influence and actually stabilize the climate and atmospheric composition is a fertile and far-reaching idea.

British chemist James Lovelock first introduced the idea of the Gaia hypothesis in the 1970s, although it grew out of work conducted about a decade earlier. Indeed, Lovelock was involved with the early planning of the Viking Lander missions to Mars and the search for life experiments that they would carry out (recall Vignette B). The basic tenant of Gaia, named after the Greek goddess who personified Earth (see Figure 6.20), is that it is a closely coupled system of numerous feedback cycles that have the goal of maintaining a climate that is best suited to support the life forms (the plants and animals) that exist at any specific epoch. It should be



FIGURE 6.20. Central part of a great floor mosaic at the Roman villa in Sassoferrato, Umbria. Constructed circa A. D. 200–250. The mosaic shows Aion, god of eternity, encircled by a braid decorated with zodiacal signs, between a green and a defoliated tree that signify summer and winter. Before Aion is the mother-earth Tellus (the Roman version of Gaia) with four children who represent the four seasons. Photograph by Bibi Saint-Pol.

noted at this stage that Gaia theory is still controversial and not universally accepted.¹² The general problem associated with the theory is not the idea of a close interconnectedness, but because the proponents of the theory often use such expressions as “Gaia’s goal is” or “Gaia actively maintains. . .” Many biologists, geologists, and physicists object to the idea that Earth—Gaia—might have “reasons” for doing things. However, what is of interest here is the undisputed fact raised by Lovelock that the Earth’s atmospheric composition has been altered by its biota (i.e., through the photosynthetic production of oxygen). Not only this, but through his development of Daisy World, Lovelock has shown that the Earth’s temperature has also been regulated by its biota.

Lovelock’s Daisy World is an imaginary world. It is a world, however, that is envisioned to orbit the Sun along the same path as that followed by Earth, and it is populated by two kinds of daisies.¹³ The two daisy types differ only with respect to their color: one set has white petals, the other has black ones. Each species of daisy has an optimum growing temperature of 22.5°C. At temperatures above and below the optimum the daisies can still grow, but they do so less vigorously.

How, then, might the distribution of black and white daisy types control the environmental temperature? The answer, as Lovelock points out, is by altering the albedo of the planet. Recall Equation (5.1). In this equation the temperature of the planet is governed according to its distance from the Sun, the Sun’s luminosity, and the albedo (A), which is a measure of how much of the incoming solar radiation is reflected back into space. The larger the value of $0 < A < 1$, so the greater the amount of solar radiation reflected back into space and the lower the planet’s temperature. In this manner, the more white daisies that exist—that is, the greater the surface area of the planet that they cover—the higher the albedo ($A \approx 1$) and the cooler the planet. In contrast, the greater the area covered by black daisies, the smaller the albedo ($A \approx 0$) and the higher the temperature of the planet.

Where all this give and take between the numbers of daisy types becomes even more interesting is when the effects of solar forcing are also considered. As we saw at the end of Chapter 4, the Sun’s luminosity has been steadily increasing with age (see Figure 4.17). Indeed, the Sun was some 25% less luminous when life first

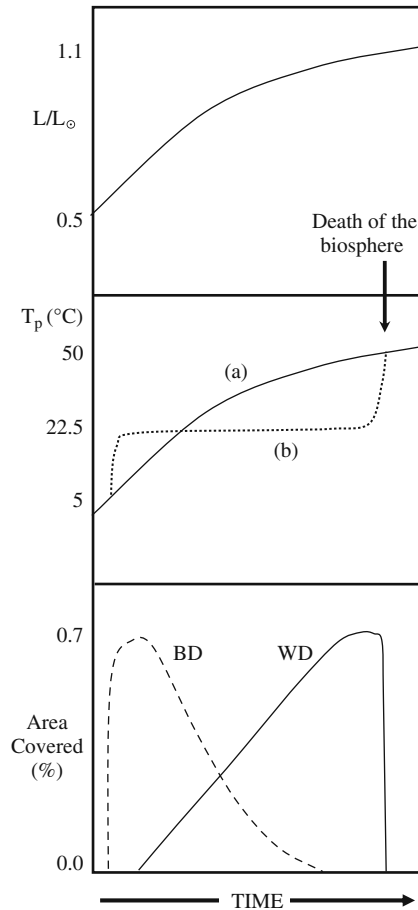


FIGURE 6.21. The top panel shows the increase in the Sun's luminosity with time. The middle panel shows the temperature of Daisy World when (a) there is no albedo modification and the temperature increases in step with solar forcing, and (b) when the daisy population is allowed to control the albedo. The lower panel shows the respective area covered by the black (BD) and white (WD) daisies as a function of time. As the system ages, and the Sun becomes more luminous, so the population of white daisies grows, since they reflect more light back into space. The death of the biosphere (Gaia) will take place when the Sun's luminosity is about 1.1 times its present value, some 2–3 billion years from the present.

arose, and yet the temperature of the Earth, as revealed through the ancient ice-core and rock record, has remained nearly constant for the past 3.5 billion years. The reason for this, Lovelock argues, is that Earth's albedo has changed with time because of its biota.

Going back to Daisy World, when the Sun was less luminous many billions of years ago, the dominant daisy species would have been the black ones, since they produce a low albedo ($A \approx 0$), resulting in less of the Sun's radiation being reflected back into space and hence a warmer atmosphere. As the Sun's luminosity increases in the future, however, the dominant daisy species will be the white ones, since they have a higher albedo ($A \approx 1$), causing more of the Sun's radiation to be reflected back into space, and this keeps the atmosphere cool in spite of the Sun's increased luminosity. Figure 6.21 shows a schematic time evolution model for the temperature regulation of Daisy World.

There is no doubt that the temperature of a planet can be controlled by modifying its albedo, and whether this effect is achieved by space mirrors, sunshields, or through genetically engineered plants, the albedo modulation of other worlds will be an important part of the future terraformers toolkit.

Notes and References

1. James Head III et al., Possible ancient oceans on Mars: evidence from Mars Orbiter laser altimeter data. *Science* **286**, 2134–2137 (1999).
2. Taylor Perron and co-workers, Evidence for an ancient Martian ocean in the topography of deformed shorelines. *Nature* **447**, 840–843 (2007).
3. The classic research paper, Making Mars habitable by Christopher McKay, Owen Toon, and James Kasting was published in *Nature* **353**, 489–496 (1991). A second important research paper is that by Robert Zubrin and Christopher McKay, Technological requirements for terraforming Mars, published in the *Journal of the British Interplanetary Society* **50**, 83–92 (1997).
4. By this I refer to the remarkable mistranslation by Percival Lowell of the Italian word *canali*, used by Giovanni Schiaparelli to describe the linear features he thought he could see on the Martian disk during its 1877 close approach to the Earth. Lowell translated the word as “canals” and thereby interpreted the observations to indicate that water was being directed along deliberately built linear grooves cut into the Martian surface by intelligent beings. Later observations with larger telescopes revealed that the *canali* seen by numerous observers were not real features at all but were optical artifacts created by the physiology of the human eye working at the limits of its resolution.

5. The surface pressure P_s and atmospheric mass M_{atm} are related as $M_{atm} = 3.88 \times 10^{11} (R^4 / M) P_s$, where R and M are the mass and radius of the planet. For Mars, this provides the relationship $M_{atm} = 3.88 \times 10^{13} P_s$, where P_s is in pascals and the atmospheric mass is in kilograms. The amount of material in a cometary nucleus of mass M_{comet} and radius R_{comet} with internal density ρ is $M_{comet} = \rho (4 \pi / 3) (R_{comet})^3$. In the calculation for delivering ammonia to Mars through cometary impacts we take $\rho = 800 \text{ kg/m}^3$ and assume 1% of the comet's mass is in the form of ammonia ice.
6. On the Earth, methane and ammonia are generated biologically, and eventually this might also be the case on Mars. The atmospheric residency time against destruction, however, for these gases is very short, being perhaps just a few tens of years. This short lifetime brings into question the economic viability of mining and transporting methane and ammonia from the Jovian planets. There is a ready and very large supply of cometary nuclei within the Solar System, however.
7. Solar mining has been discussed by numerous authors, but the ideas described by David Criswell in his article 'Solar system industrialization: implications for interstellar migrations' [published in *Interstellar Migration and the Human Experience*, R. Finney and E. Jones (Eds.) University of California Press, Berkeley (1985), pp. 50–87] are especially well presented.
8. In this calculation, the optical-depth term for a mixture of CFC gases derived by McKay et al. [Making Mars Habitable, *Nature* **352**, 489–496 (1991)] has been used. For PFC warming the specific expressions derived by Marinova and McKay [Radiative-convective model of warming Mars with artificial greenhouse gases. *Journal of Geophysical Research*, **110** E03002, 1–15 (2005)] are employed. The various mathematical expressions are given in Appendix B of this book.
9. The height and temperature stratification of flora and fauna are described in detail by James Graham in his article, The biological terraforming of Mars: planetary ecosynthesis as ecological succession on a global scale, published in *Astrobiology* **4**(2), 169–196 (2004).
10. See Taylor's article, with the rather lengthy but complete title, Why Mars?—even under the condition of critical factor constraint engineering technology may permit the establishment and maintenance of an inhabitable ecosystem on Mars, published in *Advances in Space Research* **22** (3), 421–432 (1998).
11. The effect of CO_2 abundance levels on plant growth is discussed by Ned Stafford in, The other greenhouse effect, *Nature* **448**, 526–528 (2007). The consequences of the geologically long-term trend in which

most of the atmospheric CO₂ will be lost through weathering reactions with calcium silicate rock have been discussed by Ken Caldeira and James Kasting in their article, The life span of the biosphere revisited, *Nature* 360, 721–723 (1992).

12. Some of these issues are discussed by Tyler Volk [*Nature*, 440, 869 (2006)] in his review of Lovelock's most recent book *The Revenge of Gaia: Why the Earth Is Fighting Back—and How We Can Still Save Humanity*, Allen Lane, London (2006).
13. See, for example, the very readable book by Stephan Harding, *Animate Earth: Science, intuition and Gaia*. Chelsea Green Publishing Company, Vermont. (2006). Lovelock describes the Daisy World model in his article, The ecopoiesis of Daisy World, published in the *Journal of the British Interplanetary Society* **42**, 583–586 (1989).

7. The Terraforming of Venus

The eyes of Perelandra opened, as it were inward, as if they were the curtained gateway to a world of waves and murmurings and wandering airs, of life that rocked in winds and splashed on mossy stones and descended as the dew and arose sunward in thin-spun delicacy of mists.

When C. S. Lewis wrote these words¹ in 1943 describing Perelandra, his invented name for the planet Venus, he was describing his vision of an unspoiled Eden, a world that had not been corrupted by original sin. Sidestepping the theological issues, his description is in perfect resonance with the aims of the terraforming ideal. Venus is Earth's twin, certainly in body and, who knows, perhaps she is also a kindred soul.

Historically recognized as the alternating morning and evening star, Venus in its orbit never moves more than 45° away from the Sun as seen from the Earth. When it is at its closest approach to the Earth, the planet is just 0.277 AU away from us, a mere 41.4 million kilometers, and thus it is periodically the closest celestial object to the Earth after the Moon. At the time of closest approach, however, Venus cannot be seen from the Earth at optical wavelengths, due to the overwhelming glare of the Sun. At best, Earth-bound astronomers can only observe the partially illuminated disk of Venus, as the ever-irascible Galileo first observed with his new telescope in 1610. It is partly for this reason that Venus has remained, until the past several decades, one of the least well-known planets in the Solar System.

Venus is often described as the Earth's twin, and indeed, Table 7.1 shows us that it has very similar physical characteristics to those of the Earth. The Venusian² atmosphere (Figure 7.1), however, is in complete contrast to that which surrounds Earth. Predominantly composed of carbon dioxide (96.5%), with a smattering of nitrogen (3.5%) and a trace of gases such as sulfur dioxide, water vapor, helium, and argon, the atmosphere of Venus provides

Table 7.1. Comparison of Venus and Earth. Note the high obliquity of Venus, which indicates that it spins in a retrograde direction. The comparison data is from Table 4.2.

Property	Value	Venus/Earth
Total mass (kg)	4.8685×10^{24}	0.815
Average radius (km)	6051.8	0.950
Polar [Equatorial] radius (km)	6051.8 [6051.8]	0.952 [0.949]
Surface area (km ²)	4.6×10^8	0.902
Bulk density (kg/m ³)	5243	0.951
Average surface temperature (°C)	464	30.93
Escape velocity (km/s)	10.36	0.926
Surface gravity (m/s ²)	8.87	0.905
Sidereal spin rate (hr)	5832.5	243.686
Spin velocity (at equator—km/s)	1.81×10^{-3}	3.89×10^{-3}
Obliquity (°)	177.36	7.55
Magnetic field (Tesla)	None	—
Sidereal (orbital) period (days)	224.701	0.615
Average distance from Sun (km)	1.0821×10^8 km	0.723
Average orbital speed (km/s)	35.02	1.176

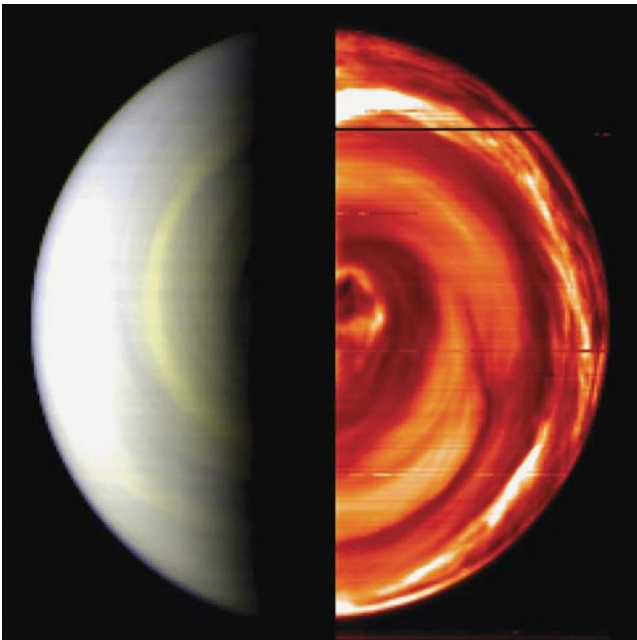


FIGURE 7.1. The upper cloud deck of Venus. This image shows a composite day/night split, with the day-side image (*left*) being taken at optical wavelengths. The night side image (*right*) is taken at infrared wavelengths. Image courtesy of ESA Venus Express.

a staggering surface pressure of 150 kPa, about 95 times greater than that on the Earth's surface, and it supports a blistering surface temperature of 737 K, which is comparable to the melting point of metalloid tellurium.³

The present-day Venus is certainly no Eden. Indeed, it is a veritable model for the blackened furnaces of hell. This likeness to the fire pits of Mordor, however, may not always have existed, and in the halcyon days following its formation Venus may well have supported superheated oceans. Some researchers have even speculated that perhaps extremophile-like life forms may have evolved there. The interplanetary meteorite conveyer belt, described in Chapter 3, also allows for the very remote possibility that life on the Earth and in the rest of the Solar System was seeded from Venus. No Venusian meteorite, however, has so far been recognized among the many tens of thousands of meteorites that have been collected on the Earth.

At the turn of the twentieth century, astronomers generally believed that Venus had a surface temperature and climate similar to that of the Earth. This belief came about through the basic observation that while Venus must receive a greater influx of solar energy than the Earth (over two times greater, in fact), its atmospheric albedo ($A = 0.65$) is very high (again, about twice that of the Earth). The combined effects, however, of the greater solar energy flux and higher atmospheric reflectivity seemed to cancel each other out, and consequently, Venus was theoretically heated to about the same temperature as the Earth. It was further speculated that the dense Venusian atmosphere was caused by and shrouded a vast global ocean (as so wonderfully described by C. S. Lewis), and later, the observation that the Venusian atmosphere was CO₂ dominated led famed planetary astronomers Fred Whipple and Donald Menzel to further suggest that the veiled planet was washed over by a global soda-water ocean.

This minds-eye image of a water-bathed Venus only began to change in the 1950s, when observations collected with radio telescopes revealed that the surface temperature of the planet must exceed 400°C—a temperature far too high for the existence of surface water and one that blighted the possibility of any surface life forms. The desert-like picture of the surface of Venus continued well into the late 1950s (recall Figure 3.1), but after the Mariner 2

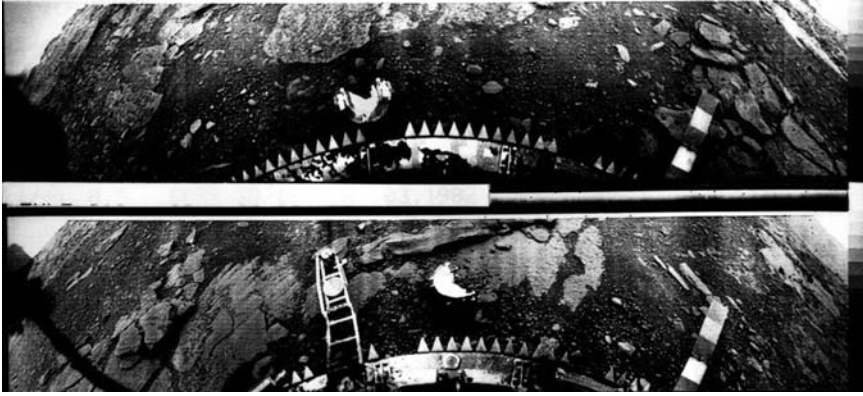


FIGURE 7.2. Venera 13 images of the surface of Venus. Flat rocks are seen to lie on top of a relatively smooth basaltic plain. Image courtesy of NASA.

mission to Venus in 1961 it became clear that the surface temperature was a staggering 464°C and that the surface pressure was nearly 100 times greater than that experienced at the Earth's surface.

By the close of the 1960s, it was clear that Venus was truly a dead world. Images of the Venusian surface obtained by the Russian space agency's Venera landers (Figure 7.2) revealed a sterile, scorched, desert-like landscape bestrewn with jagged rocks and flat-sided boulders. In some images (Venera 13 and 14) the surface rocks sit upon a flat basaltic plain, while in others (Venera 9) the rocks sit upon an apparently worn and weather-stained surface of soil and gravel.

Radar altimetry measurements obtained with the NASA Pioneer Venus Orbiter (1979–1992) and Magellan spacecraft (1990–1994) revealed the first detailed topological maps of the Venusian surface (Figure 7.3). These maps indicated that Venus has a surprisingly smooth and geologically young surface. Something like 70% of the surface is in the form of smooth, rolling plains, with the remainder being comprised of distinct lowlands and highlands. The highlands, or *Terrae*, cover about 10% of the Venusian surface, and four main continent-like regions are generally recognized: Ishtar, Lada, Aphrodite, and the Beta Phoebe and Themis region. Ishtar has an area similar to that of Australia and is mostly some 3 km higher in altitude than the mean planetary radius. It is bordered by numerous mountain chains, and at its

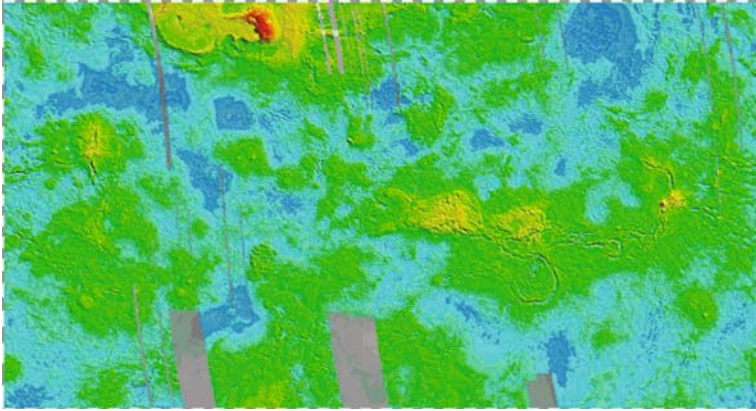


FIGURE 7.3. Topographic map of Venus showing the major highland regions. The map is based on radar observations conducted from the Magellan spacecraft. Image courtesy of NASA.

center resides the magnificent Maxwell Montes, extending upward to an altitude of some 11 km above the planet's surface.

The Himalayas and the 8-km-high Chomolungma were produced on the Earth by tectonic activity, specifically through the collision of the Indian plate with the Eurasian one, but no such plate motion is evident on Venus, and accordingly it is generally thought that the Maxwell Montes are supported by the vigorous convection associated with a fixed hot spot in the planet's mantle. Long, narrow linear features, called chasmas, that cover great swaths of the Venusian surface are also interpreted in terms of strong mantle convection effects. It is not entirely clear why no large-scale tectonic plate activity ever developed on Venus, but it is generally thought that the lack of water in its thick outer crust and the high surface temperature all combined to make for a surface that cracks more easily than that on the Earth. Rather than producing a few large tectonic plates that slowly move around, as on the Earth, the Venusian plates are presumed to have broken into many small pieces as a result of crustal cracking.

The Venusian lowlands, or Planitiae, are geologically young, featureless regions that appear to have formed through geologically recent large-scale basaltic flooding. These regions indicate, therefore, that extensive volcanism has shaped, and continues to shape, the surface of Venus. Indeed, the Magellan spacecraft radar survey

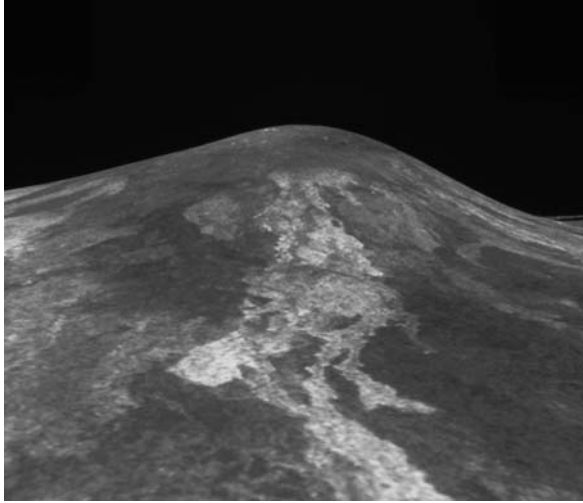


FIGURE 7.4. The Venusian volcano Sif Mons. Named after the wife of the Norse god Thor, Sif Mons stands some 2-km high and is about 95 km across at its base. A series of dark and light lava flows extend away from its summit. The image was created from the radar survey data gathered by the Magellan spacecraft. Image courtesy of NASA.

has revealed many volcanic features (Figure 7.4) on Venus that are variously described according to their size and appearance as anemones, ticks, arachnids, and pancake domes. River-like features have also been imaged at radar wavelengths on the planet's surface, and while they cannot be the result of running liquid water it is thought that they might be produced by a fluid derived from the mineral carbonatite, which has a melting point just below that of the planet's surface temperature. In addition, the spacecraft surveys also revealed that all of the Venusian terrain having an altitude greater than about 2 km is highly reflective at radar wavelengths. This odd and unexpected effect is thought to be due to a snow-capping effect, not of ice but of elements such as tellurium (Te) and iron pyrites (FeS)—more commonly known as fool's gold on the Earth—and a lead-based bismuth sulfide (PbS), which are able to condense at the temperatures and pressures that prevail above the 2-km altitude mark. The various Venusian features revealed by the space-based radar studies are shown schematically in Figure 7.5.

It is generally thought that the Earth and Venus formed under similar circumstances within the solar nebula some 4.56 billion

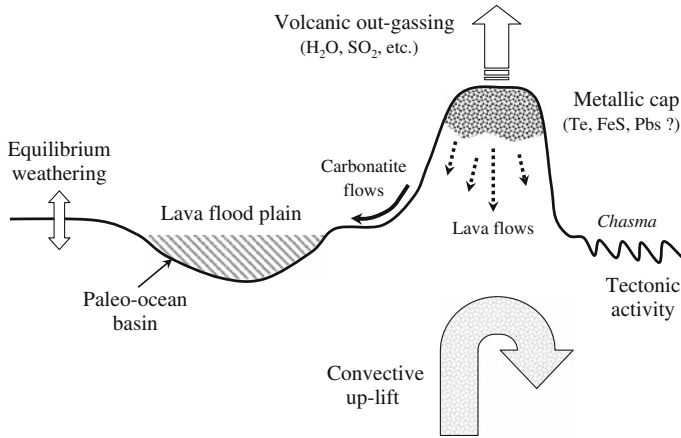


FIGURE 7.5. Schematic illustration of the geological and chemical activity observed, or deduced to be active, on the surface of Venus.

years ago. Accordingly, Venus should have an interior composed of a hot and partially molten high-density nickel-iron core, occupying about half of its interior by radius, and an overlying crust of low-density silicate rocks. Indeed, the mean density of Venus (5243 kg/m^3), being some 95% of that for the Earth, is consistent with this picture of an interior arranged according to increasing material density. Unlike the Earth, however, Venus has no magnetic field, and this is probably a consequence of its very slow rotation (See Table 7.1). The Earth's magnetic field is produced deep within its molten core, where the mixture of positively charged ions, rotation, and convective motion combine to produce a magnetic dynamo. While Venus has a molten core, its glacially slow rotation rate (some $1/244$ that of the Earth's) is just too small for the dynamo mechanism to operate efficiently, and this means that the solar wind plows unhindered into the upper Venusian atmosphere.

The similarity of the circumstances of their origin within the solar nebula also suggests that, just like the young Earth, Venus probably had a massive liquid water ocean. There is no geological evidence to support the existence of a paleo-ocean in the form of, say, an ancient shoreline, but the observed deuterium to hydrogen ratio (D/H) is more than 100 times larger than that observed on the Earth and in meteorites, and this observation is generally

interpreted as indicating the presence of an early ocean. As Venus warmed the oceans would have evaporated, placing large quantities of water vapor in the atmosphere. The atmospheric water vapor would then interact with solar UV photons and become dissociated, with $\text{H}_2\text{O} + \text{UV photon energy} \Rightarrow 2\text{H} + \text{O}$. The hydrogen atoms, being much less massive than the oxygen atom, will eventually be lost into space since their typical velocity will be greater than the planet's escape velocity (see Figure 5.11). Deuterated water molecules (D_2O) will also be split apart by solar UV radiation, but since deuterium is much heavier than hydrogen, less of it will be lost from the atmosphere per unit time, and consequently the D/H ratio will slowly increase over the millennia.

The Moist Greenhouse Effect

The process by which Venus lost its initial water ocean is slightly more complicated than the straightforward evaporation of H_2O and its dissociation in the upper atmosphere. Indeed, the loss of the oceans of Venus is believed to have been a runaway catastrophe called the moist greenhouse effect. The amount of water vapor in the young Venusian atmosphere would have been controlled by the evaporation rate of the oceans, but since water vapor is a very efficient greenhouse gas, a positive feedback cycle is readily established. In this manner, a small increase in the atmospheric temperature results in a greater ocean evaporation rate, which places more water vapor in the atmosphere, which then warms further, and so on—an unstoppable runaway evaporation of the oceans will set in. Ultimately, the oceans will be entirely denuded and in essence they will have become airborne, making for a very hot, steamy Venusian atmosphere. Atmospheric water vapor will be dissociated into its three components, with the two lighter hydrogen atoms being lost to interplanetary space (recall again, Figure 5.11).

Of great importance to the debate concerning the possible existence of life in the young Venusian oceans is, "How long did it take before the oceans were boiled away?" Various estimates concerning this time interval have been published. Andrew Ingersoll (California Institute of Technology, Pasadena), interpreting the

most recent results from the ESA Venus Express spacecraft, has suggested that it might have taken about 1 billion years after their formation for the Venusian oceans to have evaporated away. This is an uncomfortably short time for life to have evolved, but not an impossibly short one.

David Grinspoon (Denver Museum of Nature and Science, Colorado) has argued, however, that the Venusian oceans could have realistically survived for more than 2 billion years, which allows for life to have possibly evolved on Venus on a similar time-scale to that in which it appeared on the Earth.⁴ Greenspoon and fellow researcher Mark Bullock (Southwest Research Institute, Boulder) further point out that there is a possible test for determining how long the Venusian oceans might have survived. Key to the proposed test is the mineral tremolite, which is a metamorphic silicate rich in calcium and magnesium that forms in the presence of water. Since the temperature-sensitive weathering rate of tremolite is known from laboratory studies, it can be used as a chemical clock to determine when the oceans finally evaporated. A further, particularly interesting, point about the tremolite test is that it could be performed *in situ* by a robotic Venusian Lander. There are currently no funded missions for a Venusian Lander or sample-return mission, but the case for funding such missions within the next several decades is growing.

Cloud Life

With the realization in the 1950s and 1960s that Venus was not, in fact, a botanically lush, soda-water soaked, habitable world, it became the subject of the first semidetailed, peer-reviewed scientific publication concerning terraforming. Indeed, American astronomer Carl Sagan, whose terraforming ideas we first encountered in the Chapter 6, speculated in a remarkable 1961 review paper on the possibility that Venus could be transformed into a new Earth (see Note 2). Sagan's paper, which was published in the prestigious journal *Science*, was mostly concerned with the Venusian atmosphere and what the Soviet-launched Venera spacecraft might observe during their specific encounters. His paper ended, however, with a far-reaching discussion on the possibility that life might

have evolved in the ancient Venusian oceans. Realizing that surface life would no longer be possible on Venus, Sagan speculated that there was still a “distinct possibility of biological contamination of the upper Cytherean (see Note 1) atmosphere.” Microbial life, he argued, may have literally taken to the skies and found an Aeolian home in the region between about 40 km and 60 km altitude, where the temperature varies between the freezing and boiling points of water and where the atmospheric pressure is similar to that at the Earth’s surface.

Working with Harold Morowitz (Yale University), Sagan published a second paper on Venusian cloud life in September of 1967, and in this work it was argued that a photosynthetic microorganism constructed as a “float bladder” or as a “hydrogen gasbag” might reasonably eke out a cloudtop existence. (Sagan also suggested that floating life forms might exist in the upper cloud deck of Jupiter, as will be discussed in Chapter 8.) In 2002, Dirk Schulze-Makuch and Louis Irwin (University of Texas at El Paso) picked up on the idea of Venusian cloud life and specifically noted that its atmosphere lacks large amounts of carbon monoxide (CO), a gas that should be produced copiously by, for example, lightning. In addition, they also note that carbonyl sulfide (COS), which is exceptionally difficult to produce inorganically, has been detected within the veiled planet’s atmosphere.

Schulze-Makuch and co-workers have argued that these combined observations indicate that there must be a colony of microbes living within the cloud deck, at about the 50-km altitude region, which is removing CO but adding COS. Although there is no universal consensus that this interpretation of Venusian atmospheric chemistry is correct, the Swedish space agency has become sufficiently excited by the possibility of cloud life that it is looking for international partners to help develop an atmospheric sample-return mission to our nearest planetary neighbor.

The possible existence of Venusian cloud top life may be answered in the relatively near future—time will tell. However, Sagan, in his 1961 review paper, suggested that if indigenous cloud life didn’t exist, then Venus might be terraformed through the introduction of appropriately chosen microbes into its upper cloud deck. Specifically, Sagan argued that microbes that could undergo photosynthesis to produce O₂ via the reaction

$\text{CO}_2 + \text{H}_2\text{O} + \text{light} \Rightarrow (\text{CH}_2\text{O}) + \text{O}_2$ were required. Eventually, the microbe would go through its life cycle and upon death sink through the atmosphere to become roasted in the lower atmosphere. At this cremation stage, the reaction $(\text{CH}_2\text{O}) + \text{heat} \Rightarrow \text{C} + \text{H}_2\text{O}$ would operate to return water to the atmosphere, and, importantly, it would also act to dissociate carbon dioxide into carbon. The end result of this microbial engineering would be to bring down the carbon dioxide content of the atmosphere, but at the same time build up the oxygen abundance. Sagan then argued that the reduced CO_2 content would result in a weakening of the greenhouse-heating effect, and the planet would begin to cool.

The argument was deceptively simple, and a whole cottage industry arose with numerous variants of the microbial terraforming idea being developed. Indeed, the small and miniscule were apparently destined to inherit the surface of a new Venus, and humankind would follow their pioneering path shortly thereafter. It all seemed too good to be true—and, of course, it was. The problem is that Venus is currently an exceptionally dry world, and the initial photosynthetic stage as envisioned by Sagan was simply not going to happen naturally.

Although water is an extremely scarce resource in the Venusian atmosphere, this does not mean that microbial life can't possibly exist. Indeed, acid life is entirely possible, and sulfuric acid is in abundant supply in the Venusian cloud deck. In the absence of water, sulfuric acid can act as a medium to support life, and some researchers have suggested that bacteria similar to *Picrophilus Torridus*, which thrives in hot sulfur springs on Earth, may be found in the upper Venusian cloud deck. If cosmic life is as tenacious as life on the Earth appears to be, then the veiled planet may yet harbor our closest extraterrestrial cousins. Time, of course, will tell if this is the case, but what is most heartening is that the answer to this question may be available to us before the mid-way point of this century.

Perelandra Remade

The Venus that has emerged from the multitude of observations gathered during the past several decades marks the planet out as a very different world from Mars, and accordingly the terraforming

processes that will be developed on the Red Planet will not work on the Earth's twin. Indeed, the transformation of Venus into a habitable domain will require that the following actions be taken:

1. The planet's atmosphere must be cooled down.
2. The planet's atmospheric mass must be reduced.
3. Most of the atmospheric CO₂ must be removed.
4. Water must be imported to the planet.
5. (The planet's rotation rate must be increased.)

Conditions 1 and 2 follow from a glance at Figure 5.8, and the end result of this part of the terraforming process will be to enable liquid water to exist on the planet's surface. Condition 3 is mostly a response to the ideal of making the Venusian atmosphere breathable for humans.

Condition 4 must be satisfied in accordance with conditions 1 and 2 and is a response to the fact that Venus is an exceptionally dry planet, there being virtually no H₂O observed in its atmosphere. This being said, scientists analyzing the ESA Venus Express spacecraft data announced in February of 2008 that water vapor certainly exists in the planet's lower atmosphere (in the 30–40 km altitude range). Condition 5 is something that might be attempted in order to enhance the biotic potential of a terraformed Venus.

Just as we have seen in the last chapter when discussing the terraforming of Mars, a combination of processes and actions will likely be required to make Venus a potentially habitable planet. A few of the possible options that various researchers have presented for the terraforming of Venus are outlined below.

Atmospheric Blow-off, Cooling, and Mining

Although Table 7.1 makes it seem as though Venus has many similarities with Earth, it actually differs greatly from our home world in not having a natural satellite. Our Moon was produced within the first few million years of the Earth's formation and is most probably the result of a glancing blow struck by a wayward Mars-sized proto-planet (Figure 7.6). As a consequence of this impact, material ejected from the mantle mingled with the debris from the disrupted proto-planet and formed a ring of boulders and



FIGURE 7.6. A Mars-sized proto-planet collides with the young Earth to produce our Moon. Similar such impacts appear to have taken place on Mercury and Venus, which both disrupted the majority of the former planet's outer mantle and tipped the spin axis of the latter over by nearly 180° . Artwork by Lynette R. Cook, for the Gemini Observatory, Hawaii.

dust around the Earth, from which the Moon was able to coalesce and grow. Indeed, it is perhaps appropriate that our terrestrial muse of romance and love was formed through the fleeting union of two colliding bodies.

No permanent moon resides in orbit around Venus, but the planet has nonetheless undergone some of the same intensive battering that produced our Moon. That Venus must have suffered a massive collision or close encounter with a large planetesimal shortly after it formed is betrayed by its high obliquity (177.36° ; see Table 7.1) and resultant retrograde spin. For, indeed, to tip the planet's spin axis over from the expected $\sim 0^\circ$ obliquity to its observed value requires a close encounter with an object comparable in mass to Mars (that is, $\sim$ one-tenth the mass of the Earth; see Table 6.1) is required.

If, as is apparently the case, massive collisions were an important agent in shaping the properties of the young terrestrial planets, then, as many researchers have suggested over the years, why not

engineer additional collisions to shape their future properties? It is now known, for example, that there is an abundant supply of multiple 100-km-sized bodies in the outer Solar System, the Kuiper Belt objects (KBOs), that could be utilized as celestial cannonballs.

Made predominantly of water ice and silicates, the orbits of some of these KBOs could be altered to produce either direct or grazing collisions with Venus. Direct collisions would result in the ejection of atmospheric gases, while grazing, that is, off-center collisions, could be arranged so as to increase the planet's spin rate, or to generate a planet-encircling ring of material or numerous small Venusian moons.

Direct impacts onto the Venusian surface could partially satisfy conditions 2 and 3 of the terraforming requirements listed earlier, although the process is not likely to be overly efficient. At best, a large impact could eject the atmospheric material located above the so-called tangent plane (see Figure 7.7). In the early 1990s, Sagan and his former student, the late James Pollack, estimated that perhaps a few ten-thousands of the mass of the Venusian

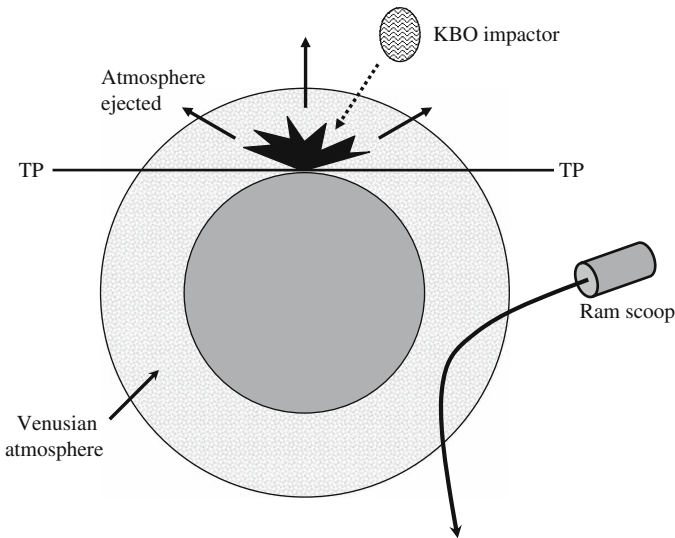


FIGURE 7.7. Atmospheric-mass-reducing scenarios. Large impacts can at best eject the atmospheric material situated above the tangent plane (TP-TP). The ramscoop would make multiple passes through the atmosphere before taking its cargo to another location in the Solar System, possibly the Earth's Moon (as described in Chapter 8).

atmosphere might be ejected during a large body impact. This result indicates that multiple thousands of impacts would be required to reduce the planet's atmospheric mass to something similar to that of the Earth's. There is a ready supply of KBOs within the outer Solar System that might be diverted to achieve this end, but one is left somewhat uncomfortable at the possibility of so many impacts being engineered on a body that has an orbit inside of the Earth's. Certainly a few impacts might well be arranged, but perhaps atmosphere mining via ramscoops (Figure 7.7) is a more esthetically pleasing and practical solution⁵ to the problem of reducing the planet's atmospheric mass.

Rather than engineer thousands of direct KBO impacts onto Venus to reduce its atmospheric mass, it might be more practical to engineer a few grazing impacts to generate a circumplanetary debris disk. Such a disk might then be maintained through the addition of material mined from the asteroid belt to produce a partial sunscreen over the equatorial regions of Venus. This would have the effect of cooling the atmosphere through a reduction in the solar insolation.

As such, the formation of a circumplanetary debris disk won't appreciably reduce the mass of the Venusian atmosphere, but its cooling effect might well be important in the long-term maintenance of a terraformed atmosphere (as described below). In fact, an asteroid-debris ring located about the Earth has been described by Jerome Pearson and co-workers (Star Technology and Research, Inc., Mount Pleasant, South Carolina), who suggest that such a structure might be used to offset global warming. This approach also reduces the potential asteroid-impact risk on the Earth (as well as on Venus if the idea is adopted there, too), since the best material to utilize in the ring construction is that which comes naturally close anyway.

An alternative debris cloud method for cooling Venus was proposed in the early 1980s by Christian Marchal (Office National d'Etudes et Recherches Aerospatiales, France), who advocated the destruction of one or more asteroids at the so-called Venusian L_1 point. The first Lagrange⁶ point (L_1) is located on the Venus-Sun line at the point where the gravitational attractions of the two bodies, on a zero-mass test particle, are equal and opposite in the rest frame rotating with the planet. Accordingly, the L_1 point is

located about 1.03×10^6 km, or 169 planetary radii, away from the center of Venus.

The reason for engineering a debris cloud at L_1 is that it is a relative good spot with respect to stability. Material placed at L_1 tends to stay close to L_1 . The material will eventually drift away from the L_1 position, but the residency time there should last for at least a few years. This latter point unfortunately means that the debris cloud will need to be repeatedly replenished, but, on the brighter side, there is a large reserve of asteroids within the Solar System. Just as with the collisional induction of Venusian atmosphere loss, the debris cloud at L_1 cooling idea also lacks esthetic appeal, but sometimes brute force is the only cost-effective way of getting the job done.

The most recent incarnation of the debris cloud-shielding concept, developed again as a means for offsetting global warming, is that proposed by astronomer Roger Angel⁷ (University of Arizona, Tucson). Rather than produce an asteroid debris cloud, however, Angel proposes to launch a swarm of some 16 trillion pico-sats (that is, small, semi-autonomous satellites that are just a few tens of centimeters across), each weighing in at perhaps 1 gram, to the Earth's L_1 point (see Figure 7.8). Each of the Sun-fliers, as the pico-sats have been called, will have fins that can be controlled to maintain an L_1 location for periods of perhaps up to 50 years, and the combined swarm of Sun-fliers will cover an approximately rectangular area with sides 6,200 km by 7,200 km.

The cost of constructing a pico-sat swarm to stave off the effects of global warming are clearly going to be large, and Angel estimates that it would carry a price tag of perhaps a few trillion dollars spread over a time interval of several decades. (The cost is equivalent to about 10 years' worth of the current annual US Defense Department budget.) Compared to the accumulated costs that will likely result from the damages wrought by unchecked global warming, however, the price tag for the swarm is actually a very competitive one. One would hope that by the time the terraforming of Venus begins, perhaps several hundreds of years from now, the cost of manufacturing the individual fliers and the expenditure of launching them will have fallen dramatically from those of the current day. Time, of course, will tell how this particular technological approach to solving global warming, and possibly the cooling of Venus, will play itself out.

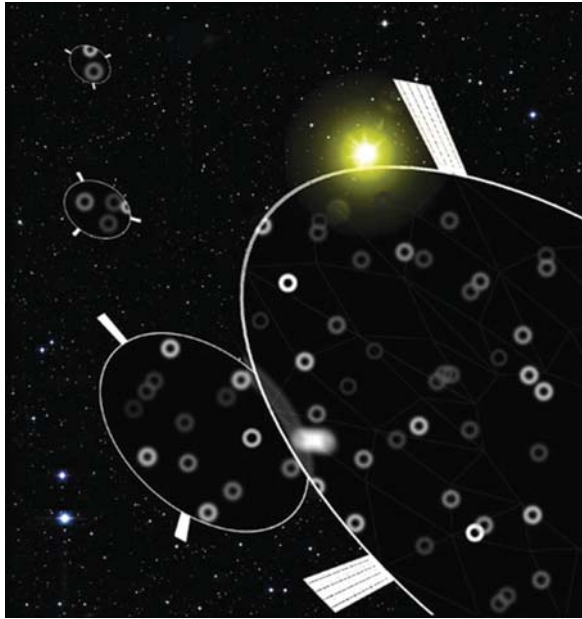


FIGURE 7.8. Artist's impression of Sun-flier pico-satellites. Each flier is equipped with small fins to allow for orbit and orientation control, and in this illustration consist of a transparent substrate that spreads any incident light into a diffuse ring. A swarm of some 16 trillion such pico-sats could be placed at the Earth's L_1 point and collectively act as a giant solar shade (or more correctly a giant solar light diffuser), alleviating the effects of global warming. A similar such swarm of pico-sats placed at the Venusian L_1 could be used to cool its atmosphere. Image courtesy of the University of Arizona and Steward Observatory.

Roman Blinds, Spin Up, and Spin Apart

Before moving on to discuss how the present atmosphere of Venus might be made breathable for humans, there is one additional topic, related to the collisional impacts issue discussed earlier, that should be addressed. This concerns the incredibly slow rotation rate of Venus, equivalent to a slothful 224.7 Earth days (see Table 7.1).

To a certain extent, the slow rotation may be a nonissue, but many researchers have suggested it might be desirable to increase the Venusian spin to something like that of the Earth's. Here the idea is that many terrestrial plants and crops do not grow well in permanent daylight conditions. This is likely a problem that can

presumably be solved by genetic modification, and we should also note that initially all the food crops will be grown in artificial environments where the outside light can be easily controlled. If one does wish to produce a more rapidly spinning Venus, however, then it had better be done early on in the terraforming stage, before human colonization has begun.

Perhaps the simplest way to both cool Venus and induce an artificial day/night cycle shorter than the natural one (a period equivalent to 116.75 Earth days) is to place a louvered sunshade or variable transparency parasol at the Venusian L_1 point. A circular parasol located at the Venusian L_1 point would need to be about 25,000 km in diameter in order to completely obscure the Sun. This is a colossal size, over twice that of the planet itself, and a poignant reminder of just how complex the engineering and material resource requirements for terraforming Venus will be. By introducing a variable transparency or louvered system the sunlight levels on the daylight hemisphere of Venus could be turned on and off as required. On the night-side hemisphere of Venus, however, one would have to use either a series of orbital mirrors to reflect sunlight onto inhabited regions, or rely solely on artificial lighting.

The most basic spin-up mechanism would be one resulting from glancing impacts. This is not a mechanism that is active now, but when the Solar System was newly formed (4.56 billion years ago) and the planets themselves were still growing through accretion, there were many large, multithousand kilometer-sized objects moving along dynamically unstable orbits around the Sun. Indeed, the origin of Earth's Moon, the large obliquity of Venus along with its slow rotation rate, the relatively large iron core of Mercury, and the high obliquity of Uranus are all attributed to off-center impacts from large proto-planetary bodies that occurred late in the planetary formation stage.

Arranging collisions from large, several hundred kilometers in diameter KBOs is probably the most straightforward way to increase the spin rate of Venus.⁸ Indeed, there is much to recommend the collisional method for partially denuding the Venusian atmosphere, spinning up the planet, and potentially generating Venusian moons and/or an equatorial debris shade. Certainly, the directed-impacts method smacks of a rather Neanderthal approach, but it is nonetheless a highly practical way of achieving some of the

desired initial goals in the terraforming of Venus. There is a ready supply of large KBOs in the outer Solar System to perform the task at hand, and the essential technical means of altering and guiding an impactor's orbit are already known to us in principle. The practical ability to realize the required engineering, however, is still likely to be many centuries away—a further indication, if one was actually still needed, that the terraforming of Venus will not be a quick or easy task.

Directed collisions are by no means the only ways by which our descendants might spin-up Venus or for that matter an asteroid, satellite, or other planet. Freeman Dyson (Institute for Advanced Studies, Princeton), who is never afraid of thinking both big and bold, suggested in the mid-1960s that an electric motor arrangement could be engineered to increase the spin rate of a planet. His starting point for the idea came about from thinking about how the existence of a technically advanced extraterrestrial society might be recognized. This line of thinking eventually led Dyson to the idea of what are now called Dyson spheres and the concept of what are known as Kardashev Type II civilizations.⁹

Since an advanced civilization would undoubtedly require a vast resource of raw material, it seemed reasonable to conclude that it would develop the means of disassembling large asteroids and possibly even planets (planets, presumably, that is, not required for terraforming). Rather than disassemble such objects by direct mining, Dyson reasoned that it would be simpler for the asteroid or planet to disassemble itself. This self-destructive step could be achieved, he argues, by inducing rapid spin. Indeed, if the centrifugal force due to rotation exceeds the tensile strength of the material body, then the body will literally fly apart, and this is what Dyson had in mind. In a somewhat medieval sense, it might be said that this mechanism literally flogs itself to death.

The full physical details of the Dyson motor need not concern us here,¹⁰ but the idea is to turn the planet (or asteroid) into a giant electric motor. Indeed, by generating very specific magnetic field topologies around the object to be spun up and by placing numerous electrical generators in orbit around it, the planet/asteroid will behave like a massive armature. At this stage, suffice it to say, the end result of the engineering is that angular momentum is transferred to the entrapped body, and it will begin to spin faster.

Eventually the spin limit, the point at which the object flies apart, will be achieved, and the assorted pieces can then be captured and further processed into building material.

Dyson's idea is certainly elegant, but it seems overly complicated. Although the directed-collision approach can achieve the same end goals more simply than the Dyson motor in the asteroid or small moon disruption cases, the physical destruction of a planetary-sized object, should this ever be desired, may well have to proceed by a method such as that proposed by Dyson.

Back to Basics

Rather than reduce the mass of the Venusian atmosphere by external means, by, say, collisions or ramscoop mining, our descendants might try to make the atmosphere shed its own mass. In a somewhat counter-intuitive manner, this effect, it turns out, can be achieved by adding molecular hydrogen (H_2) to Venus's atmosphere. This scenario was first discussed by American author and NASA engineer James Oberg in the early 1980s and developed more fully by British terraforming expert Martyn Fogg in the late 1980s.

The Oberg-Fogg process for terraforming Venus begins in a similar fashion to that envisioned by Carl Sagan in the early 1960s. Through the addition of, for example, cyanobacteria into the upper atmosphere of Venus, its CO_2 is broken down through photosynthesis to produce oxygen (O_2). Rather than letting the O_2 simply accumulate, however, the simultaneous importation of hydrogen (H_2) into the atmosphere will enable water vapor (H_2O) to form (see Figure 7.10). The process then becomes self-supporting, with the H_2O enabling the cyanobacteria to thrive and perform photosynthesis, thereby producing more O_2 that will combine with the imported hydrogen to make more water, and so on. This part of the terraforming process will require the importation of a lot of hydrogen. Oberg estimates that some 4×10^{19} kg of hydrogen will be required to complete the job, and he further suggests that the hydrogen might be mined from the atmosphere of Saturn. Fogg points out, however, that it might be slightly easier to mine the hydrogen from the planet Uranus, since it is a less-massive planet and therefore easier to escape from. Fogg also envisioned a whole

fleet, perhaps swarm is a better descriptive term, of autonomous robots being tasked with the goal of extracting and delivering the hydrogen to Venus.

As the atmospheric CO_2 continues to be broken down, carbon will begin to precipitate out of the atmosphere and accordingly begin to accumulate on the planet's surface. By the end of the atmospheric-conversion process, it is estimated that a layer of carbon some 100-m thick will have accumulated around the planet. This carbon layer need not be thought of as a waste product since, as geologist and science-fiction writer Stephen Gillett has pointed out, "With molecular nanotechnology carbon becomes the most valuable raw material."¹¹ Indeed, many of the construction materials of the future will likely be engineered according to nanotechnology principles, and, accordingly, a by-product process that produces large quantities of carbon can be considered a very definite bonus.

As the process of hydrogen importation continues, a massive steam atmosphere is eventually formed, and importantly this is the gaseous form of the new Venusian ocean to be. To produce Perelandra's new surface ocean, however, the atmosphere will have to be cooled, a process that will enable the steam atmosphere to first condense and then literally rain out.

The cooling of the Venusian steam atmosphere can be achieved by any of the shading mechanisms described earlier in this chapter—a large Roman-blind style solar shade placed at the Venusian L_1 point, for example. The important point here is that by totally removing the solar-heating effect, the steamy atmosphere can begin to cool and condense, eventually allowing water to rain down onto the planet's surface. Fogg estimates that perhaps as much as 1 m per Venusian surface square meter of scalding water per year will precipitate out of the atmosphere. After several hundred to perhaps a thousand years, large bodies of cool, liquid water will have been established under a predominantly nitrogen (N_2) and oxygen (O_2) atmosphere. At this stage, Venus is ready to be warmed up again and primed to be seeded with new life. The warming will be achieved by allowing some sunlight to reach the planet's atmosphere. This is where a louvered or Roman-blind style solar shade (Figure 7.9) will come into its own, since the appropriate level of solar insulation can be controlled in an ongoing fashion.¹² If the temperature of the new Venus is not controlled externally, then a moist runaway

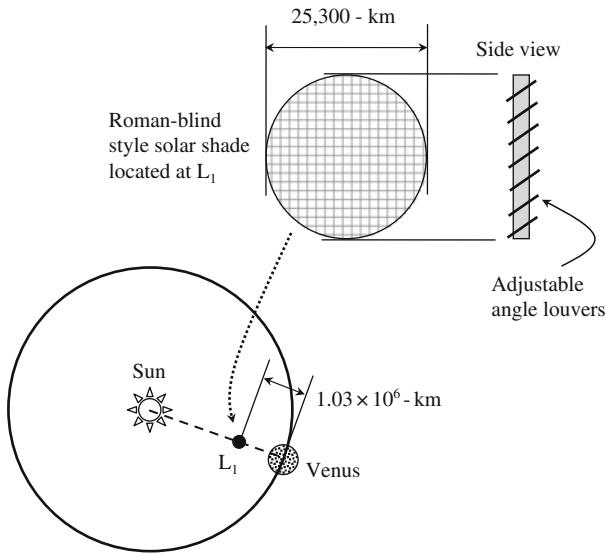


FIGURE 7.9. A Roman-blind solar shade placed at the L_1 point of Venus. In this form of solar parasol, the amount of shading could be precisely controlled by the angle louvers, varying from full eclipse when the louvers fully overlap to near-full illumination when they lie parallel to each other.

greenhouse effect will once again kill off the planet's potential to support surface water and life.

Getting CO₂ Stoned

In a series of three papers, each produced at intervals of about 10 years apart starting in 1981, Stephen Gillet has suggested that the Oberg–Fogg scenario might be modified with respect to its hydrogen-importation requirements. Indeed, he argues that perhaps only 10^{19} kg of H₂ might need to be imported (a quarter of the amount prescribed in the original scenario) to terraform Venus. The atmospheric carbon dioxide would still need to be reduced, however, and this Gillet suggests might be achieved by importing calcium (Ca) and magnesium (Mg) especially mined from the surface of Mercury (where a rich and relatively nearby supply of such materials can be found). Once the calcium and magnesium had been deposited within the Venusian atmosphere, Gillet envisions a two-step process that will take place, whereby, for example, two calcium atoms

will interact with an oxygen molecule to produce a calcium oxide (schematically: $2\text{Ca} + \text{O}_2 \Rightarrow 2 \text{CaO}$). The calcium oxide will then react with a carbon dioxide molecule to produce calcium carbonate (schematically: $\text{CaO} + \text{CO}_2 \Rightarrow \text{CaCO}_3$). A similar chain of reactions with magnesium will produce magnesium carbonate MgCO_3 . Through this chain of reactions, an inert carbonate dust will fall to the surface of Venus. Once the atmospheric CO_2 has been predominantly locked away in the carbonate layer, the final terraforming and seeding for new life phase can proceed in a similar manner to that described by Oberg and Fogg.

In many ways, the scenario outlined by Gillett reduces one importation problem (that of the H_2) only to replace it with another, potentially more severe, one (the importation Ca and Mg from Mercury). Certainly one might imagine that most of the work will be done by autonomous robot systems, but the process is perhaps a good deal less than ideal. Indeed, Gillett was well aware of this problem and consequently suggested in a paper published in 1999 that there is perhaps one way in which the entire Venusian atmosphere can be purged of its CO_2 without importing any additional elements. This rather miraculous possibility comes about through the production of a crystalline structure (yet to be synthesized in the laboratory) called carba.

The atomic structure of carba resembles that of the tetrahedral arrangement of carbon atoms in diamond, but in the carba situation each of the carbon-carbon bonds (C-C) are replaced by a C-O-C chain of bonds (the O being an oxygen atom). Gillett envisions that the carba might be grown, just as a mollusk grows in a calcium carbonate shell, by genetically modified microorganisms. These microorganism workers would be introduced into the Venusian atmosphere, grow their carba shells, and then upon completing their lifecycle fall to the surface of Venus, where they could be left to accumulate or mined for export as a raw material.

A Cold New Dawn

The scenario outlined above (Figure 7.10) for terraforming Venus is just one of the many that have been proposed. It is difficult to estimate exactly how long the precipitation process might take to transform

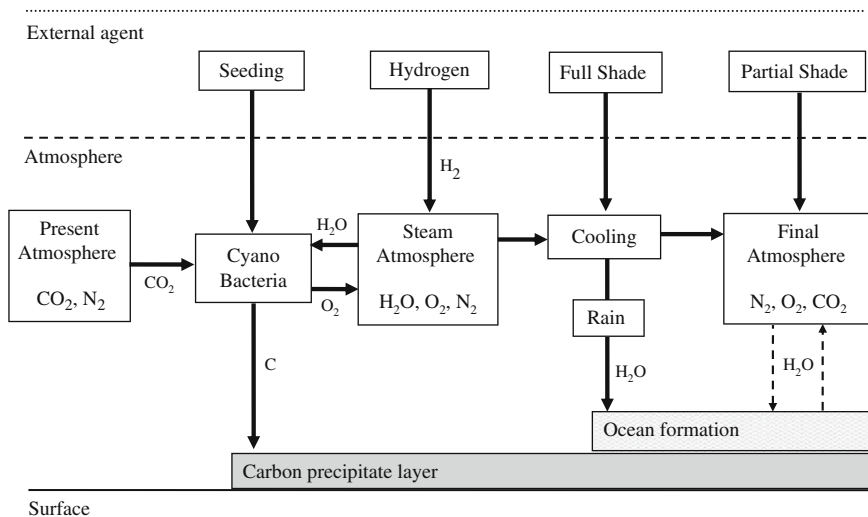


FIGURE 7.10. A schematic timeline (time increasing to the right) for the Oberg--Fogg terraforming scheme for Venus. The process begins by adding hydrogen and cyanobacteria to the present atmosphere and ends by evoking a "Big Rain" stage to produce a new Venusian ocean and a breathable atmosphere.

Venus, but somewhere between 10^4 and 10^6 years is the usual estimate of time required. Some researchers feel, however, that this sort of time scale is far too long, and accordingly they advocate the implementation of more rapidly acting terraforming schemes. British engineer Paul Birch, for example, has suggested one highly technical approach to terraforming Venus that begins with a massive atmospheric freeze out. For Birch, the terraforming process begins with the construction of a massive sunshade, located at the Venusian L_1 point, with the sole purpose of blocking out all of the incident sunlight.

Cloaked in the freezing darkness of permanent night, the Venusian atmosphere will begin to cool, according to Birch's calculations, at rate of about 5°C per year. Within 100 years, therefore, the temperature will have fallen to near 273 K (or 0°C). Birch further estimates that within 200 years of the beginning of the Venusian darkness the temperature will have dropped to a level at which the atmospheric CO_2 will begin to freeze out. In short order, a solid glacial blanket of carbon dioxide ice will coat the entire surface of Venus.

Birch further suggests that it would be wise to selectively illuminate the highland areas of Venus so that these could be colonized relatively rapidly. The driving idea here is that by allowing for some regions to be quickly inhabited and “worked” there would be some early return on investments process. However, this kind of activity commercializes the terraforming process. If humanity cannot move beyond its current focus on short-term investment and rapid-return economics, then it (and terraforming) has no future.

To continue with Birch’s scenario, after the freeze out has been completed, and before sunlight can once again be allowed to illuminate the planet, the CO₂ ice layer must be covered and insulated against subsequent sublimation. Birch suggests that this might be achieved by laying down a layer of linked, artificially produced hollow rocks. One might also initiate the large-scale exportation of CO₂ ice from the planet. Clearly, this latter process will consume a considerable amount of time, certainly longer than the initial few hundred years of the freeze-out phase. Birch’s argument, however, is that it can be achieved in an ongoing, expansive manner, with economics driving the process. Indeed, while Venus might be rich in CO₂ ice and mineral deposits after its freeze out, it will require the importation of massive quantities of water to support the Venusian colonies.

Surface Turnover

Perhaps the ultimate in collisional terraforming ideas for Venus is that proposed by British researcher Alexander Smith.¹³ Writing in the *Journal of the British Interplanetary Society*, Smith suggests that Venus might be pummeled by hundreds of specially constructed impact vehicles. With an eye to dealing with industrial waste, Smith suggests that these vehicles might be constructed in the outer regions of the Solar System and be composed of water ice and the mineral/silicate detritus from asteroid and outer-moon mining operations. Smith envisions the construction of some 200 impact vehicles, each weighing-in at an impressive 5×10^{18} kg.

Once the vehicles have been constructed, a massive engineering undertaking in its own right, the terraforming process begins by

inducing the standard long Venusian night via a solar parasol located at the L_1 point. Each impact vehicle is then directed through the Solar System to produce a series of withering explosions. The aim is not to specifically denude the Venusian atmosphere through the impacts (although this will take place) but to spin up the planet (as described earlier), to introduce vast quantities of water to the planet's surface, and to induce substantial surface turnover. Indeed, the hope is to initiate substantial volcanic activity. The reason for all this apparent planetary violence is to encourage the entrapment of atmospheric CO_2 in the Venusian crustal rocks. Essentially, the idea is to greatly increase the Venusian weathering rate and to thereby produce large quantities of carbonate rocks (recall Figure 7.13).

Smith further calculates that the ice component of his envisioned impact vehicles will provide enough water to produce both large and deep bodies of surface standing water. After perhaps 1,000 years, Smith estimates that the atmosphere will have cooled to about 40°C , and oxygen will have begun to accumulate in the atmosphere, now only partially eclipsed by the solar shade at L_1 , from water vapor dissociation via UV photons.

Although the impacts will rain down on Venus in rapid succession, Smith estimates that it might take between 15,000 and 30,000 years for Venus to become completely habitable. A less-explosive method than that proposed by Smith for the gardening of the Venusian surface was outlined by polymath Robert Freitas, Jr. (Institute for Molecular Manufacturing, California) in the mid-1980s. Writing in the *JBIS*, Freitas argued that the simplest way of turning over the top 100 km of the Venusian surface would be to send a fleet of what he describes as self-replication systems (SRSs) to do the job.¹⁴ These highly autonomous robotic systems would initially be launched as small seed systems that are programmed to build much larger factory systems once they arrive at their intended target. The SRS could be programmed to build, for example, greenhouse gas-producing factories on Mars, or burrowing excavators for turning over the surface of Venus; or, they could even manufacture Smith's impact vehicles in the outer Solar System. There seems to be absolutely no reason to doubt that advanced robotic, at least semi-autonomous systems will play an extremely important role in the future terraformers toolkit. Indeed, semi-autonomous robots

are at the very core of present-day planetary exploration, and, as such, it seems only natural to suppose that perhaps within the next several decades, the first self-repairing and then self-replicating spacecraft will be built and flown.

Flying High

Humanity is on the very cusp of beginning its expansion into the Solar System, breaking free, once and for all, from the nurturing bonds of the Earth. This coming-of-age liberation has seen its first baby steps over the past 30 years with the Apollo Moon landings (see Vignette E at the end of this chapter) and the construction of Skylab, MIR, and now the International Space Station (ISS). This list of small, temporary colonies in low-Earth orbit will soon be joined by commercially run space hotels (see Figure 7.11), and by the close of this century, it seems reasonably safe to conclude that the first generation of humans to be born, raised, and nurtured in large Earth-orbiting space structures, will have appeared.



FIGURE 7.11. The Bigelow Aerospace Genesis II prototype space hotel module. Successfully launched in June 2007, the test-bed inflatable cylindrical structure is 4.4-m long and 2.5 m in diameter. By 2012 Bigelow Aerospace plans to offer a 4-week orbital trip, the price of the holiday coming in at about \$500,000 a day.

With respect to terraforming, these present-day Earth-orbiting space stations are the forerunners of space stations that will eventually orbit other planets and moons. The workforce and planning offices during terraforming, for example, might initially be housed in such structures, and indeed the space tourism industry probably won't be too far behind. "Come see the re-genesis of Mars," or "Get your front row seats for the Venusian impacts! Book now for this Solar System spectacular," are some of the slogans and jingles that our descendents might eventually be subject to. Here, indeed, is a clear example of an evolutionary pathway for both technology and space infrastructure operations that will take us from the current ISS, in the here and now, to the first attempts at terraforming perhaps several hundred years hence.

Space stations will presumably become more than just research platforms and temporary housing structures in the future. Certainly, many futurists and science-fiction writers have envisioned the construction of large sky cities that might permanently house many thousands of people. Indeed, for the terraforming pioneers, living within the artificial confines of a sky city will not be significantly different from living within the artificial confines established on the planet's surface.

At the Space Technology and Applications International Forum held in Albuquerque, New Mexico, in 2003 engineer Geoffrey Landis (NASA Glenn Research Center, Cleveland) presented a paper suggesting that permanent sky cities might be constructed in the Venusian atmosphere in the 50-km altitude region, where the temperature falls between 0° and 100°C. At this location the atmospheric pressure is similar to that at the Earth's surface, and while the inhabitants would need breathing apparatus outside of the city structures, they wouldn't require pressurized suits. The cityscape zone is the same region, as described earlier, in which the microbial seeding, leading to the terraforming of Venus, might eventually take place, and sky cities (even if enshrouded in full eclipse) would presumably make ideal locations from which to initiate and monitor the progress of the atmospheric conversion. One would have to be careful, however, since as Landis notes in his exploratory document, the city zone at 50-km altitude partially works because of the buoyancy support provided by the underlying Venusian atmosphere. Remove the buoyancy, and the cities will come a tumbling down.

A Distant Dawn

Although Venus is about twice the size of Mars (four times the surface area), the effort needed to terraform it will, as we hope this chapter has made clear, be many orders of magnitude greater than that required to make the Red Planet habitable. Indeed, it is not at all clear that it will make sense, or indeed that the technology will exist to terraform Venus immediately after the terraforming Mars. It might well be the case that the asteroid belt and the moons of the Jovian planets will be colonized before the technology exists to make Venus habitable.

Vignette E: Back to the Moon

Plans to renew and revitalize the human exploration of space were announced by US President G. W. Bush in 2004.¹⁶ At the heart of this new exploration directive is the aim of ultimately sending

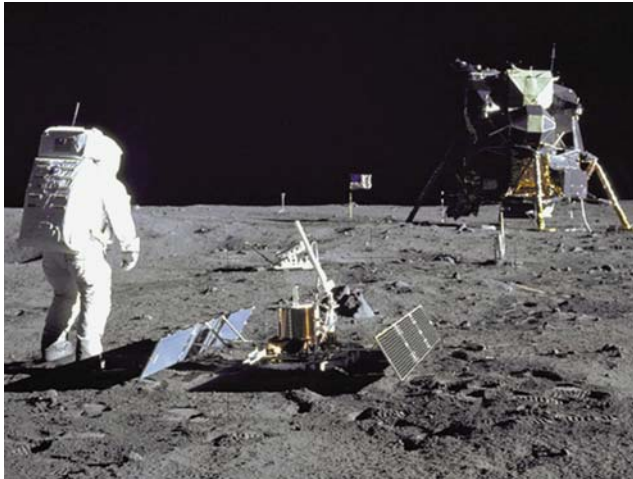


FIGURE 7.12. Astronaut, and first human to walk on the Moon, Neil Armstrong took this photograph of fellow lunar explorer Buzz Aldrin during the Apollo 11 mission at the Sea of Tranquility. The lunar module Eagle can be seen in the background, while Aldrin stands by the Passive Seismic Experiment Package. The third member of the Apollo 11 crew, astronaut Michael Collins, remained in lunar orbit aboard the command and service module Columbia. Between 1969 and 1972, a total of 12 astronauts walked upon the Moon's surface. For the last 35 years, however, manned spaceflights have been limited to low-Earth orbit.¹⁵ Image courtesy of NASA.

astronauts to explore Mars. The first steps in this great adventure, however, call for the establishment of a permanently occupied Moon base. The NASA strategy, announced in December of 2006, established the goal of returning astronauts to the Moon by 2020. The longer-term goal is to establish a self-sufficient Moon-base colony that will allow astronauts to establish mining operations, perform scientific research, and hone their skills for the eventual push toward planet Mars.

A quick glance at Figure 5.3 indicates that the Moon undergoes a wide swing in surface temperature (due to its very slow rotation and lack of atmosphere). At the Moon's poles, however, the temperature modulation is much smaller, amounting to about 35° . This moderated temperature environment makes the polar regions ideal locations for a lunar base. The Moon's south pole is of particular interest, since a vast impact-generated depression (the Aitken Basin) is located there, and the Earth-based radar observations indicate that vast water-ice deposits might exist within it. Indeed, the upcoming Lunar Crater Observation and Sensing Satellite Mission (LCROSS), scheduled for launch in October of 2008, is being flown in order to quantify the amount of water-ice that exists at the Moon's poles. The LCROSS spacecraft will observe the impact of an upper-rocket-stage crashing on purpose into one of the poles, allowing for observations of the impact plume to be made. The spacecraft itself will also eventually strike the Moon, enabling the Earth-based observers to view its impact plume. Water is clearly a valuable resource that any permanent Moon base will require, not just for drinking and agriculture but also for the generation of hydrogen and oxygen. It has been suggested that semi-autonomous mining robots might not only extract water-ice from the Aitken Basin region but also Moon rocks and regolith, which are rich in oxygen, titanium, iron, and aluminum.

The 19-km wide, 2-km deep Shackleton Crater, located inside the south polar Aitken Basin, has been proposed as one site for the first Moon base (see Figure 7.13). The Moon's rotation axis passes, in fact, through the rim of this crater, allowing for the permanent illumination of some segments of its outer ramparts. This permanently sunlit region will be ideal for the situation of habitation modules, since solar arrays will be able to generate power continuously. The design of the habitation structures has not been



FIGURE 7.13. Shackleton crater, one of the proposed locations for the first permanently occupied Moon base. Situated inside the Moon's south polar Aitken Basin (one of the Solar System's largest impact structures, the crater is some 2,400-km across and 12-km deep). Part of the Shackleton crater rim is in permanent sunlight (lower left of image), and this would be the location of the habitation modules. Deeper into the crater there are regions cast into permanent darkness and these will be ideal locations for deployment of astronomical science stations. Smart-1 spacecraft image courtesy of ESA.

finalized, but they may resemble the pressurized modules presently being used in the International Space Station (ISS).

Also envisioned are large inflatable structures made of Kevlar-toughened fabrics. Not only will the habitation modules have to provide a breathable atmosphere for the astronauts, but they will also have to provide protection from cosmic rays and solar radiation (since the Moon has no protective magnetic field or atmosphere), as well as protection from the continual rain of micrometeoroids that pummel the Moon's surface. One proposal for advanced protection calls for the habitation structures to be buried under layers of lunar soil. An overview of possible building and construction concepts has recently been published by Haym Benaroya (Rutgers University) and Leonhard Bernold (North Carolina State University), who

argue that a concurrent engineering approach will be needed on the Moon.¹⁷ This construction approach simultaneously considers system design, as well as manufacturing and construction techniques, in parallel with the building schedule.

Although the Moon cannot be fully terraformed because of its low gravity, its colonization clearly forms a very important first step in the development of our future terraforming skills. There is already a clear chain of experience and skill-set development emerging from the present use of ISS-habitation modules to lunar-habitation modules (by 2025), then to the first journey of humans to Mars¹⁸ (by 2031), and the eventual initiation of terraforming Mars (perhaps by 2150). The dates by which the various steps might be achieved are highly uncertain, but they set a potential timeframe, and it is not inconceivable to think that the children of our children will be among the first permanent residents on the Moon.

Notes and References

1. C. S. Lewis, *Perelandra: Voyage to Venus*. HarperCollins Publisher (1943). *Perelandra* is the second book in the science-fiction trilogy written by Lewis. The first book, *Out of the Silent Planet*, concerns a voyage to Mars (or Malacandra, as Lewis called it), while the final book, *That Hideous Strength*, is set upon Earth.
2. In his *Science* review paper of March 1961 (volume 133, 849–858) Carl Sagan argued with some passion that the term Venusian was entirely incorrect. “We do not say Sunian or Moonian, or Earthian,” he noted, and indeed, this is so. Sagan suggested, and used throughout his review, the adjective Cytherian, since this was the Ionian island upon which the mighty Aphrodite is said to have emerged. In spite of Sagan’s well-reasoned argument, the term Cytherian has not caught on, rightly or wrongly, in the general literature, so we have kept to the word Venusian.
3. Tellurium is a silver-white metal commonly used in semiconductor devices and has a melting point of 722.66 K. It is often written that the surface temperature of Venus is greater than that of the melting point of lead. This statement, while true, is not particularly useful, since lead actually melts at a temperature of 600.61 K, a temperature some 136° cooler than the surface temperature of the planet.

4. In a highly influential paper published in the journal *Icarus* [Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. **74**, 472–494] in 1988 James Kasting (Pennsylvania State University) developed one of the first detailed models describing the characteristics of the moist runaway greenhouse effect. He suggested that the initial oceans on Venus might have survived *for a minimum time* [my italics] of about 600 million years. Most people who have read Kasting's paper since, however, have forgotten that he derived a minimum time for the oceans to evaporate. The time estimate is a minimum since Kasting intentionally left out from his model the cooling effects of clouds. If one allows for clouds to reflect more of the Sun's radiant energy back into space, then the oceans of Venus might reasonably survive for several billion years. Likewise, the often-projected demise of the Earth's oceans in about 1 billion years from the present is a minimum time, and it might not occur for perhaps 2 or 3 billion years even if nothing is done to cool the Earth down via the use of sunshades and/or the many other geoengineering options described in the Prolog and Chapter 4.
5. When it comes to terraforming, esthetics should not dominate our thinking. At the end of the day, humanity will have to get down and dirty. You cannot change a planetary atmosphere without making a great deal of mess first. The only proviso is, of course, that the initially induced chaotic mess will ultimately end in a beautiful result.
6. First described by the Italian-French mathematician Joseph-Louis Lagrange, the five Lagrange points identify the locations where a small mass moving under gravity alone can remain stationary with respect to two larger objects. They represent special-case solutions to the three-body gravitational problem.
7. Roger Angel, Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Science* **103**(46): 17184–17189 (2006).
8. Key to determining the effects of an impact is the angular momentum transfer. The angular momentum of the impactor is given by the expression $M_I V_I d$, where M_I is its mass, V_I is its impact velocity, and d is the offset distance of the impact location relative to the center of the target. The spin angular momentum of the planet (treated as a constant density sphere) will be $(2/5) M_P R_P^2 \omega$, where M_P is the mass of the planet, R_P is the planet's radius, and $\omega = 2\pi/P$ is the planet's angular velocity, with P being the planet's spin period. If we assume that there is no appreciable change in the size of the planet after the impact and that the mass of the impactor is much less than that of the planet, then after the impact the planet's new spin rate will be $\omega_{\text{new}} = \omega_{\text{old}} + (5/2)[M_I / M_P] V_I [d / R_P^2]$, assuming that the direction of impact is

in the same sense as that in which the planet is rotating. The largest possible offset distance for the impactor is $d \approx R_p$, and if we take $M_I / M_p = 10^{-6}$ (that is, the impactor is a million times less massive than the target planet), then with an impact velocity of, say, 25 km/s we have in the case of Venus that $\omega_{\text{new}} = \omega_{\text{old}} + 2.05 \times 10^{-9}$, which translates into an increase of about 1.4 days in the planet's spin period. To produce an appreciable spin-up effect on Venus, therefore, a KBO impactor would need to be about 170 km in diameter. There is clearly a lot of room for maneuvering in such calculations. The impact velocity could certainly be twice as high and the impactor mass ten times larger than assumed in our earlier calculation, and accordingly the spin period might be increased by about 88 days (a 40% reduction of the initial spin period). There is certainly a good supply of appropriately sized KBOs in the outer Solar System so that our descendants may reasonably try to increase the spin rate of Venus to a value of perhaps 50 Earth days (which would require five large KBO-grazing impacts).

9. The idea behind the Dyson sphere is that a sufficiently advanced civilization will have extremely high energy demands, and that one way of acquiring this energy is to tap more of the reserves from its parent star. The ultimate energy trap would, of course, be a sphere placed around the star. Russian radio astronomer Nikolai Kardashev suggested in the mid-1960s that a civilization might be classified according to how much energy it can tap and use. A civilization capable of generating and using the energy equivalent of its parent star was accordingly classified as a Kardashev type II civilization. A civilization capable of using the energy equivalent to that of its host galaxy is called a Kardashev type III civilization. We, that is, all humanity, are currently classified as a Kardashev type I civilization, in that we nearly tap all of the energy that the planet (Earth) can provide. Searchers for Dyson spheres, at infrared wavelengths where they will radiate most strongly, have been made, but no good candidates have been found. James Annis (Fermi National Accelerator Laboratory, in Batavia) has also performed a study of several hundred nearby galaxies to see if Kardashev type III civilizations might exist; none has so far been detected.
10. Dyson describes the detailed physics behind his planetary spin motor in his article *The Search for Extraterrestrial Technology*, which was one of a series of essays honoring Professor Hans Bethe published in *Perspectives in Modern Physics*, B. E. Marshak and J. W. Blacker (Eds.), Interscience Publishers, New York (1966).
11. Stephen Gillett, Diamond ether, nanotechnology, and Venus. *Analog* Nov. 1999, pp. 38–46.

12. Stephen Gillett remarked in his article *Second planet—second Earth*, published in *Analog Science-Fiction/Science Fact* [**104**, 64–78 (1984)] that he thought terraforming would be “a pointless exercise” unless the end result provided a long-lived, stable, and self-regulating environment. Although the thinking is laudable, it is also probably wishful thinking, and Gillett is destined to be disappointed with the results of future terraforming, although hopefully he would still conclude that, “It seems to be worth it.” External control of terraformed environments will always be required, but this, fortunately (yes, fortunately) places great demands on humanity’s future development; humankind must either learn how to look after its future worlds using good stewardship or it will perish, and if the latter result occurs, well, perhaps it is good riddance.
13. Alexander Smith, Terraforming Venus by induced turnover. *Journal of the British Interplanetary Society* **42**, 571–576 (1989).
14. Freitas’ ideas are described in NASA Conference Publication 2255. These proceedings can found at http://en.wikisource.org/wiki/Advanced_Automation_for_Space_Missions.
15. Deborah Cadbury’s *Space Race* (Harper Collins, New York, 2006) is an exceptionally well written and very readable account of the struggle and rivalry between the United States and the former Soviet Union to land a man upon the Moon in the 1960s (although the origins of the rivalry essentially stretch back to the end of World War II). Marina Benjamin’s *Rocket Dreams* (Free Press, New York, 2003) is also a very informative read that looks into how the space age has shaped our everyday lives.
16. Details of the *Moon, Mars and Beyond* vision of NASA can be found at http://www.nasa.gov/mission_pages/exploration/mmb/index.html.
17. Haym Benaroya and Leonhard Bernold, Engineering of lunar bases. *Acta Astronautica* **62**, 277–299 (2008).
18. The current NASA timeline calls for a manned 30-month roundtrip mission to Mars beginning in 2031. The supporting cargo and habitation systems will be launched ahead of the astronauts during 2028/29, and it is anticipated that the Mars exploration phase will last about 16 months.

8. An Abundance of Habitats

As every practicing scientist and investment analyst well knows it is always a risky venture to extrapolate beyond the known data. Nature (and the economy), history tells us, is very good at throwing us curveballs, and what may seem like a sound and logical prediction can, when the correct observations are finally gathered in, be entirely wrong. This method of prediction, testing against the observations and making corrections, of course, is exactly what makes the scientific approach so powerful. But when it comes to understanding the origins of life, and predicting where life might be found in the universe, we are presently at a distinct disadvantage.

The disadvantage is not so much a lack of ideas and possibilities, however, but one of too many ideas and too many possibilities that are not constrained by actual data and observations. We are also at a disadvantage in the present epoch with respect to not knowing what it is that we don't know.¹ The existence, or not, of other life forms, microbial and otherwise within the greater Solar System and the vast expanse of the universe beyond is a subject profoundly unknown to us. If we use the Earth as an example then it is clear that life is tenacious and can survive anywhere where there is liquid water, and this is our present best piece of information to guide the search for extraterrestrial life among the potpourri of possibilities.

Likewise, a world that already has water is a good place for human colonization, terraforming, or utilizing as an intensive agriculture region. Within our Solar System, these various resources certainly exist, and some of them will be discussed below. On a grander, galactic scale, it is also known that planets are commonly found in orbit around low-mass stars, and this leads to the speculation that other civilizations may have adopted "terraforming" strategies in the utilization of their own planetary systems. Martyn Fogg has further speculated that our very distant descendants might eventually initiate an interstellar-expansion program based upon

the terraforming of any suitable planets encountered during their journey to discover the galaxy. Let us begin with a look at the greater Solar System's resources first.

The Moon's a Balloon

The Moon, as we all know, has no atmosphere. It is an exposed world that has no protective cover from impacting meteoroids, small or large. Indeed, that the Moon has been repeatedly struck by asteroids and cometary nuclei is clear from its massively cratered surface, and its continued strafing by small meteoroids is betrayed by the many brief impact flashes that have been recorded on its darkened disk during meteor showers.²

Could, however, a meteor or fireball trail ever be witnessed in an artificial lunar atmosphere? Surprisingly, perhaps, the answer to this question is yes, and the means by which an artificial lunar atmosphere might be created was discussed as early as 1974 by physicist Richard Vondrak (now Director of the Solar System Exploration Division, NASA/Goddard Space Flight Center, Maryland).

When, in Chapter 5, we discussed the properties of an atmospheric gas, it was argued that molecule–molecule collisions brought about the Maxwell distribution of velocities (recall Figure 5.10), and that it was the continuous production of a few high-speed molecules, Maxwell's tail particles, which enable matter to eventually escape into space. In the case of the Moon, however, the few molecules that are ultimately outgassed at the surface and produced by sputtering are so well separated that collisions essentially never happen. Any particles that have a velocity greater than 2.38 km/s, the Moon's escape velocity, will be lost directly into space along ballistic (i.e., noncollisional) paths, a process known as thermal escape. In addition, however, any ions (atoms or molecules that carry a net charge) that might be produced by the Sun's ultraviolet radiation in the Moon's exosphere will be swept up by the solar wind and carried away in very short order.

Indeed, it has been estimated that any gases that might be introduced into the Moon's exosphere will be lost within a matter of a few weeks. What Vondrak noted, however, in a short article

published in the journal *Nature*, was that there is a limit to how much material the solar wind can carry away at any one instant. Specifically, Vondrak found that when the solar wind encounters a dense atmosphere located around a planet (or a moon), then any newly formed atmospheric ions tend to load down the flow and deflect the wind around the body. If, therefore, the Moon could be artificially induced to hold a denser gas envelope, an inflated atmosphere if you will, then the base of the exosphere would be pushed upward and a relatively long-lived atmosphere might be established. Vondrak, in fact, calculates that the transition from a surface exosphere to a *bona fide* low-pressure atmosphere comes about once the total atmospheric mass exceeds about 10^8 kg. With this atmospheric mass, the mass loss rate induced by solar wind interactions is about 100 kg/s, and remarkably this mass-loss rate remains essentially constant even if more gas is added to the artificial atmosphere.

The Moon's exosphere contains, at any one instance, about 10,000 kg of gas. To create an inflated Vondrak lunar atmosphere, therefore, the current exosphere mass must be increased by a factor of about 10,000. Given that the solar wind mass-loss rate peaks at about 100 kg/s, it perhaps makes sense to build up the Moon's atmospheric mass at this same rate. Indeed, with an atmospheric gas inflation rate of 100 kg/s, the Vondrak limit is reached after just 2 years, and the atmosphere will then enter into a steady state phase, with the solar wind mass-loss rate being balanced by the artificial gas input rate. The input (inflation) gases might reasonably be obtained in a number of ways. They might be produced, for example, by the industrial heating of lunar regolith material, or through subsurface nuclear-bomb mining. The latter mining method would be a straightforward means of rapidly starting the process, while the industrial process would support the atmosphere in a steady, ongoing manner.

In principle, the inflated lunar atmosphere could be built up to masses well in excess of 10^8 kg. Indeed, the greater the atmospheric mass, the greater the surface pressure. At 10^8 kg, the inflated lunar atmosphere would provide a surface pressure of about 4×10^{-6} Pa, which is some 2×10^{10} times smaller than that exerted by the Earth's atmosphere at sea level. It is not presently clear, however, that there is any specific advantage to pushing the mass of the inflated lunar atmosphere beyond that of the Vondrak limit.

One very practical and useful reason for creating a lunar atmosphere is that it will provide some surface protection from meteoroid impacts. Current designs for lunar housing modules either call for the structures to be covered by a layer of surface regolith or for the structure walls to be made of some form of self-sealing material. There is little one can physically do to protect a lunar-habitation module against a direct strike from large multiple-kilogram mass meteoroids. Fortunately, the impact rate of such objects is very low, with recent observational results obtained by Bill Cooke (Marshall Space Flight Center) and co-workers (see Note 2) placing the rate of sporadic 1-kg mass meteoroids as one hit somewhere on the Moon's surface every 5.5 hours.³ This impact rate will be higher, by perhaps a factor of a few, during the peak times of strong annual meteor showers. Taking the typical velocity of an impacting meteoroid to be 25 km/s, a 1-kg meteoroid will hit the Moon's surface with an astonishing 300 million Joules worth of energy—the equivalent of 75 kg of TNT explosive.

Smaller-mass meteoroids hit the Moon's surface with essentially the same velocity as the larger ones but have less impact energy. A 1-g meteoroid, for example, will carry some 300,000 Joules worth of impact energy (equivalent to about 75 g of TNT explosive—more energy, in fact, than that used in a standard hand grenade). Even a 1-g meteoroid could clearly cause considerable damage to an unprotected structure, and importantly, the flux of such meteoroids will be many orders of magnitude higher than that of kilogram-mass meteoroids. The Earth's atmosphere is a very effective barrier against ground impacts from low-mass meteoroids, and a lunar atmosphere would serve essentially the same protective function. Indeed, once the mass of any lunar atmosphere exceeds about 3×10^{10} kg, then it will provide the same density variation as that encountered by meteoroids in the Earth's meteoroid ablation zone.⁴

Figure 8.1 shows the results from a series of detailed model calculations⁵ in which the minimum mass for a meteoroid to penetrate through the Moons inflated atmosphere was determined. It has been assumed that the test meteoroids strike the Moon's artificial inflated atmosphere vertically with an initial speed of 25 km/s. As the meteoroid descends through the lunar atmosphere, it loses mass through collisional heating and slows down.

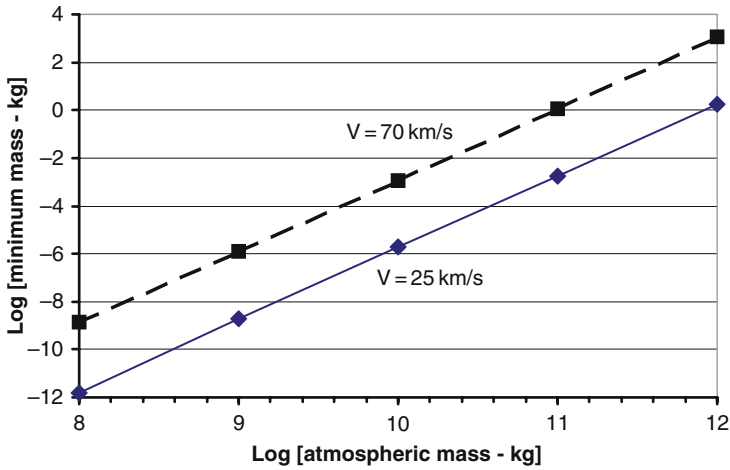


FIGURE 8.1. Minimum mass meteoroids capable of impacting on the Moon's surface. As the mass of the lunar atmosphere is increased, so the minimum mass for impact also increases, providing greater protection for lunar colonists and structures.

The computer simulations are repeated for different initial masses to determine the limit at which a meteoroid will just make it through the atmosphere to strike the lunar surface.

When the lunar atmosphere has a mass of 10^8 kg, the minimum-mass meteoroid capable of striking the Moon's surface is found to be 1.5×10^{-12} kg (with a diameter of 10 microns) when the initial velocity is 25 km/s. At the maximum possible speed of a meteoroid 1 AU from the Sun, a velocity of 70 km/s, the minimum mass for hitting the Moon's surface is 1.4×10^{-9} kg (diameter of 0.1 mm). The limiting size impacting meteoroid for different mass atmospheres is shown in Figure 8.1, where it can be seen, as expected, that the greater the mass (and hence extent) of the inflated lunar atmosphere, the more massive (larger) a given meteoroid has to be in order to penetrate to the lunar surface.

An additional advantage, perhaps even more useful than meteoroid protection, that a lunar atmosphere would provide is protection against cosmic rays. These energetic particles originate both from the Sun and from supernovae and other high-energy events taking place in the Milky Way galaxy. Although called rays, they are in fact particles, with the vast majority being either protons ($\sim 90\%$), helium atom nuclei ($\sim 9\%$), or electrons ($\sim 1\%$).

Cosmic rays are one of the most important sources of ionizing radiation that the inhabitants of the International Space Station have to be protected against. Indeed, even short-duration exposure to cosmic rays can result in damage to human DNA, and it can further cause various kinds of cancer, as well as cataracts and neurological disorders. The Earth's atmosphere is a very effective shield against cosmic rays, and accordingly, any level of lunar atmosphere would help address the exposure problem to the residents living and working on the Moon's surface. Cosmic rays are destroyed through interactions with gas molecules within the atmosphere, and even a minimum-mass 10^8 -kg lunar atmosphere would provide enough shielding to significantly reduce the flux of cosmic rays at the Moon's surface.

The present NASA timeline calls for the return of astronauts to the Moon by 2020 (see Vignette E at the end of Chapter 7 in this book), and hopefully by the close of this century the first lunar cities will have well-established communities. Humanity's future is tied to the Moon; just as the Moon pulls at the tides of Earth, so it pulls at our destiny. A Moon with an artificial atmosphere will be a new world for humans to live upon and to explore. It will also be a new Moon, literally, for those who remain on the Earth, since the artificial atmosphere, if established, will result in a much brighter reflective glow than it displays at the present time.

Hot-Footed Hermes

The planet Mercury is about one-third the size of Earth and some two-and-half times closer to the Sun. In spite of the fact that it is two times nearer to the Sun than Venus, Mercury has a maximum surface temperature lower than that of the veiled planet because it has no atmosphere—a point that further illustrates the immense power of the greenhouse effect. This being said, upon its sunlit side, the noon-time highs on Mercury can still reach a withering 430°C .

Due to its location deep within the Sun's gravitational potential well Mercury is not an easy planet to visit. Neither is it an easy planet to view from the Earth because of its perennial closeness to the Sun and its inherently small angular size. Consequently, until

very recently, only about 45% of the planet's surface has ever been photographed and mapped.

Mariner 10 was the first spacecraft to encounter Mercury, and this was some 30 years ago now, in the mid-1970s. Currently on route to orbit insertion around Mercury, however, is NASA's MESSENGER (which is the highly contrived acronym for MErcury Surface, Space ENvironment, GEochemistry, and Ranging) spacecraft. Following a 4-year journey, the spacecraft first encountered Mercury on 14 January 2008. It will make a series of further close approaches to the planet through 2008 and 2009, with a final orbital insertion taking place in March of 2011.

The MESSENGER spacecraft mission will without doubt change our understanding of the fleet-footed planet, and it will certainly complete in relatively short order the surface mapping begun by Mariner 10 in 1974 (see Figure 5.17). A joint ESA/JAXA spacecraft mission to Mercury, the BepiColombo mission, is due for launch in 2013 (arriving in 2019), and again we might well anticipate that this mission will provide new and detailed information about the Mercurian magnetosphere and the distribution of surface elements.

What we do know at the present time about Mercury makes it an oddity within the Solar System. First, Mercury has a very large nickel-iron core that occupies some 70% of its interior; the percentage for other terrestrial worlds is more like 50%. That the core occupies such a large proportion of Mercury's interior is most probably due to catastrophic mantle ejection through massive impacts shortly after the planet formed. The planet does have a magnetic field, and accordingly the solar wind is diverted around the planet by a magnetosphere that partially protects the surface from direct solar wind particle impacts. Mercury is too hot and of too small a mass to hold on to any substantial atmosphere (recall Figure 5.11). More importantly for future exploration, however, and in spite of its blisteringly hot daytime temperatures, there are crater floors at both Mercurian poles that are never illuminated by the Sun, and accordingly water-ice has been able to accumulate there (Figure 8.2). The ice is probably derived from past cometary impacts onto Mercury's surface.

Mercury has a very slow rotation rate of 58.646 days, and as illustrated in Figure 5.3, this results in a spectacular 600°C

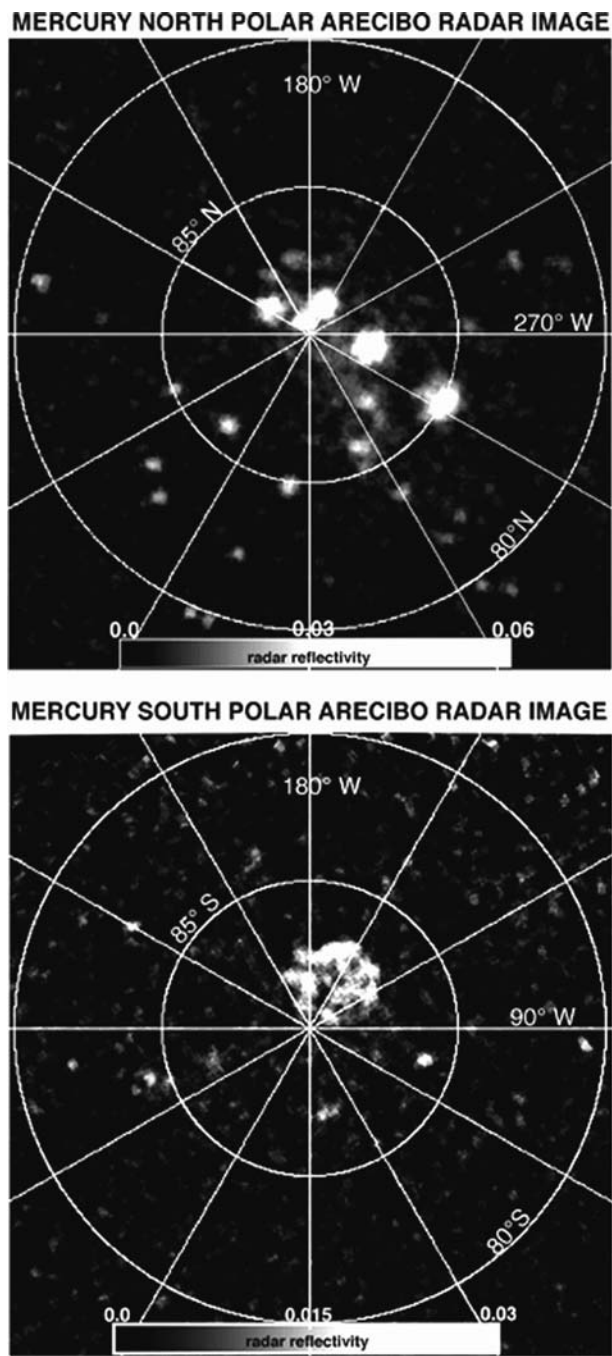


FIGURE 8.2. Radar reflectivity maps of the north and south poles of Mercury. The bright, reflected regions indicate the water-ice deposits located in deep-walled craters where no sunlight can directly heat them. Image courtesy of NASA.

day/ night temperature variation at the planet's equator. At the poles, however, the diurnal temperature swings are much less severe, amounting to about 300°C. There seems little prospect of terraforming Mercury such that any animals or plants might exist there, and we are apparently left with its most likely future role as being one of a mining reserve. Indeed, as we saw in Chapter 7, the terraforming of Venus may depend upon the importation of calcium and magnesium mined from Mercury. Being located so close to the Sun, future explorers of Mercury will have no shortage of solar energy, and with its polar reserves of water-ice it seems that mining and refining industries might eventually be supported there. This potential future role for the planet appears entirely appropriate, since Hermes, the Greek god equivalent of the Roman god Mercurius, was considered to be the patron of commerce and weights and measures.

Although introduced as a textual backdrop, one possible plan for colonizing Mercury has been described by author Kim Stanley Robinson. Known for his highly readable three-volume work relating to the terraforming of Mars, Robinson introduces at one stage in his book *Blue Mars* the rolling city of Terminator. In this vein, Robinson writes, "The lone city currently on the planet was therefore a kind of enormous train." The city is envisioned to literally move around Mercury on a closed, circular track placed at a latitude of 45° north. The city's rate of motion is controlled so that it is always placed just ahead of sunrise. In this manner, the city resides in the terminator region, which divides the illuminated from the nonilluminated part of the planet.

Providing that the appropriate heat-resistant materials for the rails can be developed—Robinson suggests they will be made of a "metalloceramic alloy"—there seems to be no physical reason why such a colony might not eventually be constructed. Indeed, such a city would have access to an incredible amount of solar energy and presumably could be supplied with at least some water from the polar regions of Mercury by shuttle mining craft. Although it seems unlikely that Mercury will ever be converted into any resemblance of a green and pleasant land, there is no specific reason why it can't support a large human population in the distant future.

A Fragmented Neighborhood

Life on asteroid B612 was apparently not so bad for the Little Prince, although he was ultimately beset by a sense of great wanderlust. The charming story of *The Little Prince*, penned by French aviator Antoine de Saint-Exupéry in 1943, was written as a child's story, but it points in a prescient way toward a possible future.

The asteroids located in the main-belt region between Mars and Jupiter might in principle support a large population of human beings. The by no-means-large city of Regina, in Saskatchewan, Canada, where the author lives, covers an area of 118.4 km² and provides work and accommodation for a population of 194,971 people (2006 census). A spherical asteroid having the same surface area as Regina would have a diameter of about 6 km. There are of order 30,000–50,000 asteroids of 6-km diameter and larger in the main-belt region.

Now, while it is entirely unrealistic to expect that each of these asteroids might eventually be engineered to support a population similar to that of Regina, if they could be so converted, then the asteroid belt alone might accommodate over 6 billion human beings. This estimate, of course, assumes that each asteroid could feed itself and provide enough energy and work to meaningfully occupy its citizens.

An enthusiastic believer in the potential role of asteroids as future homes was pioneering aerospace engineer Dandridge MacFarland Cole. Indeed, in the last few years of his lamentably short life, Cole wrote three remarkable books on the topic of the human exploration of space, and he specifically advanced the idea of hollowing-out large asteroids to provide the room for interior living spaces. Recent developments in our understanding of the internal structure of a kilometer-sized asteroid, however, unfortunately casts some doubt upon the practicality of Cole's hollow-world concept. Specifically, current observations appear to indicate that the interiors of kilometer-sized asteroids are, in fact, not solid through and through but rather are rubble piles composed of multiple, loosely bound fragments (see Figure 8.3).

No doubt some asteroids will be amenable to the hollowing-out process advocated by Cole, but the advantages afforded by such



FIGURE 8.3. Asteroid Matilda as revealed by the Near-Shoemaker spacecraft in 1997. The asteroid has an irregular profile, some 60 km by 50 km across, and reveals several large craters. The bulk density of Matilda has been determined to be about 1400 kg/m^3 , but since its surface is composed of rock that has a density of some $3,600 \text{ kg/m}^3$, it must be highly porous within its interior. Image courtesy of NASA.

living are still unclear. Indeed, rather than the smaller asteroids being populated in any great numbers it is more likely that they will be utilized in purely commercial mining ventures. Their role will be to provide the raw material (hydrates, silicates, and nickel-iron) that will be used in planetary terraforming projects elsewhere, as well as in the construction of space habitats (such as the O'Neill colonies, which will be discussed later). Poetically, James Oberg in his wonderful book *New Earths: Restructuring Earth and Other Planets* (Stockpile Books, Harrisburg, Pa. 1981) writes, "The asteroids appear to be ripe for plucking. They come in bite-size nuggets, and they roam through a wide variety of orbits, some quite convenient for Earth."

Many researchers have looked at the ways in which an asteroid might be mined, and, as we saw in Chapter 7, Freeman Dyson has suggested a dynamo method by which asteroids might be spun up and thereby disrupted, each "bite-size nugget" then being crushed, sorted, and re-formed by a fleet of "feeder" spacecraft. Other researchers have suggested that orbit shifting might be employed in order that a specific asteroid can be mined in close proximity to the actual construction site.

A small asteroid, perhaps just a few kilometers across, might reasonably support just a few tens to perhaps hundreds of human beings, although one can also easily envision some of the more modest-sized asteroids being engineered to support small communal villages. In terms of living conditions, however, such converted worlds would have to be entirely self-contained, and therefore they offer little to no relative advantage over those provided by an orbiting spacecraft.

Gerard O'Neill, writing in his book *The High Frontier: Human Colonies in Space* (William Morrow and Company Inc., New York, 1976), suggests that a homesteading approach to asteroid colonization, similar to that of the great wagon train expansionism across the western United States in the late 1800s, might take place, the expansion outward being driven by a spirit of adventure and the desire to search for new and ever-richer pastures. This may or may not be a good way to proceed, and there is no specific reason to suppose that the Solar System should be colonized according to what are essentially North American economic ideals. Again, it seems worth reiterating the point that humanity itself will have to change its present consumer approach to life long before it makes any reasonable sense to begin terraforming planets and colonizing the rest of the Solar System. Exporting the currently dominant ethic of short-term economic gain over long-term investment and stewardship, and the continued acceptance by richer nations of crippling poverty in the poorer nations and resource mismanagement that is rampant in many places will not result in a viable, long-lived, and harmonious Solar System community.

Perhaps the ultimate long-term asteroid habitat is that described by Dandridge Cole and co-author Donald Cox in their book *Islands in Space: The Challenge of the Planetoids* published in 1964, where they suggest that a hollowed-out asteroid might be used as an interstellar arc to carry humanity to the stars. Such a venture would in many ways represent the ultimate panspermia mission (recall Figure 3.11).

Life on a Dwarf Planet: Ceres World

Since its discovery by Giuseppe Piazzi on 1 January 1801, astronomers have struggled to classify Ceres. It was first thought to be a new planet (recall Figure 4.4 and Table 4.1), then it was downgraded

to being the largest minor planet (or asteroid), and now it is classified as a dwarf planet. Even if one accepts the current classification scheme to include dwarf planets, and not all astronomers do, Ceres is still an oddity, with respect to its Solar System location and composition, especially so when compared to its current dwarf planet companions Pluto and Eris. Be all this as it may, after the colonization of the Moon and the first attempts at terraforming Mars, Ceres is possibly the next-best candidate body within the Solar System for human colonization.

There are about 30 asteroids with diameters greater than 200 km, and Ceres (Figure 8.4), with a diameter of some 974.6 km, is the largest of all the objects within the main-belt region. Although all these larger worlds may well become colonized in the future, they will certainly be strange worlds upon which to live. The surface gravity on Ceres, for example, is just 3% of that

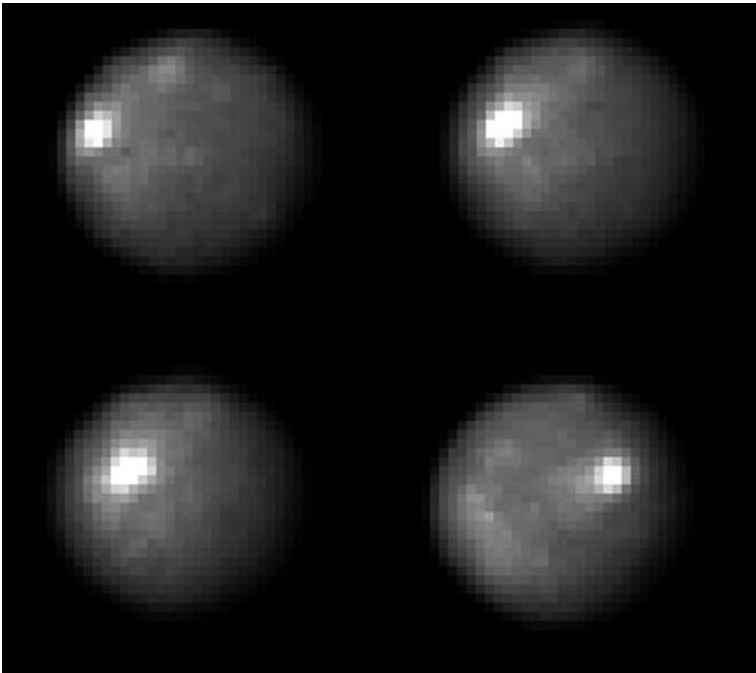


FIGURE 8.4. The nearest dwarf planet to Earth, Ceres. Formerly a planet and a minor planet (recall Figure 4.4), Ceres is 974.6 km in diameter and rotates once every 9.074 hours. The bright spot seen in each of the four images is probably a recently formed impact crater. HST image courtesy of NASA.

experienced on the Earth, and the horizon would be a disconcertingly close 1.4-km away for a 2-m tall, basketball-player-sized human.

Before its category change to dwarf planet status, astronomers classified Ceres as a C-type asteroid, meaning that it shows distinct absorption features associated with hydrated minerals in the infrared part of the electromagnetic spectrum. In a recent study by astronomer Peter Thomas (Cornell University) and co-workers, it has been estimated that the ice-rich mantle that surrounds the inner dense (nickel-iron) core of Ceres is perhaps 140-km thick and may contain as much as 200 million cubic kilometers of water-ice. The surface area of Ceres is about 12 million square kilometers, which is about 8% of Earth's land area, and accordingly it could conceivably support a large population of many tens of millions of people.

Californian school teacher Zachary Whitten recently presented a paper, at the 25th annual International Space Development Conference held in Los Angeles in May of 2006, on the role that Ceres might play in the future development of the Solar System. He envisions a gradual buildup of people and infrastructure, but concedes that life on Ceres will be far from easy for any human born on the Earth. Indeed, the bone loss and other negative physiological changes that astronauts undergo in weightless conditions are now well documented, but only poorly understood at the present time in terms of positive changes. In addition, there may well be new toxicity issues associated with common bacteria that will have to be understood and dealt with.

Writing in the September 2006 issue of the *Proceedings of the National Academy of Sciences*, James Wilson (Arizona State University) and co-workers have reported on an increase in the virulence of *Salmonella typhimurium* when grown in space. The research suggests that it is not so much the low-gravity environment that directly affects the bacteria but rather the very low fluid-mixing conditions that operate in low-gravity environments. The bacteria are not actually mutating; rather, it is their development, or if you like, their cellular personality that is altered because of the low mixing environment in which they are forced to grow. It is presently unclear exactly how these affects come about, and neither is it clear how other, normally harmless bacteria might change in

low-gravity environments. Future, home-born Cererians will presumably become better adapted to their low gravitational environment, and perhaps they will also develop the appropriate immunity to the possibly more virulent bacteria that will live among them.

In his brief study, Whitten notes that Ceres is not only a possible future home world but that it occupies an important strategic position within the Solar System. Moving along a nearly circular orbit with a semi-major axis of 2.765 AU, Ceres sits a little less than midway between Mars and Jupiter. It accordingly provides a convenient staging post for overseeing the mining activities in the main-belt region, the terraforming of Mars, and the exploration of the Jovian planets and their many associated moons.

Within the next 10 years we will know much more about Ceres as a result of the Dawn spacecraft mission, which was successfully launched from Cape Canaveral in September of 2007. The spacecraft will first encounter and then orbit asteroid Vesta for 9 months (beginning in 2010). After surveying Vesta, the spacecraft will then head for a rendezvous with Ceres in 2015. During its planned 10-month mission at Ceres, the Dawn spacecraft will map the surface of the dwarf planet and quantify the surface mineralogy of this potential new, low-gravity home for humanity.

Living in the Clouds

Jupiter is the planetary behemoth of the Solar System. It is 317.7 times more massive and 11.2 times larger than the Earth and is second only to the Sun in terms of gravitational influence. It sculpts the asteroid belt, producing the depopulated regions (so-called Kirkwood gaps) predicted by American astronomer Daniel Kirkwood, and it controls the dynamical evolution of a whole host of short-period comets. The vast majority of the mass of Jupiter is in the form of the two lightest elements, hydrogen and helium, and although it most probably has a solid core, weighing in at perhaps 35 times the mass of the Earth, the core is buried so deep within the planet's gaseous envelope that it is completely beyond the reach of terraforming.

It is not entirely beyond the realms of possibility that life presently exists within the upper cloud deck of Jupiter, and the ever-optimistic Carl Sagan, along with co-author Edwin Salpeter

(one of the towering intellects of recent times) have suggested⁶ that various gas-filled organisms, called “floaters and sinkers”, might occupy various ecological niches in the great planet’s outer atmosphere. Be all this as it may, the point is that there is a region in the outer cloud deck of Jupiter at which the temperature is warm enough for liquid water to exist, and in which large orbiting cities, similar to those described in Chapter 6, might be constructed. Again, these will not be ideal long-term habitats since they will have to be entirely self-contained, and the harsh radiation environment at Jupiter will greatly restrict any exterior operations.

Supramundane Planets and Shell Worlds⁷

In contrast to the low-gravitational environment that exists on Ceres, the gravitational acceleration in the outer atmosphere of Jupiter is 2.53 times greater than that experienced on the Earth. British engineer Paul Birch has suggested, therefore, that a vast honeycombed shell might be built around Jupiter at a stand-off distance of 42,000 km from the upper cloud deck. Such a suprajupiter structure, as Birch calls it, would have a surface gravity the same as that on Earth, and a surface area some 318 times larger than that of Earth. Here indeed, albeit in the form of a proxy surface, is a terraformed Jupiter, a vast world with a core full of energy and resources. Indeed, there is so much wealth in terms of surface area and energy within a suprajupiter system that Birch estimates it could support a population of some 200 billion people.

Smaller versions of Birch’s suprajupiter have been proposed by engineer Kenneth Roy (The Ultimax Group Inc., Oak Ridge, Tennessee) and co-workers, who suggested at the Space Technology and Applications International Forum at Albuquerque in 2004 that shell worlds might be constructed around large asteroids and planetary moons. Such structures are similar in concept to the Worldhouse idea advocated by Richard Taylor (and as discussed in Chapter 6), where the idea is to build a spherical roof around the parent body and establish a breathable atmosphere underneath it. In some sense, this is still spacecraft living, but it is at least living large. In keeping with the notion espoused by Gerard O’Neill that, “At least some of the settlers in space will model their cities and villages on

the prettier areas of old Earth," the shell worlds, according to Roy, will have surfaces designed to look and feel-like our home world. Indeed, the idea appears to be that one might only tell a manufactured world from the Earth by the lower gravity that will be experienced on the smaller, less-massive shell worlds.

The issue of what spaceship colonies, shell worlds, and supramundane planets might look like to their initial inhabitants and future citizens is a topic that has drawn some impassioned debate over the years, with both extremes of the possibilities being argued. Some believe that the new worlds should be doppelgangers (even clones) of the Earth, while others promote the idea of "new world, new outlook," with functionality, or perhaps more to the point, safety being the only design constraint. While the interior design and color scheme of shell worlds, space colonies, and supramundane planets is a problem for others to consider, there are some properties of these potential habitats that are truly constrained by the requirement that the environments must support human life. The atmosphere cannot be just any old collection of gases; surface gravity cannot be just any value; the day/night cycle cannot be just any combination of hours.

In what has become a classic reference source (albeit a little dated now) on the conditions for planetary habitability is the report prepared by Stephen Dole (of the Rand Corporation) in 1964 for the US Air Force. Entitled *Habitable Planets for Man*, Dole comments in his introduction that the "central purpose of this book is to spell out the necessary requirements of planets on which human beings as a biological species (*Homo sapiens*) can live." Among the key issues that Dole considers for habitability are:

- atmospheric pressure and composition
- surface gravity
- temperature variations (diurnal and annual).

If an atmosphere is to be breathable by humans then it must contain oxygen and it must provide a minimum surface pressure. For an atmosphere providing 1 bar (10^5 Pa) surface pressure, the same as the Earth's, the percentage volume of oxygen must be greater than about 10%, or else hypoxia will result, and it must be less than about 70%, or oxygen toxicity will ensue. In addition, to avoid catastrophic fires from being ignited the volume percentage of

oxygen must not exceed 25% of the total. For a surface pressure of 0.5 bar (5×10^4 Pa) the volume percentage of oxygen must exceed 20% to avoid hypoxia, but there is no upper limit with respect to toxicity. If one can control the flammability constraint, the lowest-possible pressure for a breathable pure oxygen atmosphere is about 0.14 bar (1.4×10^4 Pa).

Nitrogen is the dominant gas in the Earth's atmosphere, accounting for 78.08% of the volume (oxygen accounts for 20.95% of the volume; see Table 5.2), and provided its partial pressure is less than about 3 bar (3×10^5 Pa), then it won't be narcotic. Important as well, the nitrogen also acts a fire inhibitor, and it is hence a vital component to a nurturing breathable atmosphere.

The surface pressure (P_S) conditions for a breathable atmosphere places very specific conditions upon the mass of the atmosphere (M_{atm}) and surface gravity (g), since $P_S = g (M_{atm} / 4 \pi R^2)$, where R is the radius. Since the oxygen and nitrogen will need to be either mined or manufactured, the smaller the amount of material required to produce an atmosphere the better. Most of the surface pressure will have to come from the atmospheric mass, since there is an upper limit to the surface gravity under which humans can work comfortably. Indeed, Dole argues that the upper limit is of order 1.25–1.5 times the Earth's surface gravity.

It has already been made clear that the presence of liquid water is vital to human survival. On a terraformed world, therefore, a mean temperature that is above the freezing point of water is clearly required. In artificial worlds, liquid water need not necessarily be present on the surface (it must, of course, be available), but the typical temperature still needs to be above zero in order for humans to feel comfortable in their surroundings. Dole notes, for example, that the majority of people on Earth live in those regions where the annual temperature variation falls between about 5°C and 27°C. Although there are also geographical and climate conditions that apply to this majority distribution of the populace, the temperature range seems a reasonable one to aim for on any new world. The human body can certainly withstand a greater range of temperatures than the annual variation just given, but exposure to temperatures lower than about –10°C for more than 1 day will result in hypothermia. Temperatures warmer than about 35°C for more than 1 day will further result in hyperthermia. For temperatures outside

of these extremes, protective clothing of one sort or another will need to be worn, and this will severely limit everyday new-world activity and life.

O'Neill Colonies and Orbiting Cities

Even if human beings haven't physically traveled very far into the Solar System—a mere 0.002 AU from home⁸—the human imagination has traveled to the very edges of the universe (and in some cases far beyond). Although one could argue that the political motivation and initial drive to place the first astronauts in space and then on the Moon was misguided (see Vignette E at the end of Chapter 7 in this book), the Mercury, Gemini, Apollo, Vostok, and Soyuz missions mark, nonetheless, a tremendous milestone in human history.

The Mercury, Gemini, and Apollo missions inspired a whole generation of American space enthusiasts, and during the 1960s and 1970s many detailed plans for vast space colonies and interstellar travel aboard rocket ships were developed. By far the best known and still the most commonly discussed one to this day are the space colonies envisioned by Princeton University physicist Gerard O'Neill⁹ (Figure 8.5). We need not discuss the engineering details of these incredible structures here, but they do fit into the overriding theme of our topic. People will no doubt live in such orbiting city structures in the future, and many of those future flying cities will probably orbit terraformed Mars and Venus.

One of the issues that O'Neill and fellow designers spent much time thinking about was how the interior of the habitat structures should look and feel. Mountainous regions, rivers and streams, along with lush parkland regions were all incorporated into the interior décor. A 24-hour day/night cycle was maintained by vast system of shutters and mirrors, and an active weather system was envisioned (there were to be rainy days even in space paradise). The whole system was also to be set in rotation so that the inner wall-hugging inhabitants could walk through their curving world under an Earth-like gravitational pull. Indeed, the interior of an O'Neill colony was intended to be a new, paradise-like Earth. In essence, the colonies are terraformed spacecraft, or a fully working version of

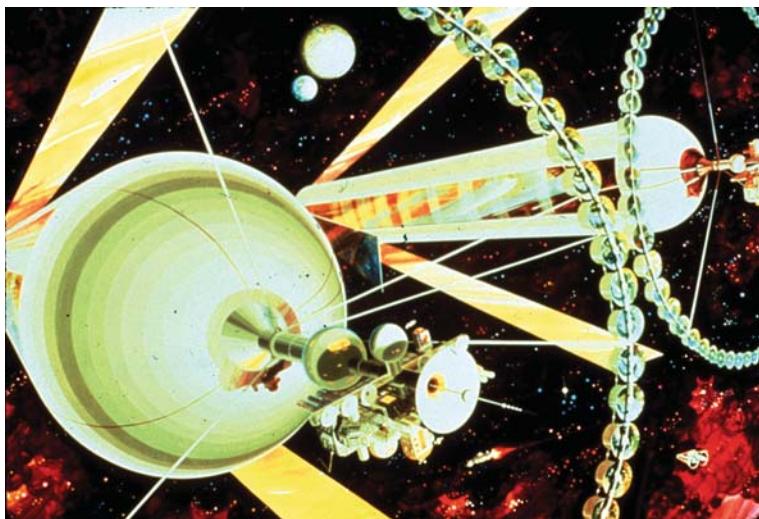


FIGURE 8.5. A space community as designed by Gerald O'Neill. The main cylindrical structures have a diameter of 6.5 km and are some 32-km long. The large circular rings house the various agriculture chambers. Each large cylinder has a set of three angled mirrors that direct sunlight into the inhabited areas. Image courtesy of NASA and the Space Studies Institute (update.ssi.org/).

Biosphere 2 (see Figure 2.3) relocated in space. O'Neill warns us, however, that "we should realize that the humanization of space is quite contrary to the spirit of any of the classical Utopian concepts." Indeed, people who live in space and upon other worlds will still have to find work, pay taxes, struggle for pay raises, and bicker about politics—such things, after all, are at the very core of being human.

The Coming of a Second Sun

From Earth, Jupiter is one of the resplendent jewels of the night sky. After the Sun, Moon, and Venus, it is the brightest nighttime "star" that we can see. Moving sedately through the zodiacal constellations once every 12 years, it shines on us with a quicksilver light. In the distant future, however, it might shine on our descendants with an even greater intensity, and, even more importantly, it might also illuminate its accompanying moons.

Jupiter weighs in at about 1/1,047 the mass of the Sun, and it is sometimes, incorrectly, called a failed star. The word “failed” is inappropriate since Jupiter misses the conditions for stardom¹⁰ by a factor of over 100, which is hardly a near-miss. To say that Jupiter is a failed star is essentially the same as saying that a monkey is a failed human being. It is not as if a baby of the former had a remote chance of becoming an adult of the latter. Indeed, the only similarities between Jupiter and a star, such as the Sun, are that they are both spherical and mostly composed of hydrogen and helium. The hydrogen and helium within their interiors, however, are in vastly different states.

Within the Sun’s inner core the temperature and density are both high enough for the proton–proton chain of nuclear reactions to run and in the process convert hydrogen atoms into helium atoms, with the liberation of energy, energy that keeps the Sun from collapsing and which eventually heats the planets within the Solar System. In Jupiter, the interior is certainly hot and dense, but no energy is generated by fusion reactions. The matter inside the deep interior of Jupiter is, in fact, in a very strange state, with the hydrogen being so compressed that it is a liquid metal. If the mass of Jupiter were to be increased by a factor of about 15–20, then it would resemble a low-mass brown dwarf (which is also not a star).

Brown dwarfs differ from planets in that they were formed through the direct collapse of a gas cloud, whereas planets are formed within the remnant accretion disks surrounding newly formed stars.¹¹ The deuterium within a brown dwarf, however, can undergo fusion reactions to produce energy via the reaction $D + P \Rightarrow {}^3\text{He} + \gamma$, where the energy is carried away by gamma-ray radiation. This reaction, however, runs extremely rapidly, and there is also very little deuterium to begin with. Consequently, the deuterium-burning phase lasts perhaps just a few thousands of years, and then, when all the deuterium has gone the brown dwarf can do no more than simply cool off very, very slowly. Detailed computer models indicate that the minimum mass for a self-gravitating cloud of hydrogen gas to become a bona fide star is about one-tenth that of the Sun, or some 100 times more massive than Jupiter.¹²

To turn Jupiter into a star, therefore, would require the addition of some 2×10^{29} kg worth of hydrogen and helium to its surface—a formidable transportation problem, to say the least. Some

researchers, however, have suggested that such vast amounts of matter might one day be mined from the Sun itself by massive ramscoops (essentially much larger versions of those machines that might, in the relatively near future, mine the atmosphere of Venus; see Figure 7.7).

Why go to all the trouble of stellifying Jupiter, or making it a star? The answer, in fact, is quite simple: there is a great abundance of potentially habitable real estate in orbit around the planet, and much of it might eventually constitute the future “food basket” of the Solar System. The four major moons of Jupiter are Io, Europa, Callisto, and Ganymede. These were the moons that Galileo first observed with his newly constructed telescope in 1610. He initially named the moons the Medicean stars, in the hope of gaining patronage from the Grand Duke of Tuscany, Cosimo II de’ Medici. Luckily for Galileo his plan worked superbly, and he did get support and patronage from the duke; astronomers in general, however, have almost always referred to the moons as the Galilean moons.¹³ Not only might the Galilean moons be made habitable by stellifying Jupiter (as discussed below), but the process will also produce an incredibly rich and long-lived source of energy in the outer reaches of the Solar System.

The ever-imaginative British astronomer Martyn Fogg has outlined one particularly interesting way in which Jupiter might be stellified through the placement of a small black hole at its center.¹⁴ In this futuristic scenario, energy is generated as matter falls onto the black hole’s “surface,” and this same energy will eventually work its way through the planet’s interior to be radiated into space at its surface.

The black hole would prove useful in this activity for about 500 million years or so. After this time, the energy output from Jupiter would become so high that the Galilean moons would no longer be habitable, their surface temperatures being pushed well above the boiling point of water. Some form of disassembly or ‘black hole extraction’ process would have to be initiated at this phase. If not disassembled, Fogg suggests that an idea first developed by Freeman Dyson in the early 1960s might also be put into practice and a “Gravitational Machine” constructed. To make such a futuristic machine, a second black hole with a mass of order that of Jupiter will have to be found (or possibly created), and set in close orbit

around the remnant black hole. By creating such a binary black hole, significant amounts of gravitational wave energy would be liberated, and as Dyson notes, a sufficiently advanced civilization should be able to extract and exploit the available wave energy. Professor Roger Penrose, emeritus Rouse Ball Professor of Mathematics at Oxford University, has also described a process (the Penrose process) by which energy might be extracted from a rotating black hole. If this mechanism could be made to work, then an appropriately constructed suprajupiter shell placed around the black hole/Jupiter remnant could be provided with a nearly limitless supply of energy.

An alternative scenario to Fogg's central black hole accretion model is that in which Jupiter is stellified through the surface accretion of gas that has been mined from the Sun. In a number of ways, the surface accretion method might be the preferable stellifying approach; in particular it results in a much longer-lived configuration than that produced in the centrally accreting black hole scenario. Indeed, as opposed to the 500 million year time scale that results from black hole accretion, a 0.1 solar mass star will happily generate energy through hydrogen fusion reactions for several trillion (10^{12}) years. In addition, a 0.1 solar mass star will maintain a near-constant luminosity of about $10^{-3} L_{\odot}$ for most of its hydrogen-fusing lifetime. A Jupiter with an accreting black hole at its center will, in contrast, become more and more luminous with time unless the accretion is physically stopped.

The central accretion method, however, does have the distinct advantage over the surface accretion model in that it keeps the mass of Jupiter constant. This constancy of mass is important due to an effect known as the conservation of angular momentum.¹⁵ Indeed, this conservation rule dictates that if the mass of Jupiter is to be increased by a factor of 100, and then the orbits of the Galilean moons must shrink by a factor of 100. Reductions of this order in the orbital radii of the moons will certainly result in their destruction—not only will the entire icy mantle of each moon be boiled away, but their remnant cores will be ripped apart by the strong gravitational tides raised by Jupiter.

To investigate the effect of stellifying Jupiter by surface accretion we can modify our temperature equation [Equation (5.1)] to account for the additional energy that the moons will receive once

the mass of Jupiter is raised to about one-tenth that of the Sun (see Note 10). Accordingly, if the surface temperatures of a specific moon is to fall between 373 K and 273 K, then the distance between the surface of Jupiter and the moon must sit somewhere in the range from 3 to 6 million km (see Figure 8.6).

Not only will the change in mass of a stellified Jupiter alter the orbital radii of its associated moons, but it will also have a very definite effect upon the orbits of the main-belt asteroids. This, of course, could be a distinct problem if Ceres and other large asteroids have already been colonized, and it may also result in a greater influx of planet-crossing asteroids being produced. Here, again, the black hole accretion model described by Fogg has the advantage in that under his scenario the mass of the stellified Jupiter system doesn't change; literally, what the parent Jupiter loses the daughter black hole gains, and the total mass remains a constant.

It is not entirely clear that it is worth trying to save the Galilean moons from destruction once the decision to stellify Jupiter has been made. Although these moons certainly represent an important ice and water-world resource prior to taking the first steps in any

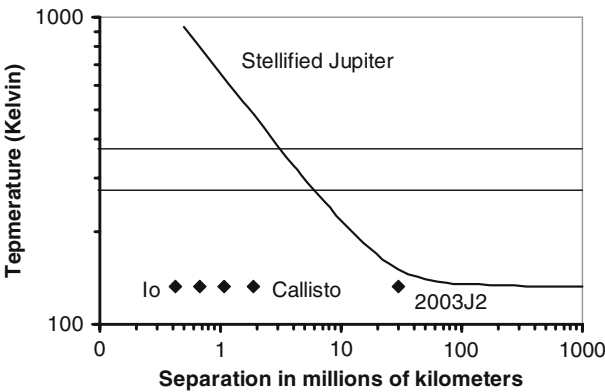


FIGURE 8.6. Surface temperature versus distance for a stellified Jupiter. The calculation assumes (see Note 15) that the mass of Jupiter has been increased to $0.1 M_{\odot}$, and that it has a luminosity of $10^{-3} L_{\odot}$. The two horizontal lines indicate temperatures of 273 K and 373 K, respectively, and the present positions of the Galilean moons and the outermost known moon of Jupiter (2003J2) are also shown. The temperature curve levels off after about 30 million km, since at this and greater distances it is the Sun's energy flux that contributes most to the surface heating.

stellification project, their role in a post-stellified system is less clear. With little doubt, water will still be a highly valued commodity, but in the deep future, when the conversion of Jupiter into a star might be possible, the ability to extract water-ice from the greater reserves contained within the Kuiper Belt and the Oort Cloud will presumably also be possible. Indeed, it is highly likely, since they are such a potentially valuable resource, that the manipulation and reengineering of the orbits of KBOs will have begun long before the conversion of Jupiter is initiated.

Not only does it seem likely that KBOs will be mined for their valuable water-ice and useful volatile inventories, but it is also likely that the actual mining will take place within the inner, as opposed to the outer, Solar System. The idea here is to modify their orbits by an appropriate change in their velocity (possibly by an attached solar sail) in order to bring them into the inner Solar System. Donald Korkansky (University of California, Santa Cruz) and co-workers have discussed¹⁶ in several publications the possibility of altering the Earth's orbit so as to compensate for the increasing luminosity of the Sun (recall Chapter 4 and Figure 4.13). Such technical skills will, it seems inevitable, be honed by mining projects in the main-belt asteroid region first. In addition, if it is deemed desirable to increase the orbits of the Galilean moons then this could be achieved by appropriately controlled-close encounters with diverted KBOs. The outer Solar System may at the present time seem very remote and of little practical value to humanity, but in the deep future KBOs will come into their own as both a valuable mining resource and as orbit-altering projectiles.

Earth Shift and a Synthetic Sun

At the end of Chapter 4 we described the possible future death of the Earth by overheating. As the Sun ages, so its energy output increases, and the habitable zone moves outward and deeper into the Solar System. One possible response to this situation is to increase the Earth's orbital radius around the Sun. By shifting the Earth's orbit outward, it can be made to track the motion of the habitable zone. Donald Korycansky (University of California, Santa Cruz) and co-workers have suggested that the Earth's orbit might be

enlarged using repeated close-passage interactions by redirected KBOs. Colin McInnes (University of Glasgow, UK), on the other hand, has advocated the use of a large solar sail to modify the Earth's orbit.

On a more extreme scale, Swiss nuclear engineer M. Taube has suggested that the Earth might be literally turned into a spaceship by positioning massive engines, with 20-km-high exhaust nozzles to help preserve the atmosphere, around the equator. In this manner, he envisions that the Earth (at least) might be saved from physical destruction during the Sun's bloated red giant phase. Taube further suggests that once the Sun has become a white dwarf remnant, a synthetic star might be constructed by transporting deuterium mined from Jupiter to the Sun's surface. The deuterium, D, would generate energy through a catalytic D-D cycle in which $D + D \Rightarrow {}^3\text{He} + n + \text{energy}$, and then $D + {}^3\text{He} \Rightarrow {}^4\text{He} + p + \text{energy}$. In this manner, Taube estimates that life might be maintained on Earth for 100 billion years. This is a truly staggering result, and it is perhaps just possible that our very distant descendants will be warmed by a phoenix star, risen from the spent embers of our present-day Sun.

Dyson Spheres and Jupiter

Freeman Dyson developed the idea of what are his now famous Dyson spheres after contemplating the energy limits that an advanced civilization might run up against.¹⁷ For any civilization, terrestrial or otherwise, the largest nearby energy reserve will invariably be that of the parent system's star.

The Sun radiates a total 3.85×10^{26} J worth of energy into space (equally in all directions) every second of every day of every year, and yet only a minuscule 10^{-17} of this total energy output is intercepted by the Earth. Clearly, therefore, if one could build a large structure around a star, then all (or at least nearly all) of its energy might be tapped and used to power commerce, and this is where the Dyson sphere comes in. Since a rigid sphere constructed around a star will be dynamically unstable, and soon therefore crash into its surface, the idea of the Dyson sphere has been extended to mean a spherical halo of many hundreds to even thousands of island

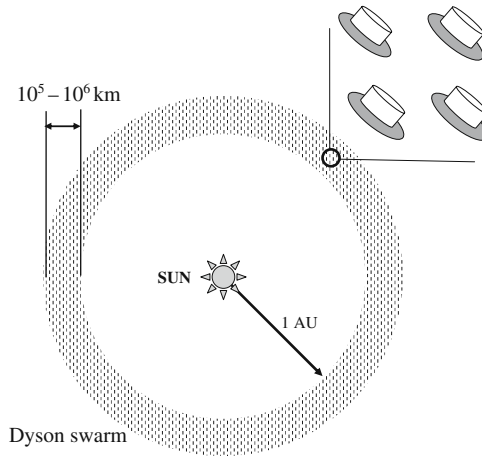


FIGURE 8.7. A schematic Dyson sphere complex of multiple-island worlds. Rather than being a rigid sphere, the structure is composed of many orbiting islands. The orbital radii and island areas are adjusted so that the entire energy output from the central star (or stellified Jupiter) is fully utilized at any one instant.

satellite worlds in orbit around a star (Figure 8.7); the expression Dyson swarm is often used to describe this modified configuration. Each island world placed within the assembly could host a city, an industrial complex, or an agriculture dome, and the individual orbits would be distributed so that each one could continuously tap the parent star for energy. In his original article Dyson suggested that a “sphere” could be built around the Sun with a radius of 1 AU (corresponding to Earth’s orbit). The surface area of such a “sphere” would amount to about $2.8 \times 10^{17} \text{ km}^2$ (551 million times greater than the surface area of Earth), providing an incredible increase in real estate for humanity, as well as an incredible increase in the energy available with which to power its commerce.

One of the interesting characteristics of a Dyson sphere (or swarm) is that it should, if efficiently made and operated, produce a near-perfect blackbody spectrum (see the Appendix of this book). This is useful since such spectra are very rare in nature. Indeed, the only near-perfect blackbody spectrum known to exist in the universe is that of the cosmic microwave background. Stars and nebula produce either distinct absorption or emission line spectra (sometimes both), and they can be clearly distinguished from the spectra produced by a

pure blackbody radiator. The characteristic, or peak emission, wavelength of a perfect blackbody is given by Wien's law (described in the Appendix in this book), and accordingly, it turns out that a Dyson sphere should radiate most efficiently at infrared wavelengths.

Although most searches for extraterrestrial intelligence have been made at radio or optical wavelengths, where it is assumed that advanced galactic civilizations will be broadcasting, the infrared signal from a Dyson sphere will exist whether a specific civilization intends to signal its presence or not; it will also exist for many millions of years (or as long as the swarm survives). A number of searches for Dyson sphere signatures have been made over the years, but to date no convincing candidate objects have been found.¹⁸

Clearly, to build a Dyson sphere complex around the Sun will require tremendous engineering skill, and it will also require access to very large quantities of material, all of which are potentially available. But by the time that the process might actually start, many of the potential material sites could already be inhabited. In contrast, a stellified Jupiter could support a Dyson swarm made from fewer material resources, and while still a very large multi-component structure it would, nonetheless, be smaller than a solar one. If the island worlds are placed within the stellified Jupiter temperate zone (as indicated in Figure 8.6), then the collective surface area would cover of order 10^{14} km² (about 196,000 times greater than the surface area of the Earth).

Structures such as Dyson spheres, whether constructed around the Sun or a modified Jupiter, are perhaps extreme examples of future engineering projects. They build upon the ideal of terraforming, however, in that regions where many billions of human beings might live, work, and thrive are created out of what would be otherwise dead, in the very literal sense of the word, space. Such structures will never replace, or even resemble, the Earth, but they may well become the central spokes of humanity in the distant future.

The Galilean Moons: Food for Thought

Of all the Jovian moons, Europa has perhaps attracted the most attention from astronomers and astrobiologists in recent years. Indeed, it is a world that has repeatedly revealed unexpected

marvels. Being some 3,161 km across Europa is just a little smaller than our Moon. Unlike the Moon, however, it has a remarkably smooth surface devoid of upland regions and impact craters. The most prominent features are long, looping chains of dark ridges and deep fissures that stretch across its surface, intermixed with chaotically jumbled terrain (Figure 8.8). The surface of Europa must, in fact, be very young and malleable, since it betrays very few impact craters.

That an under-ice ocean exists on Europa is remarkable. It is especially remarkable when it is realized that Jupiter sits well outside of the habitable zone (defined in Chapter 5, and see Figure 5.9) and given that the surface temperature of the moon is not much greater than 100 K. How, indeed, can this ocean exist? There is not enough solar energy to warm Europa above the freezing point of water, and the moon is so small that it should have cooled off relatively rapidly after formation.¹⁹



FIGURE 8.8. Galileo spacecraft image of the surface of Europa. The surface is characterized by a complex network of surface ridges and cracks, along with domes and red-colored lenticulae (freckles). The lenticulae are about 10 km across and are thought to have been produced by the upwelling of warmer ice from below the cooler surface. Image courtesy of NASA.

The answer has to do with the specific location of Europa, placed as it is close to Jupiter and between the orbits of Io and Ganymede. The importance of this placement is that: first, the gravitational interaction between Io, Europa, and Ganymede ensures that the orbit of Europa is not circular but slightly elliptical. Second, since the orbit of Europa (as well as the orbits of Io and Ganymede) is not circular, it experiences a variable gravitational tidal interaction with Jupiter, and this results in what is called tidal heating. Literally, a periodic stretching and relaxing of the moon takes place, and this heats its rocky interior. The ocean of Europa is kept warm, therefore, from below by its tidally heated rocky mantle. Io, in fact, is the extreme example of the tidal heating effect within our Solar System, since it is the most geologically active place in the entire Solar System.

In the search for life, as discussed in Chapter 3, the modern mantra is “follow the water,” and accordingly, Europa is touted as one of the most likely places that microbial life might presently exist (beyond that on Earth) within the Solar System. Arguing by analogy, astrobiologists have suggested that there may well be hot springs or black smoker-like vents at the base of the European ocean (Figure 8.9), and since similar such vents in Earth’s oceans are found to support complex colonies of shrimp, crabs, and bacteria, the suggestion has been made that they might also sustain more primitive life on Europa.

It is not clear if life itself might have evolved in the European ocean, but detailed orbital model calculations by Canadian researcher Brett Gladman (University of British Columbia) and co-workers have shown that material blasted from the surface of the Earth by a large asteroid impact can find its way to Europa. If microbes embedded within the terrestrial rocks can survive the ejection shock and many thousands of years travel times, then there is every possibility that Europa has been seeded with life from the Earth (as well as potentially Mars and Venus) in the distant past on many different occasions.

There is much that we do not presently know about Europa and its underground sea, but perhaps by the middle decades of this century the first remote landers will have begun to explore this diminutive world. Indeed, both NASA and ESA are sponsoring research programs to investigate the possibility of exploring Europa’s oceans with miniature submersible craft.

From a purely utilitarian perspective, Europa does offer several distinct advantages with respect to supporting a future human colony.

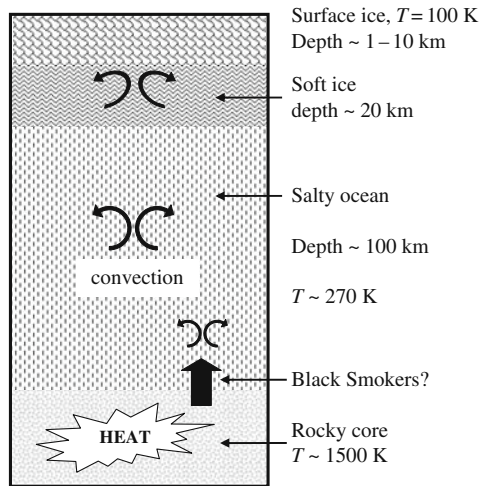


FIGURE 8.9. Schematic cross-section of the outer layers of Europa. The salty ocean is warmed from below by the tidally heated rocky mantle. In Earth's oceans, the black smoker (hydrothermal) vents support complex colonies of numerous marine species, and it has been speculated that they might play a similar role in supporting primitive ocean life on Europa.

Prior to the possible stellification of Jupiter in the deep future, Europa might in the near term provide a burgeoning human population with a valuable supply of marine food. Here, one essentially envisions the stocking of Europa's ocean with genetically modified shrimp and fish species that might eventually be harvested for food.

The possibility of terraforming Europa and, indeed, the other Galilean moons has been discussed by numerous researchers, but in all cases, bar the stellifying of Jupiter option, the biggest hurdle to overcome is that of supplying enough surface heat. At the orbit of Jupiter the solar energy flux is some 27 times smaller than at the Earth, and although the use of orbital mirrors has been proposed to help warm the moons, the required reflector sizes are so large that the whole idea soon becomes untenable.

Perhaps Io holds the best promise for future colonization, since its surface would at least be stable if warmed above 0°C ; the other Galilean moons have predominantly icy outer mantles and would undergo volatile outgassing if warmed. Before Io might be colonized the tidal heating mechanism would need to be broken. This could be achieved by either circularizing its orbit, or shifting it further

away from Jupiter. This latter option would have the additional benefit of removing Io from of its current location in the high-energy radiation belt generated by Jupiter's strong magnetic field. Having relaxed or reduced the tidal heating effect, the residual internal heat of Io might be used to warm a Worldhouse (recall Chapter 7)-entrapped atmosphere; it could also provide thermal heat for general energy consumption. The breathable gases in any Worldhouse atmosphere would need to be mined and transported to Io from other bodies within the Solar System. Due to the intensive volcanism that dominates the geology of Io, however, its surface is sulfur rich, and this would need to be either mined, or buried by surface turnover, before colonization could begin.

James Oberg, who enthusiastically advocated the terraforming of Io in his 1981 book *New Earths* has suggested that the moon's surface might be turned over and gardened through controlled asteroid and cometary impacts, the idea being to bury the surface sulfur. Clearly, this surface turnover phase would need to be completed before the Worldhouse covering was put in place. Coming in at a size just a little larger than the Earth's Moon, Io potentially holds promise for terraforming, in the broadest sense of the word, but the technical challenges required to complete the task will be formidable.

If the surfaces of Europa, Ganymede, and Callisto were to be warmed above the freezing point, and it is presently not clear how this might reasonably be done, then they would likely develop global oceans overlain by an H₂O-rich atmosphere. The melting will occur relatively slowly, taking perhaps a few thousand years to develop a 100-m-deep ocean; the end result, however, would be the production of three rich food-producing worlds. Beyond the construction of surface floating structures, or cocoonment within an overarching supramundane shell, there seems little prospect for the outer Galilean moons being able to support large, permanent human colonies.

The Deeper, Darker, Colder Solar System

Moving beyond Jupiter, we next encounter the ringed world of Saturn. Although smaller in size and less massive than Jupiter, Saturn still supports a whole host of moons, providing once again a rich supply of resources and possible worlds to colonize.

By far the largest and most interesting moon of the Saturnian system is that of Titan, the only moon in the entire Solar System that is able to support a permanent, dense atmosphere. The atmosphere is known to be nitrogen and methane rich, and interestingly resembles that thought to have been surrounding the young Earth. The highly successful and still ongoing Cassini mission to Saturn has revealed Titan to be an incredibly complex world, supporting cryo-volcanoes, liquid methane lakes (Figure 8.10), and a surface that has been repeatedly eroded and channeled by fluvial activity (recall Figure 3.6). On the utilitarian side, Titan has also been found to support massive reserves of hydrocarbons. Indeed, writing in the

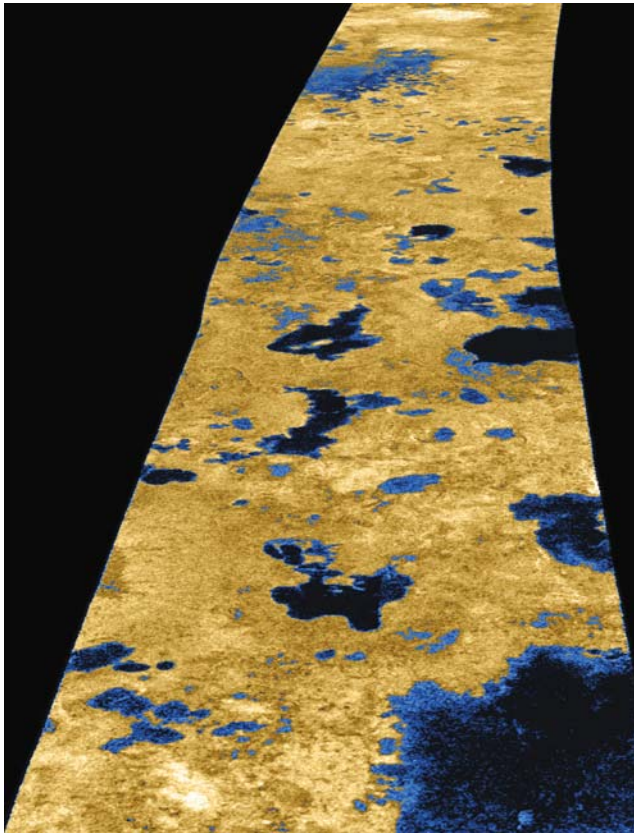


FIGURE 8.10. Liquid methane lakes on the surface of Titan as deduced by the Cassini spacecraft radar study. The radar strip is about 150 km across. Image courtesy of NASA.

29 January issue of *Geophysical Research Letters*, Ralph Lorenz (John Hopkins University Applied Physics Laboratory) and co-workers use the latest Cassini spacecraft radar data to argue that the liquid hydrocarbon deposits on Titan, in the form of liquid methane and ethane, far exceed the entire known oil and natural gas reserves on the Earth.

For all its apparent familiarity in terrain, Titan is a very cold world, and its surface would need to be heated by nearly 180°C just to reach the freezing point of pure water. Indeed, short of adopting a Worldhouse or supramundane structure approach, there appears to be little likelihood of making Titan habitable for humans at any level. This being said, Titan is one of the locations within the Solar System where indigenous life may well exist at the present time. Certainly Titan may have been seeded with microbial life from meteorites launched during past terrestrial impacts, but it has also been suggested by several research groups that life might have evolved there independently. Titan will certainly be the target for future spacecraft and Lander missions, and this large moon (Titan is actually larger than the planet Mercury) no doubt harbors many presently unanticipated surprises.

In Saturn's distant orbit, the solar energy flux is of order 1/100 that at the Earth's orbit. Indeed, the deeper we go into the Solar System the colder and darker it gets, and correspondingly the difficulties of living become harder and harder. Solar energy is no longer easily accessible in the outer Solar System (the size of the collectors being prohibitively larger), and although self-contained (Biosphere-style) colonies will, with little doubt, be established on moons in the dark of the Solar System beyond Jupiter and Saturn, it is not likely that they will support large numbers of human beings. Indeed, as we delve deeper into the Solar System, we enter a region that will likely become a busy industrial zone. The atmospheres of Uranus and Neptune will be mined for their useful gases, and Paul Birch has even suggested that these ice giants might be encased by supramundane structures.

The gravitational attraction at the Uranian surface is about 90% of that of the Earth, and the supramundane substructure would have to have a surface area similar to that of Uranus itself: $6.65 \times 10^9 \text{ km}^2$ (or about 7.7 times the surface area of the Earth). A 1-g surface constructed about Neptune would have an area of $8.77 \times 10^9 \text{ km}^2$

(or about 17.2 times the surface area of Earth). Usefully, Neptune presently radiates nearly four times more energy into space than it receives from the Sun, which indicates that it must still have a hot interior, and this thermal energy could be extracted to help power the surface world structure; Uranus, in contrast, has little internal heat energy to supplement what it receives from the Sun, and accordingly it is less well suited to powering any surrounding world structure. Both planets rotate rapidly and have atmospheres that support high-velocity wind zones, and it is possible that this Aeolian energy might be tapped by massive wind turbines, supporting orbital cities.

Pluto and other KBOs beyond will be mined for their ices and volatile elements, and in many cases they will be shepherded in toward the inner Solar System to impact upon some planet or moon, to thereby turn over a segment of surface regolith, impart some additional spin, deliver vital volatile elements that will warm a new and burgeoning atmosphere, or nudge ever so slightly an object into a marginally different orbit. In the not too distant future it is conceivable that vast solar sail "clipper ships," with their precious Kuiper Belt and Oort Cloud cometary nuclei payloads in tow, will ply the very depths of the outer Solar System, making this dark and remote region of space a vibrant and productive place.

The Pull of More Distant Horizons

Not only is life, by all appearances, tenacious. So, too, is the human desire to prosper and live well. Although the resources for securing both a full and contented human life within the Solar System are nearly limitless, they are nevertheless finite. In this light, it does not seem unreasonable to speculate that in the very distant future, perhaps millions of years from the present, that there might well be large-scale, one-way expeditions of humans into interstellar space. Such exploration will be fraught with both known and unknown dangers, and while such adventures will, for the inhabitants of the Solar System, have zero commercial or even scientific value (presumably still things of interest in the very deep future), they will perhaps satisfy the human desire to know what is beyond the ever-distant horizon.

Humans may eventually inherit our Milky Way galaxy, perhaps as the cocooned cargo housed within the hollowed-out asteroids envisioned by Dandridge Cole, and presumably the colonization of other planets will be part and parcel of that inheritance. This latter component of colonization will probably depend upon the terraforming skills developed in the Solar System, since the likelihood of any Earth-sized planets encountered being directly habitable are very small. There is a clear distinction, however, between finding a planet that is potentially habitable and one that might have supported the emergence of life from inanimate matter. This interesting question concerning the possibility of humans encountering extraterrestrial life and even possibly intelligent life is not, unfortunately, one that will be addressed here. What can be addressed at this stage, however, is the question relating to the existence of exoplanets, and how terraforming might play a role in the colonization of other star systems.

Other Worlds Abound

On 20 December 2007 (the day that these statistics were gathered), a total of 270 exoplanets had been discovered in orbit around 232 stars. Most of the exoplanetary systems discovered contain just a single massive planet located close in toward the parent star,²⁰ although, this being said, 26 stars are also known to host multiple numbers of planets. The current record holder is 55 Cancri, which boasts a total of five known accompanying planets.

A variety of observational techniques have been used to detect exoplanets in orbit about distant stars, and although the majority of planets so far detected have masses many times greater than that of Jupiter, a few have masses comparable to that of Uranus ($14.536 M_{\oplus}$) and Neptune ($17.149 M_{\oplus}$). The so-called super-Earths, which have masses up to about 10 times (recall Chapter 5) that of the Earth, have also been detected, but no Earth mass planet has as yet been discovered. It is just a matter of time, however, before an Earth doppelganger is found. Indeed, great excitement will without doubt ensue on the day, not too far hence, when an Earth-mass exoplanet is found in orbit around a Sun-like star within the system's habitable zone. Here, at last, will be an object that will enable

astrobiologists to determine if life really is as tenacious and inevitable in its appearance as is presently believed. To paraphrase the great Isaac Newton, it will be the “experimentum crucis” of astrobiology.

While we await the discovery of an exo-Earth, it is perhaps worth looking at one planetary system that has recently caught the imagination of present-day astronomers as a system that might harbor a planet within its habitable zone. The star of interest is the faint M dwarf Gliese 581. This particular star is simply identified according to its entry number of 581 in the catalog of nearby, low-luminosity stars compiled by German astronomer Wilhelm Gliese (1915–1993).

For all its obscurity, however, Gliese 581 is known to host at least three super-Earth planets (see Table 8.1), and it appears that long-lived, stable orbits are also allowed for any Earth-like planets that might reside within its habitable zone (see Figure 8.11). In addition, although it is admittedly an extreme speculation, a Titius–Bode-like law (see Vignette F at the end of this chapter) can be set up for the system with the orbital radii of the planets being given as $a(\text{AU}) = 0.038 N^{1.135}$, where N is the sequence number. The relationship, which has an overall “goodness of fit” of 98.4%, allows for the possibility of two additional (low-mass) planets between Gliese 581c and d. Of course, we do not know if these additional planets really exist, but speculation on the possibilities is part and parcel of what scientific enquiry is all about, and the intriguing point is that both of the putative planets would sit in the system’s habitable zone.

Table 8.1. Component parameters of the exoplanet system Gliese 581. The symbol $a(\text{AU})$ indicates the semimajor axis in astronomical units (see Figure 4.1); $M_{\oplus}$ corresponds to the mass of Earth; and $M_{\odot}$ corresponds to the mass of the Sun. The last two columns relate to the speculative Titius–Bode law (TBL) for the system. N is the sequence number and the percentage error indicates the “accuracy” of the TBL “prediction.”

Component	Mass	$a(\text{AU})$	eccentricity	P (days)	N	% error
Gliese 581a	$0.31 M_{\odot}$	—	—	—	—	—
Gliese 581b	$15.64 M_{\oplus}$	0.041	0.02	5.3683	1	7.3
Gliese 581c	$5.02 M_{\oplus}$	0.073	0.16	12.932	2	14.3
Gliese 581d	$7.72 M_{\oplus}$	0.25	0.2	83.6	5	5.6

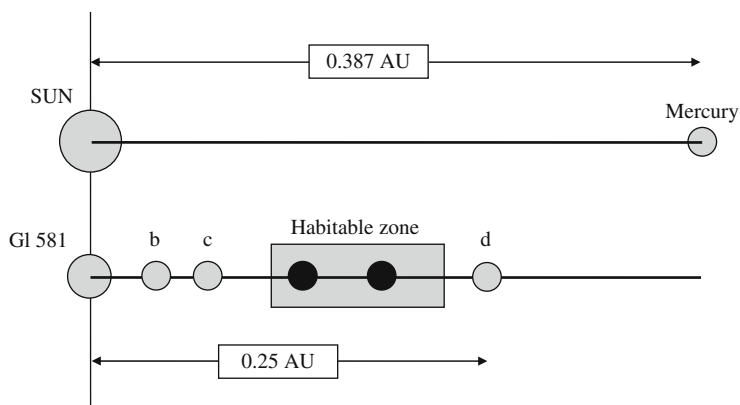


FIGURE 8.11. Scale diagram showing the locations of the three known planets in orbit about Gliese 581. The filled circles indicate the positions of the putative Titius–Bode planets (see Vignette F at the end of this chapter). As an indication of scale, the entire Gliese 581 system would fit inside the orbit of Mercury within our own Solar System.

Also of note with respect to this star is that a recent publication by Franck Selsis (Universite de Lyon, France) and co-workers has suggested that the habitable zone of the system might reasonably be extended to incorporate the orbit of Gliese 581d (the outermost of the three planets) itself, a result that opens up the possibility of moon life.

Future Prospects

It is a near-certainty that Earth-mass planets will eventually be found within the habitable zones of many star systems. As to whether advanced life will have developed on these planets is another question. Indeed, there is no apparent consensus among astrobiologists that the evolution of intelligence is inevitable; some say it is highly likely, while others say it is highly improbable.

Physicist Brandon Carter (Observatoire de Paris) has argued, however, that the probability of a highly intelligent, environment-manipulating species evolving increases with time. The older a planetary system is, the more likely it is that a technologically advanced civilization will eventually appear. If this is the case,

then Carter argues that technologically advanced civilizations are likely to be rare within our Milky Way galaxy. This result follows because there is a critical time scale at play in all planetary systems, this time scale being the main sequence (T_{MS}) lifetime of the parent stars. The main sequence time scale corresponds to the time that a star can generate energy through the conversion of hydrogen into helium within its deep interior.

Once this energy store is exhausted, a Sun-like star will evolve into a red giant—a bloated, low-temperature, high-luminosity star. Once a star enters its red giant phase, then the habitability zone is swept well outside of the typical planetary region, and what was once the habitable, nurturing zone for life will become sterilized.

This, then, appears to be the critical problem for the emergence of a technologically advanced civilization, in that its most likely appearance time is that corresponding to T_{MS} , but this is also the time at which the parent star is primed to extinguish all life within the planetary system. Carter has likened the problem to that of throwing dice and requiring a string of, say, four 6's in a row to occur. If an unlimited number of throws are allowed, then the sequence of four 6's in a row will eventually appear—it's a certainty. If, on the other hand, only, say, 12 throws of the dice are allowed, then the likelihood of getting the four 6's in a row to appear is very much reduced. The main sequence lifetime limit of the parent star acts in a similar sense to the limit on the number of dice throws.

Many highly specific conditions must no doubt come into play in order for a technologically advanced civilization to emerge on a given planet within a nurturing habitable zone. On Earth, for example, the fossil record tells us that well over 99% of all species that have ever evolved are now extinct, and consequently we learn that there is no guarantee of longevity (on time scales of order, say, many hundreds of millions of years and longer) for even the best adapted of species. Humanity is no different from all the species that have gone before it, and it is certainly unclear if our current world dominance will carry on into the deep future. Indeed, it was argued in Chapter 4 that it is rather unlikely that humanity will survive into even the near-term future on the Earth if it doesn't significantly reduce its devastating environmental footprint. It is not at all unlikely that the key condition that restricts the number of civilizations that might exist at any one instant within our galaxy (and

any other galaxy within the universe) is that of survival longevity. The shorter the survival time of an intelligent species, the less likely it is that it will be able to initiate space travel or transform its planetary system.

The essential upshot of Carter's argument that is of relevance to terraforming and the finding of possible new and distant worlds for humanity is that there should be many planets that are habitable, but are not inhabited, by intelligent life forms. Martyn Fogg picked up on this point a number of years ago and has suggested that terraforming might be one way in which humanity could successfully achieve interstellar colonization. Here the point is that while other Earths will be rare (that is, a one Earth-mass planet at 1 AU from a 4.56 billion year old Sun-like star), Earth-mass planets that one might successfully terraform are likely to be common. The path of colonization could therefore be delineated by a series of terraformed staging-post worlds.

The author recently reviewed, in the February 2008 issue of the *Journal of the British Interplanetary Society*, the possibility of inferring the existence of intelligent extraterrestrial life through the detection of terraformed planets in exoplanet systems. The key result is shown in Figure 8.12, which was constructed using the available published data on the estimated ages of exoplanetary systems along with the derived

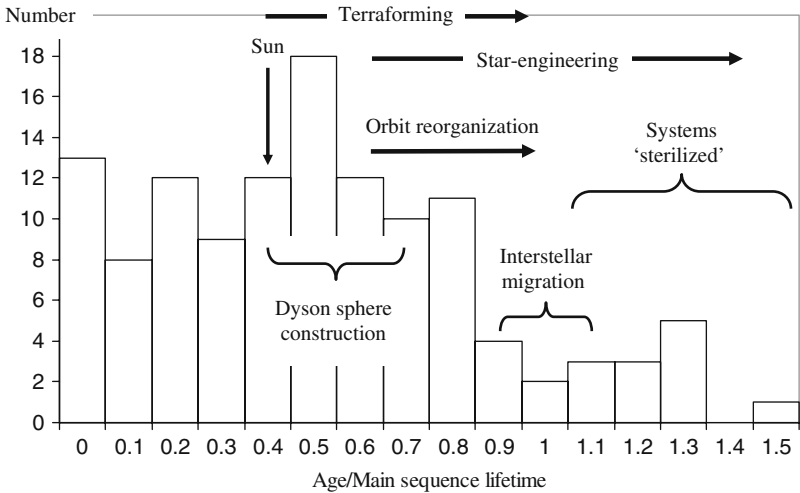


FIGURE 8.12. Relative main sequence lifetime distribution of 123 exoplanet systems. From M. Beech, Terraformed exoplanets and SETI. *Journal of the British Interplanetary Society* 61 (2), 43–46 (2008).

masses for their parent stars. In this diagram, the relative spread in main sequence age of 123 exoplanetary systems is shown.

The number of systems in each bin is not the important point at this stage, other than the bins not being empty, but rather it is the point that a few of the exoplanet systems have ages very close to the main sequence lifetime limit of their parent stars that is of interest.

Of the 123 exoplanetary systems studied, 56% had ages that were greater than half of their parent stars main sequence lifetime, while 14% had ages that fell between 75% and 90% of their parent stars main sequence lifetime. An additional six systems (5% of the total studied) had an age that was within 1% of the main sequence life time of their parent stars.

The Sun is 4.56 billion years old (recall Chapter 5) and has completed about 45% of its main sequence lifetime. It has been suggested within preceding chapters that the terraforming of Mars and Venus will likely be completed within the next several to 10,000 years. Consequently, although perhaps unwisely using humanity as the standard, any planetary system with an age greater than about 50% of the main sequence lifetime of their parent star might conceivably show signs of terraforming. The important observational point here is that such systems could have habitable worlds that are located outside of the standard habitable zone. This observation, however, further provides a means of potentially verifying the existence of an extraterrestrial civilization. A habitable planet situated well outside of the canonical habitable zone can only come about through the engineering of a directed intelligence. Likewise, the detection of a Dyson sphere or evidence for planetary orbit migration would indicate the presence of an advanced civilization. In the latter case, the key test would be to show that the dynamical lifetime of the specific planet's orbit was much shorter than the actual system age.

Habitable Exoplanets and Biomarkers

How might we recognize an exoplanet world upon which life has evolved? This is an important question, and remarkably astronomers are nearly at the point at which such a question might be answered. The key observational requirement is to identify the

so-called biomarkers—distinct features that are encoded within the reflected light from a planet (its spectra) that could only result as a consequence of biological activity. An example of a key biomarker would be the simultaneous detection of molecular oxygen (O_2) and methane (CH_4) within the reflected-light spectra of a planet. Another key biomarker would be the detection of the broad infrared absorption feature, resulting from the chlorophyll component in photosynthesizing plants.

Before distinct biomarkers might be observed, lesser indicators of the possible presence of life might first be observed. The detection of water vapor clouds, for example, would at the very least indicate that the basic solvent was present for carbon-based chemistry and life to potentially proceed. Once per orbit variations in the brightness of a planet might further indicate that a seasonal weather cycle is active with, say, the land being predominantly vegetation-covered in summer (i.e., having a low-surface albedo) but snow encrusted (with a high-surface albedo) during winter.

At the present time, astronomers are able to detect both super-Earths and their more massive Jovian cousins. Importantly, the physical data that can be derived from such observations provides us with an estimate of the exoplanet's mass and orbit size, and they also characterize the parent star. This data certainly allows for a first survey on habitability to be made, and as described earlier in this chapter the hope is to eventually find an Earth-mass planet moving along a nearly circular (or at least low eccentricity), stable orbit within the habitable zone set by the age of the parent star.

New-generation telescopes and spacecraft missions, likely to be in place within the next decade, will allow astronomers to look for habitability-consistent features (i.e., the presence of water vapor in the planet's atmosphere). Indeed, Darren Williams (Behrend College, PN) and Eric Gaidos (University of Hawaii) have recently published a paper in which it is shown that the shape of the reflected light curve can be used to distinguish between exo-Earth planets with and without liquid oceans. Specifically, planets with oceans will be measurably brighter when seen near a crescent phase, due to specular light reflection conditions. Indeed, the 'soon to be launched' Terrestrial Planet Finder (TPF; see Figure 8.13) suite of spacecraft should, Williams and Gaidos argue, be able to distinguish between water-rich planets and their drier, possibly waterless cousins.

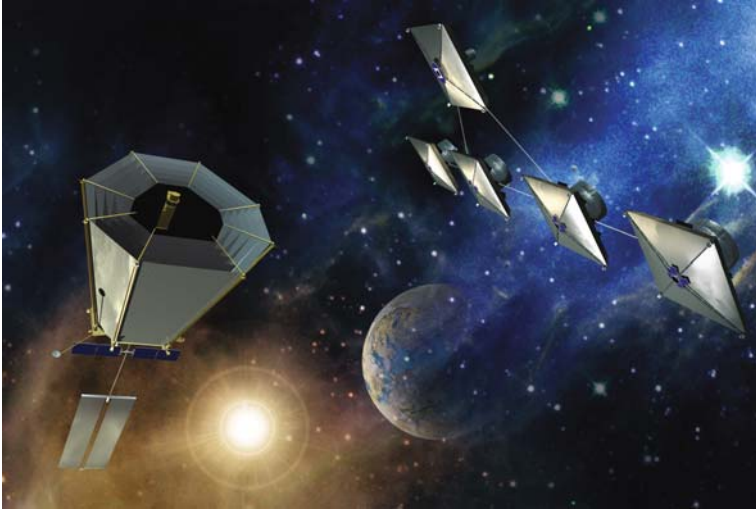


FIGURE 8.13. Artist's impression of the TPF suite of spacecraft. Due for launch by 2020, the TPF will consist of two complementary spacecraft observatories. The first will be a multiple set of spacecraft that will operate in tandem and search for small planets using an interferometric search technique. The second observatory will consist of a visible light coronagraph that will measure the reflected light spectrum from newly found planets. This latter spacecraft will be able to identify the presence of important biomarkers such as CO_2 , H_2O vapor, O_3 , and CH_4 . Image courtesy of NASA.

The boundaries that will define the map of new habitable exoworlds are now being drawn. We already know that the Solar System is not unique, and that there is absolutely no reason to doubt that many Earth-like planets located within the habitable zones of other Sun-like stars also exist. It is also reasonable to believe that some of these other Earths will be bristling with life, while yet others will be quietly biding their time, waiting for the day, many millennia from now, when our distant descendants might terraform them into new and vibrant domains where the spirit of humanity will continue to prosper and grow.

*From Clee to heaven the beacon burns,
The shires have seen it plain,
From north and south the sign returns
And the beacons burn again*

A. E. Houseman, *A Shropshire Lad*

Vignette F: The Mysterious Titius–Bode Law

Planets, as we saw in Chapter 5, grow by accretion within the circumstellar disks that surround newly forming low-mass stars. The planet-building process is driven by accretion and countless random encounters, collisions, and fragmentation events. If you took the initial nebular of gas and dust out of which our Solar System grew, made 100 exact clones of it, and allowed them all to make planets, then you would end up with 100 different arrangements of their orbits. Some features would be the same;²¹ all of the terrestrial planets, for example, would be interior to about 3 AU from the Sun, and the Jovian planets would all be beyond about 4 AU. There is no specific reason why a one Earth-mass planet should end up at 1 AU from the Sun.

All this chance and randomness in planetary formation begs the question, “Should we expect to find any order in the distribution of planetary orbits?” The answer to this question is yes, and with reference to Table 8.2 we see that the ratio of the orbital radius of planet n compared to its nearest neighbor further out (including the minor planet Ceres and continuing on through to Neptune) is approximately constant: $r_{n+1} / r_n = 1.690 \pm 0.231$.

A veritable cottage industry has developed over the past several centuries with the intent of describing the spacing laws for the planets, but the first and most famous law is that presented by

Table 8.2. The spacing of planets within the Solar System. TB refers to the Titius–Bode law, which clearly fails badly for Neptune and Pluto.

N	Planet	R_N (AU)	R_{N+1} / R_N	M (TB)	R_M (AU)-TB
1	Mercury	0.387	1.868	$-\infty$	0.4
2	Venus	0.723	1.383	1	0.70
3	Earth	1.000	1.524	2	1.0
4	Mars	1.524	1.815	3	1.6
5	Ceres	2.766	1.881	4	2.8
6	Jupiter	5.202	1.837	5	5.2
7	Saturn	9.558	2.007	6	10.0
8	Uranus	19.187	1.570	7	19.6
9	Neptune	30.121	1.321	8	38.8
10	Pluto	39.798	–	9	77.2
			$<1.690 \pm 0.231>$		

Johann Daniel Titius and Johann Elert Bode, and simply called the Titius–Bode law. History tells us that Titius proposed the law in 1766, and that Bode reprinted it without reference to Titius in 1772. It is a simple formula that provides the orbital radius of planet m , where $m = -\infty; 1, 2, 3, \dots, 9$ is the sequence number. Specifically, the orbital radius of the m th planet r_m is given by the formula:

$$r_m = 0.4 + 0.15 \times 2^m$$

The Titius–Bode formula indicates that the increase in the spacing of the planets is driven by the 2^m term, which becomes larger and larger as m increases. The last two columns of Table 8.2 show the Titius–Bode m and r_m values. The comparison of interest is between column 3 (the actual semimajor axis of the planet's orbit) and the last column. Certainly, the agreement between the two columns is very good out to the orbit of Uranus.

For Neptune and Pluto, however, the Titius–Bode law fails badly. In addition the orbital radius of Mercury requires the mathematically strange condition that $m = -\infty$, rather than the seemingly more logical $m = 0$, or $m = 1$ for the first planet.

The various opinions voiced by astronomers over the years range from describing the Titius–Bode law as being a pure numerical coincidence to the suggestion that it contains profound insights concerning gravity and planet formation. The present-day consensus appears to favor the former opinion over the latter, however, and while opinion is no basis upon which to decide scientific correctness, Canadian astronomers Wayne Hayes and Scott Tremaine²² have considered the situation in some detail and find that Titius–Bode-like laws (with $r_m = a + b \times c^m$, where a , b and c are constants) can be fit to almost any hypothetical solar system in which the planets are spaced randomly between 0.3 and 50 AU from the Sun. Hayes and Tremaine conclude from their study, in fact, that the only significance that might be attached to the Titius–Bode law is that stable planetary systems tend to be regularly spaced. From the chaos of the planetary formation process, therefore, order in the spacings of the planets should be expected.

Of the 232 exoplanetary systems discovered to date²³ (December 2007), 26 contain a multiple numbers of planets. Let us consider the system μ Ara (HD160691), which contains four Neptune to multi-Jupiter mass planets. The parent star is slightly more massive than our Sun and about twice as luminous. The planets in the μ Ara system have semimajor axes that vary between 0.09 and 5.54 AU. Following Hayes and Tremaine in allowing for the planetary sequence to have a few gaps (this was historically allowed for in the Titius–Bode law), then a Titius–Bode-like law (TBLL) can be determined for the system. The TBLL derived here for HD160691 (see Figure 8.14) assumes two gaps at $m = 2$ and $m = 5$, but can produce a reasonably good “fit” for the semi-major axis of the observed planets. The TBLL fit is best for the innermost planets, where it is perfect at $m = 1$ and $m = 3$; the fits at $m = 4$ and $m = 6$ are 18% and 5% of the observational values, respectively. (Overall, this is about the same level of fit as that offered by the Titius–Bode law for the planets within our Solar System.)

The TBLL derived for μ Ara is no more significant, or surprising, than the Titius–Bode law in our own Solar System: stable planetary systems have regularly spaced planets. What is perhaps the most interesting point about the TBLL for μ Ara is that if we actually believe it, then the implication is that there are two other

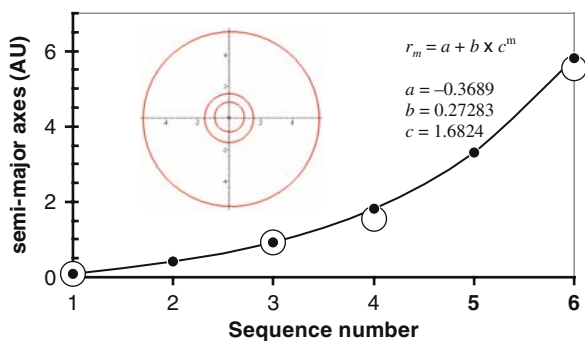


FIGURE 8.14. Orbital semimajor axis against planet sequence number (m) for the μ Ara system. Two gaps have been allowed for at $m = 2$ and $m = 5$. The observed values are plotted as large open circles, while the solid line and small dots represent the TBLL results. Inset B shows to scale the orbits of the four planets within the system (data from Gozdziewski, Maciejewski, and Miagaszewski. 2007. *Astrophysics Journal* **657**, 546–558).

planets (or possibly asteroid belts) to be found in the system. The semimajor axes for these putative objects are $a = 0.4$ and 3.3 AU, respectively. The big question, of course, is just how strongly do we believe in TBLLs?

Support for the idea that the sizes of planetary orbits should be predictable has recently received a boost from the work published by Rory Barnes (University of Arizona, Lunar and Planetary Laboratory) and co-workers.²⁴ Formulating the packed planetary system (PPS) hypothesis, Barnes suggests that planetary formation is very efficient and that wherever there is a stable orbit there will be a planet; in other words, they will be packed as closely as otherwise disruptive gravitational interactions will allow. Using the PPS approach, Barnes and co-workers successfully predicted the possible existence of, and then discovered a new planet orbiting, the star HD 74156. With the discovery of HD 74156d, the Barnes et al. group became the first astronomers since Adams and Leverrier in 1842 (recall the beginning of Chapter 4) to successfully predict the existence and size of a new planet's orbit.

Notes and References

1. The problems associated with actually recognizing intelligence have been discussed by Derek Pugsley in his article, The Recognition of Extraterrestrial Intelligence: Are Humans Up to It? [*Journal of the British Interplanetary Society* **61**, 20–23 (2008)]. Physicist Stephen Wolfram has further questioned our ability to distinguish an extraterrestrial intelligence through the standard SETI procedure of radio frequency monitoring [see the article by Marcus Chown, The Alien within Your Computer, *Astronomy Now* **20** (7), 32–35 (2006)].
2. The history of meteors apparently being observed in the Moon's supposed atmosphere has been reviewed by M. Beech and D. W. Hughes, Seeing the impossible: meteors in the Moon. *Journal of Astronomical History and Heritage* **3**(1), 13–22 (2000). The lunar impact research at the Marshall Space Center in Huntsville, AL, is described at: www.nasa.gov/centers/marshall/news/lunar/index.html.
3. These details are described in the article by Edward Flinn in Mimicking Meteor Impacts, *Aerospace America*, May, 28–29 (2007).
4. In Earth's atmosphere, most meteoroids are destroyed in the region between 110- and 80-km altitude. Once the mass of the lunar atmosphere

exceeds $\sim 3 \times 10^{10}$ kg, then the lunar surface density will be greater than the density at 80-km altitude in the Earth's atmosphere.

5. To produce this figure, the equations describing meteoroid ablation have been solved for numerically assuming an isothermal lunar atmosphere. The density at the lunar surface is derived from the surface pressure, which varies according to the mass of the atmosphere (see Note 1, Chapter 5, above) and the perfect gas equation as described in Chapter 4. It has also been assumed that the lunar atmosphere is composed entirely of O_2 .
6. The highly detailed research paper: Particles, environments, and possible ecologies in the Jovan atmosphere, by Sagan and Salpeter, was published in *The Astrophysical Journal Supplement Series* **32**, 737–755 (1976).
7. The term supramundane is derived from the Latin *supra*, meaning “above,” and *mundus*, meaning “world.”
8. By this measure, at its closest point to Earth, Mars is a factor of 260 times further away from us than the Moon. Going to Mars is by no means a simple extension of an Apollo era mission; it is many orders of magnitude more complicated.
9. The classic book by Gerard O'Neill is his *The High Frontier—Human Colonies in Space*, published by William Morrow and Company Inc. New York (1977). O'Neill discusses some of the more technical issues associated with the engineering of space structures in his article, The Colonization of Space, published in the September issue of *Physics Today*, 32–40 (1974).
10. Here we take the condition for stardom as being the requirement that sustained hydrogen fusion reactions take place. Detailed numerical models indicate that the lowest mass possible for a star is 0.08 solar masses. Objects that are less massive than this limit but are more massive than about 15 times the mass of Jupiter can undergo a short-lived deuterium-“burning” stage. These latter objects are known as brown dwarfs, and they, rather than Jupiter, might be considered to be “failed stars.”
11. Astronomers have detected the so-called free-floating Jupiters, but while they may not be in orbit around a star when found, they were nonetheless formed in and once part of a planetary system.
12. Technically, as described in Note 10 above, the minimum mass for the onset of long-lived hydrogen fusion reactions within the core of a star is about $0.08 M_\odot$, and such stars will have luminosities of about $10^{-4} L_\odot$. This minimum mass condition slightly reduces the amount of material that needs to be imported from 2×10^{29} kg to about 1.6×10^{29} kg. See also Note 3 in Chapter 2.

13. It seems worth mentioning that the title to Galileo's book, *Sidereus Nuncius*, written in 1610 to describe his new telescopic observations, has been uniformly mistranslated since the very earliest of times. The translation of the title is usually given as *The Sidereal Messenger*, when in fact it should be *The Sidereal Message*, which was Galileo's intended meaning. It appears that Johannes Kepler (see Vignette C) was one of the first people to misconstrue the meaning of Galileo's title. Such is history.
14. The details are given in Martyn Fogg, *Stellifying Jupiter: a first step to terraforming the Galilean satellites* [*Journal of the British Interplanetary Society* **42**, 587–592 (1989)]. These ideas are also discussed in M. Beech, *Rejuvenating the Sun and Avoiding Other Global Catastrophes*, Springer (2007). Details of the stellifying of Jupiter are also discussed in M. Beech, *Oscillations and settling times for black holes placed with planetary and stellar interiors*, *Journal of the British Interplanetary Society* **60**, 257–262 (2007).
15. Angular momentum is described by the formula $h = m r v$, where m is the mass, r is the radius of rotation, and v is the rotational velocity.
16. The details of this approach are explained in the detailed research publication by D. G. Korycansky et al. *Astronomical engineering: a strategy for modifying planetary orbits*. *Astrophysics and Space Science*, **275**, 349–366 (2001).
17. Dyson's original paper, *Search for artificial stellar sources on infrared radiation*, appeared in the journal *Science*, **131**, 1667 (1960).
18. Richard Carrigan, Jr. (Fermi National Accelerator Laboratory, Batavia, IL), has published a number of papers on Dyson sphere characteristics and searches, and these are available from his website: home.fnal.gov/~carrigan/index.htm.
19. The heat content of a spherical moon will vary according to its volume, which varies as the radius cubed (R^3). The energy radiated into space at its surface, however, will vary according to its surface area, which varies as the radius squared (R^2). The cooling time T_{cool} , therefore, will vary according to the ratio heat content divided by heat loss, and accordingly $T_{cool} \sim R^3 / R^2 = R$. So, the smaller the moon, the more rapid is its cooling time.
20. This is largely a selection effect in that those stars with massive planets located in small orbits produce the largest, and therefore most easily detected, Doppler effect variations in their spectra. A review of the Doppler detection techniques is given by Barrie W. Jones in his excellent book, *Life in the Solar System and Beyond*. Springer/Praxis Publishing, Chichester 2004. See also Vignette F, Note 23.

21. The essential composition at any point within a nebula is set by the temperature. Ices will not form, for example, until the temperature drops below 273 K.
22. Wayne Hayes and Scott Tremaine, Fitting selected random planetary systems to Titius-Bode Laws. *Icarus* **135**, 549–557 (1988).
23. See the highly comprehensive website *The Extrasolar Planets Encyclopedia*: exoplanet.eu/
24. The PPS hypothesis is described in Rory Barnes and Sean Raymond, Predicting planets in known extrasolar planetary systems I. Test particle simulations. *Astrophysical Journal* **617**, 569–574 (2004).

Epilogue

Chapter 4 opened with the scene of Nicolaus Copernicus on his deathbed. He was a man who did not live in vain, and his legacy lives on, an indelible point in history when human thought shifted away from the old, and began to embrace the new. During the final years of his life, however, this holy man had not wanted to publicly announce or defend his new astronomy. This was a task that fell on the shoulders of others. (Recall the vignette at the end of Chapter 5.) One of the philosophical problems, as Copernicus well knew, that his new hypothesis brought into play was that it displaced the Earth and its hapless cargo of human beings away from the center of all things. Humanity no longer resided at the very core of the cosmos. For Copernicus and his immediate followers, the Sun held station over that coveted central spot, and not even in 1618 when the ever-arrogant Galileo made his famous observation that the Sun must be rotating (as evidenced by the motion of sunspots) was its supreme position even remotely challenged.

Let time slip forward 350 years from the death of Copernicus (a time span of about 11 human generations). Now, we encounter the American astronomer and part-time philosopher, Harlow Shapley. By studying the distances to and the spatial distribution of globular clusters, Shapely was able to show in 1918 (just 90 years before the present, or a mere three human generations ago) that the Sun could not be situated at the gravitational center controlling their motion. The Sun's centrality was broken, and we now know that it is located some 8,000 parsecs away from the core of the Milky Way galaxy.

The marginalization of the Solar System was further enhanced by Edwin Hubble when in 1929 he combined his galaxy-distance estimates with the radial velocity data gathered by Milton Humason. The correlation between galaxy-recession velocity and distance, now known as Hubble's law (perhaps unfairly, given that

many people actually contributed to its discovery), revealed that the universe was uniformly expanding. The galaxies, caught like so much flotsam in an ever-roaring riptide, are all moving away from each other as the space between them expands in all directions. To some extent, this result places the Milky Way galaxy at the very center of the universe again, but it is only an apparent center. We live in a universe in which every point is the apparent center, and again, no one location is favored over another.

The ever-receding centrality and cosmic importance of Earth and its human cargo is often described under the rubric of the Copernican principle, which essentially states that we have no grounds for assuming ourselves to be special. In other words, we are not unique, we are not the first, and nor are we, most likely, the last intelligent life forms in the universe.

Well, of course, the basic tenet of the Copernican principle may or may not be true, but it is abundantly evident that if we—that is, humanity—want to survive into the deep future, then there are many serious and immediate problems (i.e., global warming, overpopulation, rampant poverty, and pollution of the environment) that must be addressed, and addressed with all haste. Harlow Shapley knew this and posed this question in his book, *Beyond the Observatory* (1967): “Civilization seems to have few active friends. Who cares deeply about its continuation? Who feels for it sufficiently to be willing to work for its prolongation?”

The answer, of course, is that we must look out for ourselves. Professor Stephen Hawking (University of Cambridge, England) has more recently picked up on this very theme and has argued that humanity must protect itself against future catastrophes by establishing new homes in space and on other planets.

In terms of human history, our immediate lives might only be affected by a maximum of three family generations: our parents, our grandparents, and our great grandparents. For most of humanity, however, now and in the past, direct ancestral connections probably only stretch back two generations. As individuals, our experience of the past is very limited, and yet human civilization is perhaps only 400 generations old, stretching back to 12,000 years before the present, when the first settled societies began to appear in ancient Mesopotamia. To the human brain, this seems an unimaginable time span, and yet to the Earth and nature it is the merest blink of

an eye. A humble creosote bush (*Larrea Tridentata*) has recently been found, for example, by Frank Vasek (University of California at Riverside) in the Mojave Desert that puts this into perspective. The bush is estimated to be some 11,700 years old. This one living shrub (and presumably others) has existed throughout the entire time interval over which humanity has risen from nomadic wanderer to planetary traveler, and here is our hope. Life is tenacious, and there are no specific reasons why humanity cannot thrive for another 400 generations (and many, many more) into the future. When we reflect upon what humanity has achieved over the last 400 generations, the next 400 will presumably yield many new and presently unimaginable wonders. Part and parcel of this vibrant, exciting future will be the freedom of human beings to live, work, thrive, and play on new worlds engineered within the great abundance that is our Solar System. Indeed, we should always remember that while the Copernican revolution ultimately removed the Sun and its planetary retinue from any supreme location within the universe, these celestial orbs are still at the very core of our long-term future, and it is to be hoped that they will provide humanity with new shelter and sustenance for many millennia yet to come.

Internet Resources

The Internet provides a great wealth of information on terraforming and future space colonization. Among the more useful websites are the following.

Solar System and Space Exploration

The eight planets—<http://seds.lpl.arizona.edu/billa/tnp/nineplanets.html>

Planetary photo journal—<http://photojournal.jpl.nasa.gov/index.html>

Earth fact sheet—<http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html>

Moon and Mars missions—<http://www.nasa.gov/topics/moonmars/index.html>

Planetary Science Institute—<http://www.psi.edu/>

The Planetary Society—<http://planetary.org/home/>

National Space Society—<http://www.nss.org/>

British Interplanetary Society—<http://www.bis-spaceflight.com/HomePage.htm>

British National Space Center—<http://www.bnsc.gov.uk/>

The Mars Society—<http://marsociety.org/portal>

Terraforming/Colonization

Terraformers Society of Canada—<http://society.terraformers.ca/>

Space Frontiers Foundation—<http://www.space-frontier.org/>

Resources page by Martyn Fogg—<http://www.users.globalnet.co.uk/~mfogg/index.htm>

Terraforming simulator for Mars—<http://www.users.globalnet.co.uk/~mfogg/simul.htm>

Terraforming—Autopoiesis—http://www.geocities.com/alt_cosmos/

Asteroid Search and Collision Avoidance

B612 Foundation—<http://www.b612foundation.org/index.html>

The Spaceguard Foundation—<http://cfa-www.harvard.edu/~marsden/SGF/>

Near Earth Object Program; current impact risk—<http://neo.jpl.nasa.gov/risk/>

NEO Space Mission Preparation (ESA)—<http://www.esa.int/SPECIALS/NEO/index.html>

The Torino Impact Hazard Scale—http://neo.jpl.nasa.gov/torino_scale.html

Astrobiology

The Astrobiology web—<http://www.astrobiology.com/>

NASA astrobiology—<http://www.astrobiology.arc.nasa.gov/>

The Goddard Center for astrobiology—<http://astrobiology.gsfc.nasa.gov/>

Astrobiology journal—<http://www.liebertonline.com/loi/ast>

Astrobiology magazine—<http://www.astrobio.net/news/>

The Society for Life in Space (SOLIS)—<http://www.panspermia-society.com/index.html>

Gaia/Global Warming/Human Population/Global Issues

Essays by James Lovelock—<http://www.jameslovelock.org/page0.html>

Essays by Sir Crispin Tickell—<http://www.crispintickell.com/>
Global warming—<http://www.globalwarming.org/primer>

World Population Clock—<http://math.berkeley.edu/%7egalen/popclk.html>

Earth's carrying capacity—http://en.wikipedia.org/wiki/Carrying_capacity

Global Issues—<http://www.globalissues.org/>

Glossary of Technical Terms

Albedo: The fraction of incoming solar energy reflected back into space.

Apelion: The point of greatest orbital separation from the Sun.

Aquifer: A permeable body of rock that can yield groundwater to wells and springs.

Astronomical Unit (AU): The semimajor axis of the Earth's orbit around the Sun. A distance corresponding to 149,597,870.69 km.

Brown dwarf: A gaseous body composed predominantly of hydrogen and helium with a mass in the range from 0.015 to 0.1 times the mass of the Sun.

Differentiation: The gravitational sorting of a body into layers of different density.

Doppler Effect: An apparent change in the observed wavelength of stellar spectral features due to the line of sight motion of the observer and star.

Ecliptic: The plane defined by the Earth's orbit as it moves around the Sun.

Electromagnetic spectrum: The wavelength region corresponding to the longest wavelength radio waves, through to the microwaves, the infrared, visible light, ultraviolet light, X-ray radiation, and the shortest wavelength gamma rays.

ESA: The European Space Agency.

Exosphere: The region of the upper atmosphere from which molecules escape into space.

Extremophiles: General name for bacteria that have adapted to survive in extreme (very hot, very cold, high salinity, high pressure, etc.) environments.

Greenhouse gas: A molecular gas that is efficient at absorbing energy in the infrared part of the electromagnetic spectrum.

Flux: The amount of energy flowing through a given area in a given time.

Heliopause: The boundary at which the solar wind no longer has enough energy to hold back the interstellar medium. This boundary is sometimes, incorrectly, taken to be the edge of the Solar System (see also Oort Cloud).

Hypoxia: Oxygen deficiency.

Insolation: The energy received from the Sun (see also albedo).

JAXA: The Japan Aerospace Exploration Agency.

Kirkwood gaps: Specific zones within the main asteroid belt region devoid of asteroids because of orbital resonances with Jupiter. (See also resonance.)

Kuiper Belt Object: An object predominantly made of ice and silicate material that orbits around the Sun in the outer Solar System beyond the orbit of Neptune in a plane close to that of the ecliptic (hence, also known as Trans-Neptunian Object). The region is also called the Kuiper–Edgeworth belt.

Luminosity: The total amount of electromagnetic energy radiated into space per unit time.

Main sequence star: A star that is converting hydrogen into helium through fusion reactions within its central core.

Magnetosphere: The region around a planet (or moon) in which the magnetic field dominates and directs the motion of the solar wind's charged particles.

Nebula model: A model for the origin of the Solar System, in which an interstellar gas cloud collapses under the influence of gravity and rotation to form a flattened disk out of which the planets form by accretion.

Oort Cloud: A vast cloud of many trillions of cometary nuclei that orbit the Sun out to distances of several hundred thousand astronomical units. The Oort Cloud defines the outer boundary of the Solar System.

Perihelion: The point of closest orbital approach to the Sun.

Planet, dwarf: A spherical object that orbits the Sun but has not cleared the regions close to its orbital track of other smaller Sun-orbiting bodies.

Planet, Jovian: A massive planet composed mostly of hydrogen and helium.

Planet, terrestrial: A planet composed of an iron core and a silicate mantle.

Photosynthesis: The manufacture of organic compounds from carbon dioxide and water, with the simultaneous liberation of oxygen.

Photolysis: The use of radiant energy to produce a chemical change.

Planetesimal: Small-sized, solid ice/rock/metal body formed in the early Solar System prior to planet building.

Regolith: A layer of finely fragmented rock on the surface of a planet, moon, or asteroid.

Resonance: When the orbital period of one object is a simple fraction of the orbital period of another. Prominent Kirkwood gaps, for example, occur in the main belt asteroid region for asteroids with orbital periods of one-half, one-third, one-fourth that of the Jupiter's.

Solar wind: A stream of charged particles that emanates from the Sun and travels out into the Solar System.

Soleta: A large space mirror used to warm the surface of a planet or moon.

Statite: A solar sail positioned sufficiently close to a planet so that it remains fixed in position relative to the line joining the Sun and the planet.

Vapor pressure: The pressure of a vapor in equilibrium with a liquid or solid surface.

Appendix A:

Blackbody Radiators

At the beginning of the twentieth century, German physicist Max Planck developed the quantum mechanical theory that underpins the study of blackbody radiators. Planck's initial research paper was literally groundbreaking, and it presented a solution to the so-called ultraviolet catastrophe predicted by classical theory. Indeed, Planck had to introduce the then bizarre and extreme idea of quantized energy.

The theory of blackbody radiation deals with the manner in which a perfect radiator of temperature T (measured in Kelvin) emits electromagnetic energy into space as a function of wavelength. Figure A.1 shows how the amount of energy radiated by a blackbody into space per square meter of its surface per second per unit wavelength (the energy flux or intensity) varies with wavelength. The key point is that at very long and very short wavelengths the energy flux is extremely small and that there is a well-defined maximum energy flux at a wavelength λ_{max} .

One of the key early experimental results concerning blackbody radiators was discovered by Wilhelm Wien, who noted that the product $T \lambda_{\text{max}} = \text{constant}$, where T is the characteristic temperature of the blackbody. A second laboratory-derived result was the so-called Stefan–Boltzmann law, which relates the total energy radiated into space by the blackbody over all wavelengths per square meter, F , to the temperature: $F = \sigma T^4$, where σ is the Stefan–Boltzmann constant.

The manner in which the Sun and the planets radiate energy into space can be approximately described by blackbody radiation theory, and this is how Equation (5.1) is derived, the essence of the derivation being that the planet receives a certain amount of energy per meter squared per second from the Sun, and this warms the planet. The planet, upon being warmed, then reradiates energy back into space according to the Stefan–Boltzmann law, and an

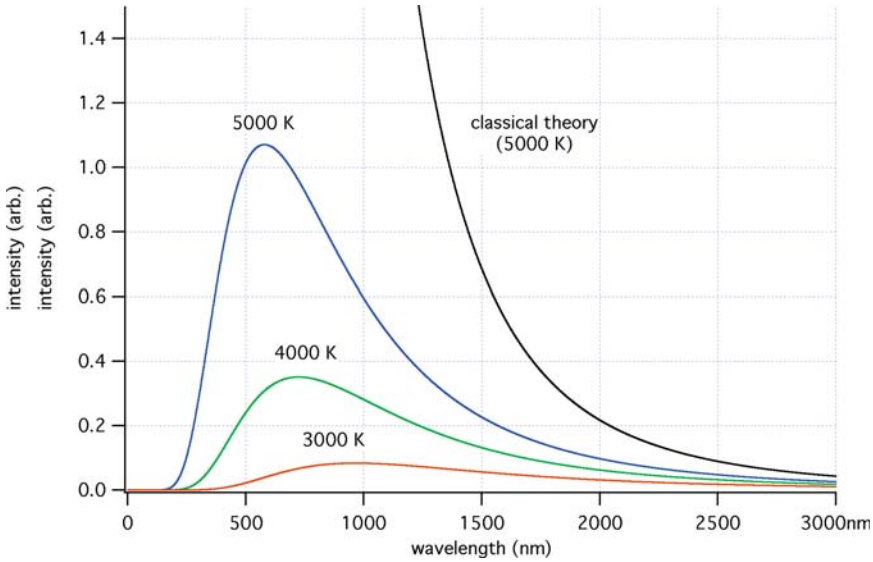


FIGURE A.1. Planck curves for various temperature blackbody radiators. The wavelength is given in units of nanometers (nm), which corresponds to 10^{-9} m. The intensity is plotted on a relative scale rather than absolute values. The curve labeled “classical theory” illustrates the origin of the ultraviolet catastrophe in that the intensity isn’t predicted to drop to small values at short (i.e., at UV, X-ray, and gamma-ray radiation) wavelengths. The quantum mechanical theory developed by Max Planck correctly predicts the laboratory-measured decline in the intensity at short wavelengths. Light has a characteristic wavelength of about 10^{-7} m, whereas ultraviolet radiation has a characteristic wavelength of 10^{-8} m. Infrared radiation and radio waves have wavelengths of order 10^{-6} to millimeters and meters, respectively.

equilibrium between energy received from the Sun and energy radiated back into space by the planet is eventually achieved at a characteristic temperature T_p .

The wavelengths at which the Sun, Earth, and Mars emit the greatest amount of energy can be determined from Wien’s law, and from their characteristic temperatures of 5,780, 288, and 213 K, we have $\lambda_{\text{max}}(\text{Sun}) = 5.0 \times 10^{-7}$ m, $\lambda_{\text{max}}(\text{Earth}) = 1.0 \times 10^{-5}$ m, and $\lambda_{\text{max}}(\text{Mars}) = 1.4 \times 10^{-5}$ m. From these numbers it can be seen that most of the Sun’s energy is radiated at visible wavelengths, while the Earth and Mars radiate most copiously at infrared wavelengths.

Appendix B:

Accounting for Greenhouse Gases

The heating effect due to greenhouse gases comes about because molecules only interact with very specific wavelengths of electromagnetic radiation. The Sun mostly provides energy for heating in the form of visible light, but at these relatively small wavelengths ($\lambda \approx 10^{-7}$ m) there is little direct absorption by atmospheric molecules. Hence, sunlight can penetrate through a planet's atmosphere to heat the ground. The planet, however, being much cooler than the Sun, characteristically radiates its energy back into space at much longer, infrared wavelengths ($\lambda \approx 10^{-5}$ m). The greenhouse-heating

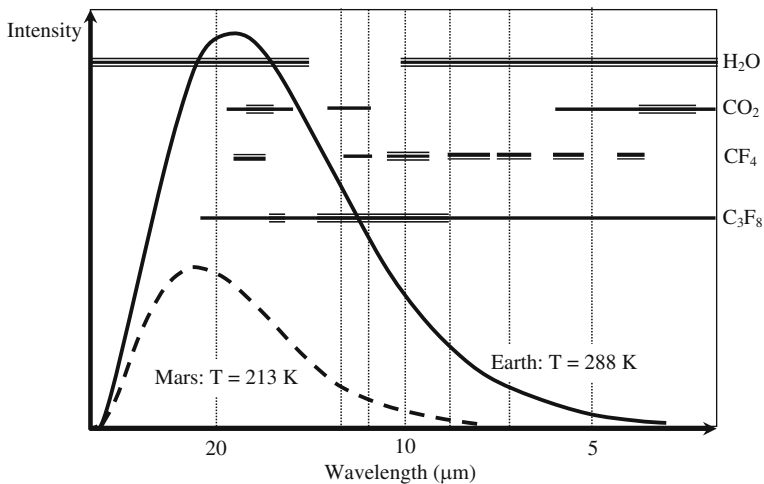


FIGURE B.1. Wavelength absorption bands corresponding to various greenhouse gases. Thick lines represent strong absorption bands, whereas thin lines represent weak absorption regions. The height of the absorption bands in the diagram is schematic and not intended to indicate relative absorption strengths. The wavelength axis is plotted on a logarithmic scale. Diagram based upon data published by Marinova et al. *Journal of Geophysical Research*, **110**, E03002 (2005).

effect now comes into play, since molecules in the atmosphere can readily absorb energy at infrared wavelengths.

The so-called absorption bands over which molecules absorb energy can be mapped out in the laboratory, or they can be determined through detailed quantum mechanical calculations. Figure B.1 shows a comparison of the positions of the absorption bands for several greenhouse gases with respect to the blackbody radiation curves for the Earth and Mars.

Appendix C:

A Terraforming Simulator Model for Mars

Equation (5.1) describes the direct surface-heating effect due to solar radiation. To account for the greenhouse-heating effect, however, the composition of the atmosphere must be specified. The key greenhouse gases we shall consider are carbon dioxide (CO_2), water vapor (H_2O), methane (CH_4), ammonia (NH_3), CFCs, CF_4 , and C_3F_8 . Without going into the details behind the calculations, we will simply present a set of approximation equations that describe the opacity terms (τ) as determined and/or published by Martyn Fogg, Christopher McKay, Robert Zubrin, and Margarita Marinova. The opacity of a gas is essentially a measure of how effective it is at trapping the outflowing infrared radiation—the larger the opacity term the greater is the greenhouse-heating effect. The key opacity terms we have are

$$\tau_{\text{CO}_2} = 1.2 P_{\text{total}}^{0.45} P_{\text{CO}_2}^{0.11}$$

$\tau_{\text{H}_2\text{O}} = \frac{4}{3} P_{\text{H}_2\text{O}}^{0.3}$, where $P_{\text{H}_2\text{O}} = R_h P_0 \exp(-L/R T_A)$ and $R_h = 0.7$ is the relative humidity, $P_0 = 1.4 \times 10^6$ is a reference pressure, $L = 43655 \text{ J/mol}$ is the latent heat, and $R = 8.314 \text{ J/K/mol}$ is the gas constant.

$$\tau_{\text{CH}_4} = \frac{2}{3} P_{\text{CH}_4}^{0.278}$$

$$\tau_{\text{NH}_3} = 12.8 P_{\text{NH}_3}^{0.32}$$

$$\tau_{\text{CFC}} = \frac{4}{3} \frac{1.1 P_{\text{CFC}}}{(P_{\text{CFC}} + 1.5 \times 10^{-7})}$$

$$\tau_{\text{CF}_4} = 352.144 P_{\text{CF}_4}^{0.682}$$

$$\tau_{\text{C}_3\text{F}_8} = 987.22 P_{\text{C}_3\text{F}_8}^{0.591}$$

The units for the partial pressure terms are given in bars, where $1 \text{ bar} = 10^5 \text{ Pa}$. The partial pressures of CH_4 , NH_3 , CFCs, CF_4 , and C_3F_8 will typically be expressed in microbars ($1 \text{ } \mu\text{bar} = 10^{-6} \text{ bar} = 0.1 \text{ Pa}$), while the CO_2 partial pressure is usually expressed in millibars ($1 \text{ mbar} = 10^{-3} \text{ bar} = 100 \text{ Pa}$). An important point to note at this stage is that the water-vapor pressure $P_{\text{H}_2\text{O}}$ varies according to the surface temperature T_A . Dalton's law dictates that the total atmospheric pressure is the sum of partial pressures: $P_{\text{total}} = P_{\text{NG}} + P_{\text{CO}_2} + P_{\text{H}_2\text{O}} + P_{\text{CH}_4} + P_{\text{NH}_3} + P_{\text{CFC}} + P_{\text{CF}_4} + P_{\text{C}_3\text{F}_8}$, where P_{NG} corresponds to the partial pressure of nongreenhouse gases such as N_2 and O_2 . The model calculation proceeds by first setting values for the individual pressure terms; some characteristic values for these terms are provided in Chapter 6. Note that we need not specify the water-vapor pressure term $P_{\text{H}_2\text{O}}$, since it is evaluated in terms of the surface temperature T_A .

In total, there are eight parameters that can be varied in this model Martian atmosphere, and they are: the albedo A , the insolation term $S / S_0 = L_{\odot}(\text{at time } t) / L_{\odot}(\text{now})$, and the partial pressure terms for the CO_2 , CH_4 , NH_3 , CFC, CF_4 , and C_3F_8 components. The mean surface temperature is now expressed through the equation:

$$T_A = T_p S^{1/4} (1 + \frac{3}{4} [\tau_{\text{CO}_2} + \tau_{\text{H}_2\text{O}} + \tau_{\text{CH}_4} + \tau_{\text{NH}_3} + \tau_{\text{CFC}} + \tau_{\text{CF}_4} + \tau_{\text{C}_3\text{F}_8}])^{1/4}$$

where T_p is determined according to Equation (5.1) with the orbital distance being that of Mars ($D = 1.52 \text{ AU} = 2.2739 \times 10^{11} \text{ m}$). Once all the constant and input parameter terms have been specified, then the procedure for calculating T_A is illustrated in Figure C.1. Having found the mean surface temperature, the approximate temperatures at the Martian equator and poles can be calculated as $T_{\text{equator}} = 1.1 T_A$, and $T_{\text{pole}} = T_A - 75 / (1 + 5 P_{\text{total}})$. The latitude extent (above and below the equator) to which the temperature might be above 273 K (that is, the freezing point) is determined through the equation: $\lambda_{\text{habitable}} = \arcsin\{[(273 - T_{\text{equator}}) / (T_{\text{equator}} - T_{\text{pole}})]^{2/3}\}$. Most computers/calculators will return the "arcsin" quantity in units of radians, so the number needs to be multiplied by $180 / \pi \approx 57.2958$ to convert the result to the more familiar units of degrees. For example calculations see the various graphs presented in Chapter 6.

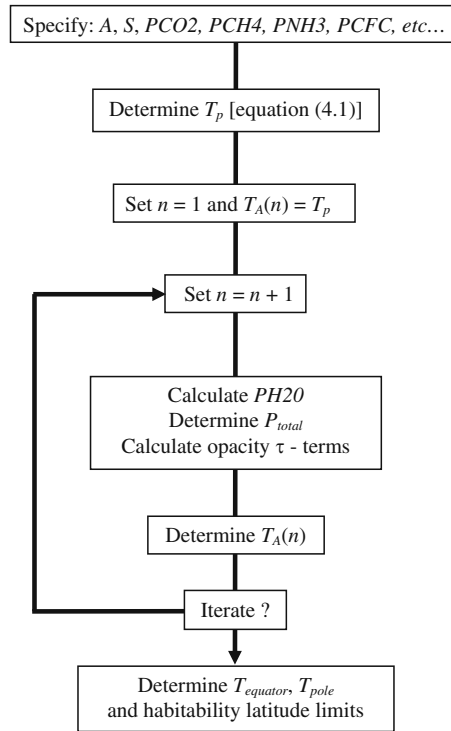


FIGURE C.1. Pseudo computer-code flowchart for the evaluation of T_A . The need for an iteration loop comes about because P_{H_2O} varies according to the mean temperature T_A ; the iteration should continue until the difference $T_A(n) - T_A(n-1) < 10^{-5}$. Convergence is fairly rapid, and typically only four or five iterations are required to determine the final value for T_A .

Once the polar ice caps of Mars have been warmed by about 20 K, the runaway degassing of CO_2 will begin to occur (recall Figure 6.15). Under these circumstances the input conditions for the model will require modification in order to take into account the increased atmospheric CO_2 abundance and its associated partial pressure. Exactly how much CO_2 might be liberated from the fully degassed Martian polar caps and regolith is presently unclear, but it is estimated to be equivalent to an additional 100–400 mbar of atmospheric pressure. The procedure described in Figure C.1 is not capable of following the time evolution of CO_2 during the runaway stage, so this quantity will have to be “added in” as an increment to P_{CO_2} .

Appendix D:

Population Growth and Lily World

The mathematical details that underscore the topics of population growth, the estimation of future populations, and the determination of the Earth's carrying capacity at a specific epoch are highly complex, and the full details are not what we need to worry about here. The researchers who study such topics, however, usually analyze the predictions of their models in terms of the so-called r - and K -processes (although other names have been used to describe the behaviors observed).

An r -process, also called a Malthusian process, describes the growth in population numbers when there are absolutely no checks on how many individuals the environment can support. Under these circumstances the population grows exponentially, with a growth rate r such that at time t the population $P(t) = P(0) \exp(r t)$, where $P(0)$ is some initial population at a reference time $t = 0$. Provided $r > 0$, then the population must always increase, and as $t \Rightarrow \infty$, so the $P(t) \Rightarrow \infty$, with the population becoming ever larger. Clearly no such population can really exist; there has to be a point at which the population exceeds the carrying capacity, and at this moment the population tends to crash catastrophically, and, rather than the apparently utopian $P(t) \Rightarrow \infty$ as $t \Rightarrow \infty$, it is found that $P(t) \Rightarrow 0$ as $t \Rightarrow \infty$, indicating that extinction has occurred.

The classic example of an r -process growth strategy is that associated with algae blooms such as what is known as a Red Tide. In these circumstances, so many bacteria form in estuarine regions that the water is literally turned red, the characteristic color of the dinoflagellates producing the bloom. Such algae blooms thrive until the entire regional food and oxygen supply is depleted, at which point the algae population dies off in a terminal Malthusian meltdown. Under r -process growth strategies, the population invariably follows a boom to bust to extinction pathway.

In contrast to the r -process, the K -process, or logistic model, as it is often called, describes the population growth when the carrying capacity K is taken into account. In this situation, as the population increases and approaches the carrying capacity, so the growth rate decreases, and after some finite time T_K the population reaches and stays at its maximum possible value, with $P(t) = K$ for all $t > T_K$. Under the K -process, a population need not necessarily crash or undergo a Malthusian meltdown—provided the carrying capacity truly remains constant with time, a situation that need not necessarily apply.

By way of illustrating how the r - and K -processes work, let us consider “Lily World.” There isn’t much to Lily World; it is a square, 1-km-sided lake with a surface area of 1 km^2 and a depth that we needn’t worry about. Upon Lily World grow square water lilies, each of which, when fully formed, has a surface area of 1 cm^2 (Figure D.1). All that a new lily needs in order to thrive in this imaginary (and certainly idealized) world is enough room to grow to its full size—that is, to 1 cm^2 .

Now, the ratio of the area of a single water lily to the area of the entire lake is 10^{-10} ; in other words, a fully covered Lily World can support up to a 10 billion water lilies. This is Lily World’s carrying capacity. In the case of Lily World we know what the carrying capacity is from the very outset (for Earth this quantity is still a

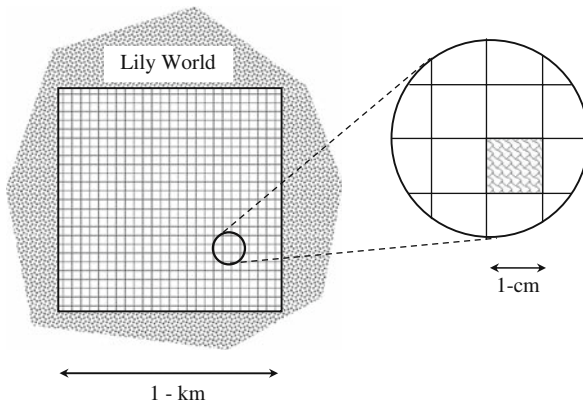


FIGURE D.1. The kingdom of Lily World is a 1-km-sided square of water upon which identical 1-cm-sided square lilies can grow. It is a finite world that can support at any one instance a maximum of 10 billion lilies.

debated issue), and the question that now arises is how long it will take before the carrying capacity is exceeded. Let us begin by setting up a time step of, say, one day such that we can express the growth rate in Lily World as the number of lilies that are produced and die per day.

As a first example, let us assume that each lily once formed lives forever (i.e., the death rate is zero per day). Under these circumstances, the population will just keep growing until the carrying capacity of Lily World is reached, and then the birth rate will switch to zero births per day. We can now ask how long might it take for the birthrate of lilies to go to zero? The answer to this question is simply the length of time it takes to generate 10 billion lilies (assuming we start with just one lily), since at this point the total area of all the lilies will equal that of Lily World—1 km². If we assume that the number of lilies doubles every day, then the population will increase in the following manner: 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024 . . . and so on, such that after T days the population will be $2^{(T-1)}$. With this doubling birthrate, the carrying capacity of Lily World will be exceeded after just 33 days, since $2^{33} = 8.6$ billion, and $2^{34} = 17$ billion. It is incredible to think that given a population that doubles every day a single 1-cm square water lily, which could be comfortably held in the palm of one's hand, can within the time span of about a month become a legion 10-billion strong covering an entire 1 km² of water. To go from something so small and harmless to a population that literally throttles its world is sobering, and it is representative of a key problem that humanity must, in the very near future, deal with.

One important point to note from the population numbers for days 33 and 34 is that the buildup to exceeding the carrying capacity is exceptionally rapid. The population of lilies does not creep up to its limit. It literally crashes right through it. If we look at the area occupied by the lilies compared to the carrying capacity [i.e., the ratio $A = N(T) \times 1 \text{ cm}^2 / 1 \text{ km}^2$, where $N(T)$ is the number of lilies on day T], then on day 33, $A = 0.43$, on day 34, $A = 0.86$, and on day 35, $A = 1.72$. In this case, we see the remarkable situation that just 2 days before the final collapse of Lily World, the area occupied by the lilies is less than half of the carrying capacity. One day before the collapse (day 32), 14% of Lily World is still open for colonization. On day 34, if it were actually possible, the number of lilies would occupy an

area nearly twice as large as the carrying capacity of Lily World. After 40 days, again if possible given the initial assumptions, the combined area of lilies would cover a 110 km^2 lake.

If, as opposed to doubling every day, the number of lilies trebled every day, then the carrying capacity of Lily World would be exceeded after just 22 days, and if the number of lilies doubled every fifth day (say), then the carrying capacity would be exceeded after some 170 days. By now, the end result should be clear and obvious, and as Thomas Malthus so aptly stated the situation in 1798, "The increase of population is necessarily limited by the means of subsistence."

Let us try another model. Clearly, as we assumed earlier, lilies do not live forever, and so let us introduce a death rate. Again, let us take an idealized death rate (given that such a terminal experience can be idealized) such that after a finite number of days a lily simply disappears, leaving its previously occupied area ready for a new lily to grow into. Keeping the growth rate to be the same as in our earlier example, such that the population on day T is equal to twice that of the population alive on day $T-1$, and also imposing a finite lifetime of (say) 8 days, what now is the time to reach the carrying capacity of Lily World? The day-by-day increase in the number of lilies will now proceed in the following manner: 1, 2, 4, 8, 16, 32, 62, 128, 256, 510, 1016 ... and so on. We can see in this sequence that the effect of the death rate kicks in on day 10, when the number of lilies is 510 rather than 512, when the death rate is zero. So, we can see that the population of lilies is increasing more slowly, but the inevitable still occurs, and the carrying capacity of Lily World is exceeded after just 35 days. This result shows that if lilies live for 8 days then Lily World lasts just 2 days longer than the utopian case when lilies never die.

Again, if we look at the area ratio of lilies to the carrying capacity, then on day 35, $A = 0.78$, and on the day 36, if further growth was allowed, $A = 1.55$. Once again, the approach to the carrying capacity is extremely rapid, and the population of lilies on day 35 could be excused (if they were sentient) from thinking that anything about their future was amiss, since some 23% of Lily World would still be open for colonization. If the lifespan of an individual lily is reduced to say 4 days, then the population increases as 1, 2, 4, 8, 16, 30, 56, 104, 192, 352, 644 ... , and the

carrying capacity is exceeded between days 39 and 40, extending the lifetime of Lily World by about a week compared to the infinite lily lifetime calculation. The shorter the lifetime of the lilies, so the greater is the amount of time required to approach the carrying-capacity limit, but the point is, the population always reaches the carrying-capacity limit if the birthrate is greater than the death rate.

As a final example, let us consider the situation where the birth rate of lilies varies according to the following rule: When $A < 1$, then $\text{Births}(T) = (1 - A) [2 * \text{Births}(T-1) - \text{Deaths}(T-1)] + A * \text{Deaths}(T-1)$. This rule says that when the total area of lilies is very much less than the carry capacity of Lily World (this is the $A \ll 1$ condition), then the number of births at a given time T is determined by the number of lilies alive at time $T-1$ minus the number of lilies that will have died since time $T-1$. In addition, while $A < 1$, the amount by which the number of lilies increases in each time interval is weighted by the factor $(1 - A)$, and this indicates that when A is small this factor will have virtually no effect, but as A gradually increases so the weighting term decreases.

If we think a little more about how this rule is going to work, we can see that there are two limits. To begin with, when A is near zero, the birth rate increases as described in our second example, where the number of lilies doubles on each time step and each lily lives for a fixed number of days. As the carrying capacity of Lily World is approached, however, so $A \Rightarrow 1$, and the birthrate will begin to approach an equilibrium with the death rate; in other words, the population is no longer increasing but simply maintaining a dynamic balance, with births and deaths marching on, adding to and extracting lilies from the total population exactly in step. In this fashion, although each lily still only lives for a finite amount of time, Lily World will last forever, supporting lilies at its maximum capacity (corresponding to $A = 1$).

If we now go back to the calculation in which each lily lives for 4 days, then the population initially increases in exactly the same manner as 1, 2, 4, 8, 16, 30, 56, 104, 192, 352, 644 ... Rather than exceeding the carrying capacity between days 39 and 40, however, with the new birthing rule the population levels off after day 40 and remains constant for all times $T > 40$ days. Rather than Lily World lasting for just an extra week due to the finite lifetime of each lily, it now lasts indefinitely. The manner in which the ratio of the total

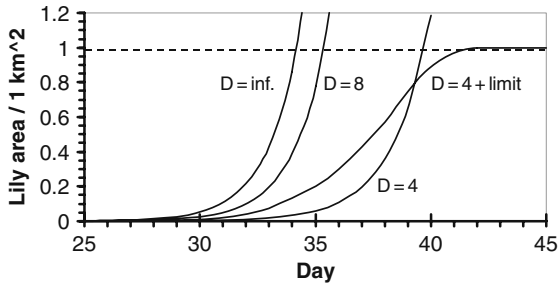


FIGURE D.2. The variation of the ratio of the total area of lilies to the carrying capacity (A) for the various scenarios described in the text. The time interval shown is from day 25 onward, since for all time steps prior to the 25th day the area ratio is essentially zero. The carrying-capacity limit occurs at $A = 1$, and if the population exceeds this limit then collapse is inevitable (the collapse is not shown in the figure). The D labels indicate the lifetime of each lily: $D = \infty$ corresponds to an infinite lifetime, while $D = 8$ indicates a lily lifetime of 8 days and $D = 4$ indicates a lily lifetime of 4 days. The $D = 4 + \text{limit}$ curve corresponds to the situation where the birthrate approaches the death rate as A approaches unity.

area of lilies compared to the carrying capacity of Lily World (the A term) varies with time is illustrated in Figure D.2. The lines labeled $D = \infty$, 8, and 4 in the figure correspond to r -process or Malthusian growth, while the curve labeled $D = 4 + \text{limit}$ is a K -process, or logistic model growth.

What are the lessons to be learned from the idealized workings of Lily World? Perhaps the first lesson is that Thomas Malthus, writing in 1798, was exactly right, and that in a world with finite resources the population cannot increase indefinitely. There is a limit to the population that any finite world can support (irrespective of any increase in the food yield per acre of land bioengineering might produce), and if the population exceeds that limit, then it is doomed. Second, we find that if the number of births over a given time interval is greater than the number of deaths in that same time interval, then the carrying capacity will always be exceeded (sooner or later), and the population must necessarily crash. A stable, long-lived population of lilies that fully utilizes the available carrying capacity, however, can be produced, but this situation requires that the rate of increase in the population be carefully controlled so that the net growth rate (i.e., the number of births minus the number of

deaths in any given time interval) goes to zero as the population approaches the carrying limit.

In Lily World the carrying capacity (by construction) was known from the very outset. The problem in the real world is that there is no consensus between researchers as to what human population the Earth can reasonably carry. The only point and it is a key point that all researchers do agree upon is that the Earth's carrying capacity has almost certainly been reached, and indeed, many researchers also believe that it was actually breached some time ago. Irrespective of whether we are talking about the Earth or a terraformed Mars or Venus, or even a Ceres world, the message for humanity is the same: utopias (if one dares to use such a word) can come about, but they are fragile, finite, and subject to change. Most importantly, however, it is abundantly clear that no one world (utopian or otherwise) can support for very long an unconstrained increase in its population.

Index

- Albedo, 83, 145, 154, 169, 177
- Angular momentum, 207, 233, 259
- Annis, James, 208
- Anthropocene, 12
- Archimedes, 148
- Asteroids
 - B612, 220, 266
 - Ceres (Dwarf planet), 46, 52, 222
 - C-type, 224
 - Itokawa, 166
 - living in, 220, 226, 246
 - main belt, 48, 114, 220, 235
 - Matilda, 221
 - mining, 193, 225
 - Vesta, 46, 225
- Atmosphere
 - breathable, 161, 227
 - pressure, 88, 91, 172, 228
 - retention of, 100
- Atomic mass, 90

- Bigelow Aerospace, 201
- Biomarkers, 251
- Biosphere project, 16, 165, 230
- Birch, Paul, 150, 198, 226
- Blackbody radiator, 273
- Black holes, 232
- Black smokers, 241
- Brahe, Tycho, 125
- Brown dwarfs, 231
- Buckminster-Fuller, 16
- Burns–Harwit maneuver, 141

- Canadian Space Agency, 159
- Carba, 197
- Carrigan, Richard, 259
- Carrying capacity, 70, 74, 167, 267, 282, 287
- Carter, Brandon, 248
- CFCs, 103, 153
- Chomolungma
 - Mt. Everest, 55, 88, 179
- Cloud life, 183, 202, 225
- CO₂ cycle, 106
- Cole, Dandridge, 220, 246

- Comets
 - Churyumov-Gerasimenko, 166
 - Halley, 47
 - Tempel–Tuttle, 58
- Copernicus, Nicolaus, 45, 53, 125, 261
- Cosmic rays, 205, 215
- Creosote bush, 263
- Crutzen, Paul, 3
- Cyanobacteria, 7, 39, 194

- Daisy World, 145, 155, 167
- Dalton's law, 90, 278
- Dawn mission, 225
- Debris disk
 - planet formation, 112
 - planetary shade, 191
- Deuterium burning, 236
- Dole, Stephen, 227
- Dyson, Freeman, 193, 221, 232, 236

- Earth
 - atmosphere, 57
 - formation, 115, 186
 - magnetic field, 59
 - oceans, 81
 - orbit change, 235–236
 - ozone layer, 58, 103, 154
 - tabulated, 54
 - tectonic plates, 56, 167
 - temperature, 83
- Ecopoiesis, 10, 157
- Ecosystem
 - height variation of, 89
 - Martian, 159
- Environmental impact, 63
- Eucatastrophy, 7, 116
- Europa, 86, 93, 238
- Exoplanets, 32, 43, 96, 118, 211, 246, 250
 - 55 Cancri, 246
 - Gliese 581, 247
 - HD 74156, 257
 - Mu Ara, 256
- Extinction, 249, 281
- Extremophiles, 39, 78

290 Index

- Feedback cycles, 105, 107
- Fogg, Martyn, 43, 118, 151, 157, 194, 211, 233, 250, 277
- Fractal, structure, 128
- Freitas, Robert, Jr., 200
- Gaia, 105, 168, 173, 266
- Galileo, Galilee, 175, 232, 259, 261
- Gauss, Carl Friedrich, 126
- Geoengineering, 3, 68
- Gilbert, William, 60
- Gillett, Stephen, 195, 196
- Gladman, Brett, 26, 42, 240
- Global warming, 74, 189
- Greenhouse effect
 - Earth, 84, 101, 110
 - moist, 71, 123, 182, 195
 - Planets, 85, 152
- Greenhouse gases, 103, 275
- Habitability
 - general, 96, 118, 235, 246
 - Gliese 581, 248
 - human, 224, 227
 - zone, 111–112, 133, 137, 266
- Hawking, Stephen, 262
- Homesteading, 222
- Houseman, A. E., 253
- Hoyle, Sir Fred, 35, 77
- Hubble, Edwin, 261
- Huygens mission (ESA), 92
- Ice
 - Antarctica, 24
 - Arctic, 1, 4
 - water, 55, 235
- Ideal gas law, 89
- International Space Station, 158, 201, 216
- Interstellar colonization, 250, 262
- Io, 86, 232, 241
- Jupiter
 - cloud life, 225
 - formation, 115
 - interior, 231
 - moons, of, 232, 238
 - stellifying, 233, 237
- Kardashev civilizations, 208
- Kasting, James, 96, 111, 207
- Kelvin scale, 82
- Kepler, Johannes, 47, 119, 125
- Kroll-Melankovich cycle, 140
- Kugluktuk, 2
- Kuiper belt objects, 50, 144, 152, 189, 235
- Kyoto, Accord, 3
- Lagrange points, 189, 195
- Leonid meteors, 58
- Lewis, Clive Staples, 175, 177, 206
- Life, 37
- Lily World, 281
- Lovelock, James, 109, 153, 168, 266
- McKay, Christopher, 148, 150, 156, 277
- Malthus, Rev. Thomas, 66, 281, 286
- Marciana, 77
- Mars
 - atmosphere, 146, 161, 277
 - comparative ages, 134
 - Express (ESA), 137
 - Global Surveyor, 130
 - habitability, 21
 - paleoshorelines, 132
 - Phoenix Lander, 23
 - tabulated, 129
 - Viking Landers, 75
 - water on, 130, 136
- Mautner, Michael, 36, 159
- Maxwellian gas, 98, 212
- Maxwell, James Clerk, 97
- Maxwell Montes, 179
- Melosh, Jay, 32
- Mercury
 - destruction of, 71
 - impacts on, 115, 217
 - MESSENGER, 217
 - mining, 196
 - terminator, 219
 - water ice on, 217
- Meteorites
 - ages of, 112, 123
 - ALH84001, 24
 - interstellar, 33
 - Martian, 159
 - Nakhla, 23, 25, 34
 - planet exchange of, 26, 32, 177
 - Tagish Lake, 31
- Microbes
 - activity of, 25, 159
 - ethical rights, 40
 - survival in space, 34
 - toxicity of, 224
- Micrometeoroids, 57, 205, 212, 257
- Midgley, Thomas, 103
- Miller–Urey experiment, 28, 108
- Miller, Stanley, 29

- Mining
 - atmospheric, 186, 244
 - impact, 153, 199, 242
 - thermonuclear, 151, 213
 - solar, 232, 236
- Montreal Protocol, 104
- Moon
 - Apollo missions, 203, 229
 - atmosphere, 212, 257
 - colonies, 166, 216, 223
 - mining, 204
 - origin, 186
 - Shackleton crater, 205
- Nanotechnology, 195
- Neptune, 46, 244
- Newton, Sir Isaac, 46, 126, 247
- Nunavut, 2
- Oberg, James, 194, 221, 242
- O'Neill, Gerald, 66, 222, 229
- Oort Cloud, 49, 79, 152, 235
- Oxford University, 162
- Panspermia, 31, 222
- Penrose, Roger, 233
- Phobos, 144, 160
- Photodissociation, 96, 182, 200
- Photosynthesis, 109, 184, 194, 252
- Pico-sats, 190
- Pluto, 48, 223, 245
- Population, 61, 267, 281
- Potter, Harry, 41
- PPS hypothesis, 257
- Proxima Centauri, 32, 49
- Red Tide, 281
- Robinson, Kim Stanley, 219
- Sagan, Carl, 138, 155, 183, 225
- Saturn, 194, 242
- Self-replicating systems, 200
- SETI, 238, 248, 257
- Shapley, Harlow, 261
- Solar constant, 84
- Solar sails, 156, 192
- Solar System
 - contents, 48, 51, 254
 - origin, 112, 254
- Solar wind, 213
- SOLIS, 36, 266
- Space tourism, 201
- Stars
 - main sequence, 249, 251
 - minimum mass, 231, 258
 - M–L relationship, 122
- Statite, 156
- Stonehenge, 164
- Sun
 - energy output, 70, 83, 236
 - evolution of, 68
 - interior, 231
 - planetary nebula, 72
 - rejuvenation, 74, 111, 250
- Super-Earths, 118, 246, 252
- Supramundane planets, 226, 233, 244
- Taylor, Richard, 165
- Tellurium, 180, 206
- Temperature, equilibrium, 83, 87, 155, 278
- Terraforming
 - etymology of, 9
 - Mars, 14, 142
 - Venus, 14, 175
- Terrestrial Planet Finder, 252
- Tikopia, 67, 79
- Titan, 27, 92, 95, 153, 243
- Titius–Bode law, 46, 247, 254
- Tolkien, J. R. R., 7
- Tremolite, 183
- Uranus, 46, 194, 244
- Urey, Harold, 29
- Venus
 - atmosphere, 188
 - cloud life, 183, 185
 - cooling, 189
 - destruction of, 71
 - Express (ESA), 176, 183
 - greenhouse effect, 86
 - ocean, 195
 - surface of, 20, 178, 181
 - tabulated, 176
- Water
 - oceans, 81, 239
 - phase diagram, 93, 137
- Weathering, 106, 200
- Wells, Herbert George, 126
- West-Edmonton Mall, 15
- Wickramasinghe, Chandra, 35, 77
- Wien's law, 102, 238
- Worldhouse, 165, 226, 242
- Zubrin, Robert, 150, 156, 277