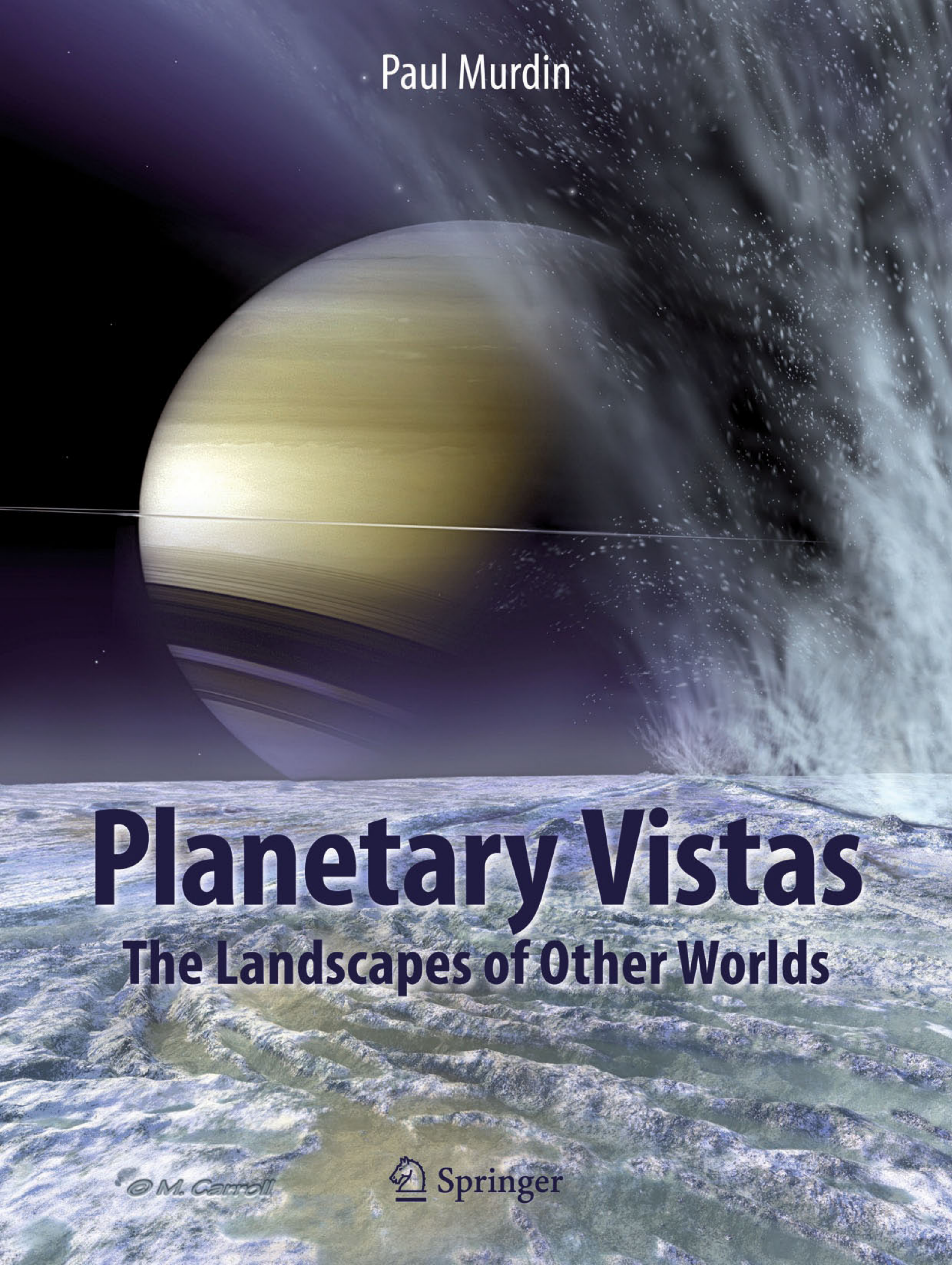
Paul Murdin

Planetary Vistas

The Landscapes of Other Worlds



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Planetary vistas on Earth and Mars: exploration and discovery.

Fig. 1 Northeastern view from the northern top of Mount Kosciusko by Eugene von Guérard (1811-1901). In 1862, von Guérard participated in an expedition to Mount Kosciusko, Australia's highest mountain, led by the Bavarian scientist Georg von Neumayer (1826-1909). The expedition served to improve the map of Australia, e.g., by measuring the heights of mountains as well as measuring Earth's magnetic field. In this painting of 1863, Neumayer is the person in the foreground, making scientific observations with an instrument, perhaps a barometer; his assistant, two guides and his dog Hector are also discernible among and against the rocks and the snow of the mountain top. Devoid of noticeable vegetation, the scene could almost be of another planet like Mars, except for the people and the cloudy, rainy sky. The picture is a painting from life, no doubt the landscape represented with painterly artifice. (The National Gallery of Australia: Wikimedia Commons, commons.wikimedia.org/wiki/File:Guerard_Mount_Townsend_1863.jpg.)

Fig. 2 Sunset at Endeavour Crater on Mars, by Cornell's Pancam team and Don Davis, 2012. The Opportunity rover, foreground, positioned on the walls of the Martian crater Endeavour, looks over the crater floor, its shadow surrounded by a solar halo. Considered against von Guérard's painting, the two pictures have the same focus on the rocky landscape, the same small human (or proxy human) foreground figures, the same composition with low sun and high horizon, the same subject of scientific exploration and the same romantic feel, although 150 years separates them. This picture uses data from a CCD camera positioned on the surface of Mars, digitally enhanced for artistic effect. (NASA/JPL-Caltech/Cornell/Arizona State University, © Don Davis, reproduced by permission.)

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For my grandchildren: Felix, Lucian, Frankie and Zoë
They will see landscapes that I can only imagine.

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I am grateful for the discussions that I have had with Frank Whitford, Alex Murdin and Valerie Shrimplin, all of whom opened my eyes to the old landscapes in fine art with which to compare the new landscapes from space science.

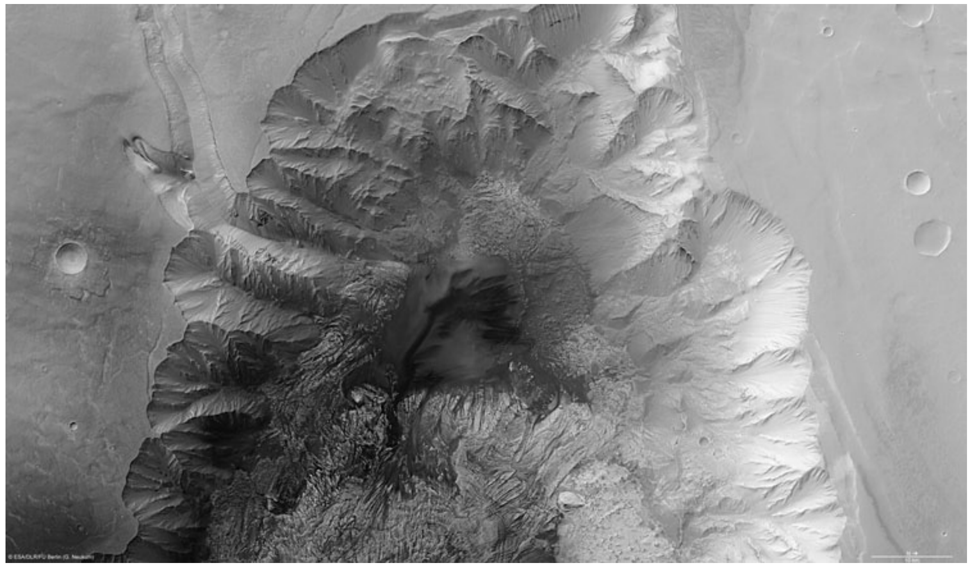
Figures 5.3 - 5.4 - 5.5 were developed from an idea by Stuart Atkinson (http://roadtoendeavour.wordpress.com/about/).

Contents

About the Author

Paul Murdin is an internationally known astronomer with a track record of well-written books and eloquent lectures about astronomy. He has been honored with an OBE in 1988, the Award of the Royal Astronomical Society for Services to [professional] Astronomy in 2011, the Eric Zucker Award of the Federation of Astronomical Societies for outreach to amateur astronomers, in 2012, and the name of asteroid 128562 Murdin.

Educated at the universities of Oxford and Rochester, NY, Paul has worked as an astronomer in the USA, Australia, England, Scotland and in Spain, where he led the operation of the Anglo-Dutch Isaac Newton Group of telescopes in the Canary Islands. He has been a research scientist (studying supernovae, neutron stars and black holes – in 1972 Paul discovered the nature of the first black hole known in our Galaxy, Cygnus X-1) and a science administrator for the UK Government and the Royal Astronomical Society. He works at the Institute of Astronomy at the University of Cambridge, England, and is Visiting Professor at John Moores University, Liverpool. He has a secondary career as a broadcaster and commentator for the BBC and CNN, as well as a lecturer and writer on astronomy, including repeat appearances on BBC Radio 4's In Our Time and at a number of literary and science festivals, like those at Hay-on-Wye and Edinburgh, and on the Cunard liner Queen Elizabeth 2. His most recent books include Secrets of the Universe: how we discovered the Universe (Thames and Hudson, 2009), Mapping the Universe (Carlton, 2011), and Are We Being Watched? The Search for Life in the Cosmos (Thames and Hudson, 2013).



Chapter 1

Landscapes on Other Worlds

Fig. 1.1 Hebes Chasma. The region is an enclosed trough situated in Valles Marineris, the Grand Canyon of Mars. It is 800 km (600 miles) wide. It is a complex region created by the collapse of the surface and subsequent landslides into huge splits in Mars caused by upwelling due to volcanic activity below. This view looks straight down, as from an overflying aircraft or spaceship. (ESA/DLR/FU Berlin-G. Neukum.) B

ALIEN LANDSCAPES

In 1543, on his deathbed, the Polish cleric Nicholas Copernicus (1473–1543) published his idea that Earth orbited the Sun, not the other way around. Earth was a planet. It was thus like the other planets of the Solar System. It was not somewhere special and different from everywhere else. The Dominican monk and philosopher Giordano Bruno (1548–1600) and the astronomer Johannes Kepler (1571–1630) immediately cast Copernicus' proposition in its logical and symmetrical reverse—if Earth was like a planet, the other planets were like Earth. This implied that the other planets were worlds like ours and probably had surfaces, as Earth does. Perhaps the other planets even had inhabitants. With the newly invented telescope, the astronomer Galileo Galilei (1564–1642) proved in 1610 that there was at least some truth in these assertions by discovering mountains and valleys on the Moon. The surface of the Moon was evidently similar to the surface of our own world.

Human beings, in person, have definitively proved that the Moon is like Earth by standing on the soil of its surface and picturing its hills, valleys and mountains. This is the only world outside Earth that has been proved by human experience to be terrestrial. However, by proxy, through the use of robots, humankind has explored, in close up and by physical presence, a number of the more distant worlds in the Solar System out to Saturn's moon Titan. Through cameras landed on mobile robots, humans have been able indirectly to venture into and picture dramatic places on these worlds. Some planets of the Solar System have been further explored by remote mapping from orbiting satellites that produce files of scientific data that can be viewed as pictures.

All this effort has built up into a number of little-known but stunning planetary landscape pictures that represent what you would see if, as a space tourist, you visited these alien worlds. So far this is not possible in actual practice, but the pictures make it possible to be a space tourist without leaving one's armchair. In this book we explore these landscapes to view the beautiful scenery of other worlds, and also to understand the scientific reality that lies behind their landscape.

The exploration of the planets of our Solar System has been driven by scientific objectives, so the scenery is the focus of the interest, pictured for geological analysis. The pictures are usually taken from above, because most spacecraft are orbiters—they fly over and therefore look down on what they orbit over. You may well have had a similar experience as a passenger in an airplane. Looking out of the window, you can likewise look down on the country you are flying over. But, as everyone who has done it knows, what you see is tantalizing—you see the country in a fascinating

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and informative way, but you do not experience it. The view engages your curiosity but not your emotions.

To experience somewhere you have to visit and be immersed in the place. A large part of this experience is looking, so an image obtained by a camera is an approximation to the experience, which is why explorers, travelers and tourists take photographs to show others back home. But, unlike most spacecraft, people do not usually take pictures that look down (Fig. 1.1). We see more naturally by looking horizontally at a scene that stretches out in front (Fig. 1.2). This is the view that we most often record as a souvenir, holding a camera up. In past times, before cameras had been invented and manufactured for a price everyone can afford, travelers might well have sketched the scene with pencil or painted it in watercolor or oils, to make a landscape picture—some travelers still do this. As human beings, looking horizontally is the way we understand scenery, a method that has developed as we have developed as a species. Photographs and pictures that represent what we see are the principal ways that we remember, investigate and re-experience the scenery after seeing it for the first time.

Artists have learned how to go beyond the mere recording of landscape. They simulate our human reaction to landscape by enhancing pictures of scenery—sketches and paintings—in characteristically artistic ways. They capture the emotion of involvement in the land, by choosing the viewpoint, subject and scope of the scenery and presenting it through some interpretation of their own choosing. Their work has become important to us and our culture—we build great galleries to display landscape pictures on the walls, and pay sometimes enormous prices to acquire them for that purpose. The reason is that, somehow, an artist's picture conveys

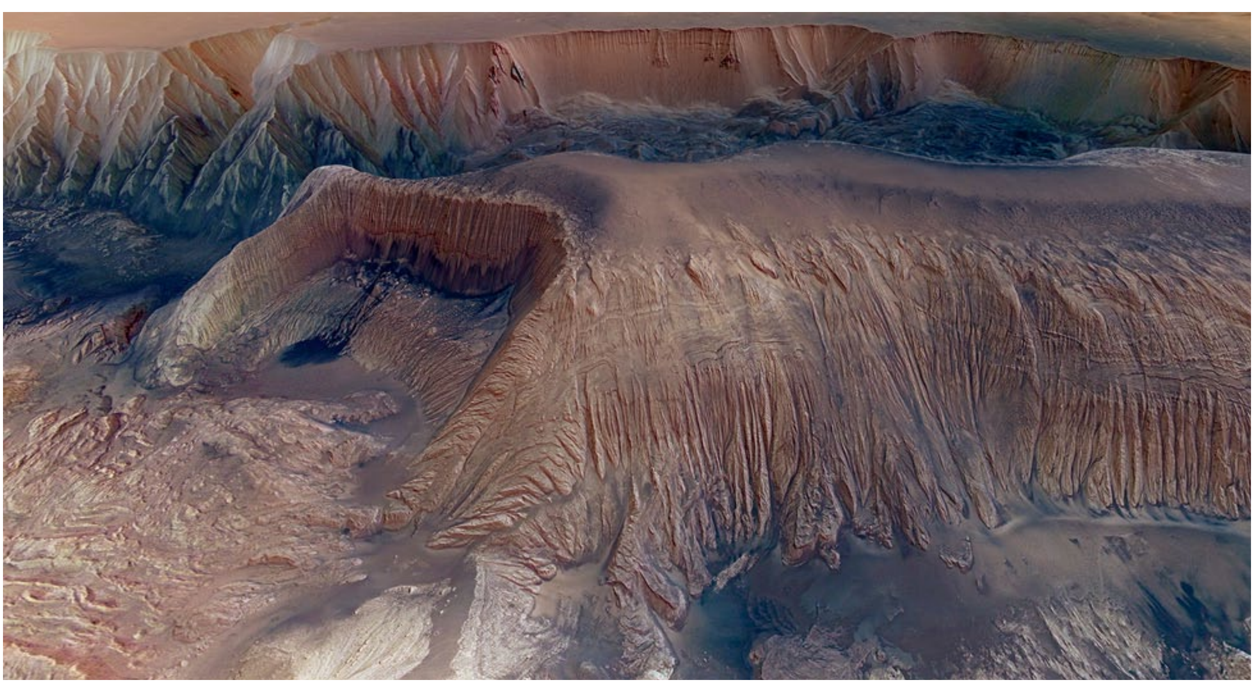


Fig. 1.2 Hebes Chasma Mesa. Imaged by the High Resolution Stereo Camera of ESA's Mars Express, the central mesa inside Hebes Chasma is seen in close-up detail in this perspective view. a horseshoe-shaped valley has been created as material on one side of the mound (left in this image); has slumped down onto the floor of the valley below. Melted ice could have played a role by weakening the rocks of the mesa to create the flow-like appearance of the landslip. Loose material has slid down the walls of the valley from a dark intermediate layer to pool on the valley floor. Layers along the side of the mound are a mix of wind-blown dust and ancient lake sediments. This is the oblique view that a space tourist would have from within the scene, much more engaging than the view from flying over it and looking down vertically. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **BB**

more about the scenery than the mere facts. A landscape picture may speak of the beauty of the land, the awe that it inspires, and its meaning for us as humans. It may even speak about what lies in the scenery's past, or over the horizon in unseen lands beyond, or in its future.

Thus the word "landscape" has come to have two equally important meanings. "Landscape" is both the scenery and a picture of the scenery.

This book is principally about landscape pictures of other worlds and what they convey. In its elements, a planetary landscape picture is one that represents the scenery of another world as seen from a low viewpoint, near the ground, into a depth of field across the surface, looking horizontally.

Most of the planetary landscapes in this book have been made by men or spacecraft that have landed on the surface of another world. There have been about 40 missions in which spacecraft have landed on planets, and even roved over the planetary terrain. These missions have delivered many pictures of the scenery around them.

Some of the landscapes in this book have been made by men or spacecraft that have been in orbit but at low altitude, skimming the surface of a planet. This is a maneuver with its dangers. A small error of control or position, or an unforeseen technical glitch, could risk a crash. Low passes over the scenery are therefore not favored by cautious spacecraft controllers, especially flights over mountainous planets. Low-altitude flights are thus undertaken as a main part of a mission usually only on an approach to a landing in a flat area chosen to minimize dangers. But a low flight may be risked for some particular reason, perhaps in the last stages of a mission, after the main work has been completed. Landscape pictures from overflying spacecraft are therefore rare. But they are often very dramatic landscapes, of scenery that is otherwise inaccessible.

We have included in the book some pictures of planetary scenery made from above, where the picture has an artistic or scientific value that adds meaning to one of the principal landscape pictures.

Planetary landscapes evidence, at one and the same time, a familiarity and an otherworldliness. The same fundamental processes happen on all terrestrial planets, so the basic structure of planets is similar—differences are differences often of degree. Mountains build and are eroded in similar ways. Their various shapes are common to most terrestrial planets, as are the plains formed from erosion material. The underlying structures of the planetary landscapes in this book are the same from planet to planet. But the differences soar over the line that separates terrestrial and planetary landscapes in fundamental ways. Planetary landscapes are both literally and figuratively otherworldly.

Some planets have no air, because some worlds are small and their gravity is weak. Their air has escaped into interplanetary space. So their landscapes lie directly under space, with daytime sunlight but an incessant black sky, like terrestrial night. This is so for the Moon, whose landscapes instantly reveal the location of their scenery (Chaps. 3 and 5). Some planets have a thin atmosphere: Mars is one and its sky is wan. By contrast, Venus and Titan have thick atmospheres and their sky lowers darkly (Chaps. 2 and 7). A cerulean sky is an exclusively terrestrial beauty, although there is one other planet in the Solar System whose sky is sometimes pale blue (Chap. 9).

If there is air on a planet, there is some strength of wind, and some wind-altered landforms: sand dunes, dust-storms with drifting sand, wind-eroded rocks, as on Mars (Chap. 6). The sky over Mars is laden with dust, circulating in the Martian air, whipped up by global dust-storms (Chap. 9). There may be frost and snow (Chap. 8). If there is no air or frost there can be no Aeolian erosion, and the breakup of rocks by ice cracking is impossible. Erosion is slower. Sharp edges of the rocks may be sandpapered away not by blown sand but by the needle-sharp, intermittent impacts of tiny meteorites.

Does the planet have abundant water, standing on its surface in pools, lakes or seas? The usual answer is "no." Our own planet lies in the so-called "Goldilocks zone" of the Solar System, the restricted zone near the Sun in which the temperature is not too hot, nor too cold, but just right to allow water to remain liquid on its solid surface. (This is helped too by the properties of Earth's atmosphere.) This means that, in terrestrial landscapes, we can see the blue of standing water, the glint of sunlight and other reflections off the water-surfaces of lakes and seas and off the snaking meanders of rivers. We can see the effects of flowing water in the carving that it makes upon the landscape—river beds and gullies, the scouring effects of floods on hills and the sides of valleys, level alluvial plains formed from sediment dropped as a river reduces speed. There is nothing of the sort on any other world in the Solar System, with two exceptions. Mars, positioned on the far edge of the Goldilocks zone, has had water in the past, which has left its traces on the Martian landscape (Chap. 6). Saturn is positioned in the frigid distant regions of the Solar System, but its moon Titan has rivers, lakes and seas—not of water but of liquid methane (Chap. 2).

However, water exists not only as a liquid but as a solid, too, in different forms such as frost, ice and snow. Some cold planets have white landscapes like the poles of our Earth, and some planetary landscapes show the effects of grinding ice, including cracking ice-floes and glaciers (Chap. 8).

No planet in the Solar System, apart from Earth, has life on it as far as we can see. Water is essential to the development of life, and it is abundant in the Solar System in solid or liquid form. There is the potential for life on many planets, but on Earth alone we see things growing. In fact on Earth life is abundant. So a major feature of terrestrial landscapes is vegetation—trees, flowers and grasses that give variety to the surface of the scenery, and color—the green of leaves and the bright colors of flowers. Animals on Earth are rarer than vegetation and in pictures of terrestrial scenery give tone to the landscape: the detail of an animal in a landscape can impart savagery, domesticity, wildness or a pastoral nature. No other planet in the Solar System has landscapes with features like these, although some may have niche environments—caves or geothermal vents—in which life may have secretly developed. Like the blue sky, noticeable life is, in our Solar System, exclusively terrestrial. We may in the future be able to peer into a dark cave on Mars and see something akin to what we might see in a cave on Earth, but nothing like this is known yet. There are no planetary landscapes that are "living" in the same sense that terrestrial landscapes are.

There is a particularly strong contrast between lunar and terrestrial landscapes. Color is one main difference. The Moon is lifeless, and there is no vegetation—no green foliage, no flowers. Its rocks are in the main, very similar, whereas terrestrial rocks come from different mineral sources, some rich in metals and their colored chemical compounds from the interior of Earth, which have been brought to the surface from below the planet's rocky mantle. The metal compounds of terrestrial rocks, weathered by rain, are sometimes highly colored, often red because of rust-like chemical compounds from iron. On the Moon there are no bodies of water, so no blue lakes or sea, no white foaming waterfalls. The sky is black, because there is no air, so no blue sky, no white cloud, no sunset lighting effects. Lunar photographs could almost be taken as being black and white, unless there are colored objects in view that have been imported from Earth, like the Stars and Stripes on a flagpole or a spacesuit.

However, like the plains, canyons and volcanoes of Mars, and the black lava mountains of Venus, the gray, dusty plains and mountains of the Moon have their own stark beauty, here displayed for you as you voyage through the Solar System, an armchair space tourist viewing planetary scenery.

For this book we have selected the clearest pictures of planetary scenery. Just as we might try to read the character of the subject in a portrait of a human face, so we have tried to convey the character of the planet pictured in these landscapes. Moreover, we might infer from a portrait the history of the subject. We have tried to show how we can read what lies inside each planet from these landscapes, and infer its past. Here is a world, Mars, that suffered a global catastrophe of climate change, due to events that have taken place in its deep core. Here are two completely opposite worlds: Titan is Earth as it was a few hundred thousand years old, frozen in time; Io is by contrast a world recreated anew, again and again, resurfaced by inner material spewed out by ever-active volcanoes. Here is a world, the Moon, that suffered a heavy bombardment of large projectiles, caused by a collision that smashed two asteroids into millions or billions of pieces or by a developing planetary configuration that jostled asteroids out of their orbits. These cosmic catastrophes inevitably left their mark upon the land.

HOW REAL ARE THE LANDSCAPES IN THIS BOOK?

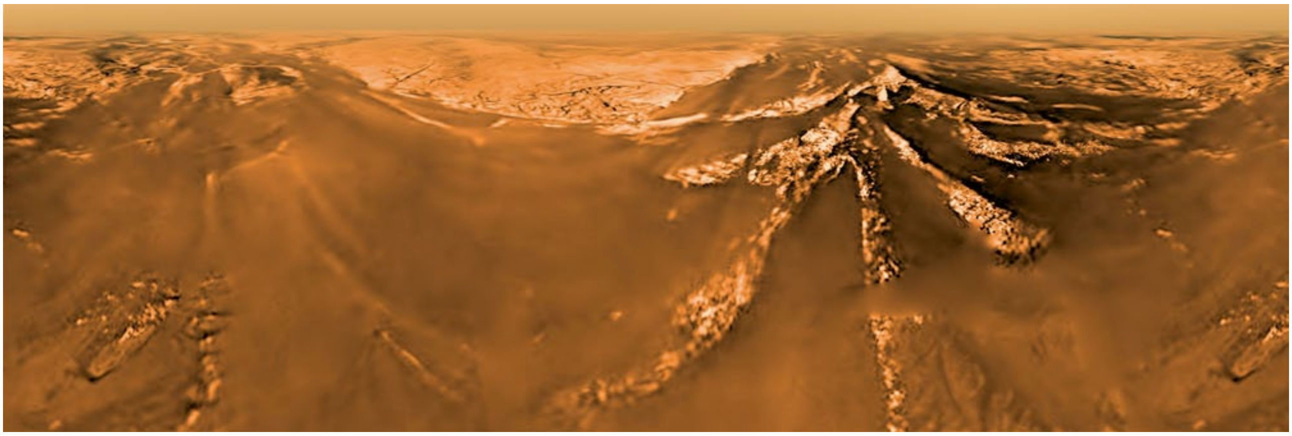
The planetary landscapes reproduced in this book have been provided by a variety of spacecraft over decades of changing technology—see Appendix 1 in this book for further details. Some of the color pictures are closer to what you would see if you stood there than others. Sometimes people wonder whether the landscapes made by space scientists are "real." A brief answer is that they are as real as any painting of a terrestrial landscape. Every picture here has reality behind it. *None* of the pictures are imaginative impressions.

To add shading to this assessment, we have given a "reality grade" to each picture in this book, along the lines of Standard and Poor's credit ratings for financial institutions or bond issues. **AAA** is as realistic as a photograph on color film or by digital photography, **AA** as realistic as a monochrome (black and white) photograph. All the subclasses of reality grade **A** are as realistic as a picture produced by an artist of what he or she sees of a scene, but as the grade is reduced to **B** or even **C** the landscape is departing from reality in ways that would be progressively jarring if the picture was held up on view and compared against the landscape, although there are many artistic landscape paintings that are equally different from reality. At grade **C** the landscapes are representative but noticeably depart from the real view in some ways. The criteria for this grading system are described in the following table, and explained in more detail in Appendix 1 of this book.

Some color pictures are reproduced in the printed version of this book in black and white; the reality grade applies to the original version (Table 1.1).

Table 1.1 Reality grades for planetary landscapes

Color	True color	Black and white	Balanced 3-color addition	Exaggerated 3-color addition	2-color	Multicolor, but invisible passbands	Synthetic colors and/or radar
Detector	Color film or TV	B/w film or TV	CCD images or similar				
A real image made by a camera on the surface	AAA	AA	AA	A	BBB	BB	
A real image made by a camera from an overflying satellite	AA	AA	A	BBB	BB	BB	B
Constructed from a contour map with a hypothetical viewpoint			A	BBB	BB	B	C
Constructed with exaggerated heights			BBB	BB	B	C	C



Chapter 2
The Lakes of Titan

Fig. 2.1 Titan's Lake District. During its descent on January 14, 2005, the Huygens probe took images of Titan's surface. From an altitude of 2 km (1.2 miles) Titan's surface shows as hilly ridges with dry river valleys. The distant landscape is made indistinct by the smog of Titan's hydrocarbon atmosphere. (Huygens: ESA/NASA/JPL/University of Arizona. Image processing by René Pascal.) **BB**

A ROBOTIC EYE AND A NEW LANDSCAPE

In January 2005, an electronic eye gazed on the fresh landscape of new land on a previously unexplored world. It saw a landscape that would, at first sight, have been familiar to many human eyes. The scenes that it recorded looked like the Lake District of northern England, the Finnish Lakeland, or the hilly areas of the Pacific Northwest, with rivers flowing through the world's hills to large lakes. One major difference between this world and ours was that this world had no life on it—no trees, no grass to cloak the shapes of the bare rock, no animals to give an air of domestic tranquility or savage wildness to the scene. What was not immediately obvious was that, underlying the scenery, behind the landscapes, was the potential for life. The landscape was like that of Planet Earth before life had arisen here. This land was a preserved fossil, like Earth was 4 billion years ago. This world was pregnant with prebiotic chemistry, literally awash with chemicals that span the gap between the inanimate and the living.

The electronic eye belonged to a robot spacecraft that was standing in cold, squelchy mud, the bottom of an almost dry lakebed. The bare shapes of the boulders that littered this level plain had been rounded by being tumbled in a stream. In the distance, across the lakebed, the robotic eye could dimly see a line of hills—the far lake shore, perhaps, or some islands. Their outlines were obscured by smog. Rain had fallen here, evaporating from the soggy ground, creating photochemical smog.

The robot was gazing at the only terrain in the Solar System, other than Earth, where there is landscape like this. But behind the familiarity of this scenery is an unfamiliar fact: the rain and the liquid in the lakes are of liquid methane, not water.

The scene was recorded on Titan, the largest satellite of the planet Saturn, second largest in the Solar System. Titan was the first satellite of a planet discovered since Galileo discovered the four largest of Jupiter's satellites in the northern winter of 1609/1610. Titan was discovered in 1655 by Christiaan Huygens (1629–1695). Huygens was born in The Hague, the son of a high-ranking civil servant, and, educated by private tutors, he at first studied law at Leiden University, in preparation for a diplomatic career. He was, however, attracted by mathematics. Traveling in France and Britain, his talent was noticed by influential scientists, and in 1666 he was invited to join the newly founded Academy of Sciences in Paris, where he remained until 1681. In the 1650s he had become interested in developing telescopes, and made larger and larger objective lenses with very long focal lengths that gave high magnifications of 50–100 times. While testing a newly made lens in 1655 he observed the planet Saturn in an attempt to find out about what at the time were called its *ansae*, or "ears." The first telescopes could see that there was something funny about the planet, which had protrusions sticking out either side, but were unable to see that

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they were part of a ring system that completely encircled the planet. Huygens was intrigued to see that the *ansae* in March 1655 were very narrow: we would now understand that the rings of Saturn were oriented edge-on. He also noticed a star that was lined up with the *ansae*. It followed the planet in its motion and Huygens realized that it was a satellite.

Huygens referred to the satellite in Latin, generically, with the simple name *Saturni Luna*, "Saturn's moon." Further moons of Saturn were discovered later in the seventeenth century and numbered in order from the planet: I, II, III, IV and so on. The numbering system kept changing as further discoveries were made, so Huygens' discovery has been known at various times as II, IV and VI. The astronomer John Herschel (1792–1871) suggested names for the seven satellites of Saturn that were known in 1847. He chose the names of Titans, brothers and sisters of Cronus, the Greek god who was the equivalent of Saturn, with Titan itself used for the largest satellite, the one discovered by Huygens.

Saturn, and therefore too its satellites, are so distant from Earth that telescopes cannot see many features on the surface of Titan, in fact very little in the way of detail. By clever techniques and detailed analysis astronomers using the Hubble Space Telescope (HST) have succeeded in finding dark areas on the surface and showed that they had not varied much over the few years that the HST has been active.

Telescopes on Earth itself can pick up the fact that the globe of Titan is shaded in such a way as to indicate that it has a substantial atmosphere. Spectroscopic analysis of the light reflected from Titan showed in 1944 that the atmosphere contained methane. The spacecraft *Pioneer 11* flew by Saturn in 1979, followed closely by *Voyager 1* (1980) and *2* (1981). These spacecraft confirmed that Titan had a cold, dense, hazy atmosphere, too opaque to see surface features. Before seeing it in 2005, astronomers had to imagine what its landscape looked like.

The close-up landscape recorded in 2005 was captured by the Huygens space probe, carried to Saturn by the Cassini space mission. This was a joint mission by NASA and the European Space Agency to explore Saturn, Titan and its other moons. The spacecraft started its journey in October 1997 from Cape Kennedy in Florida, setting out from a landscape that turned out to be not unlike its destination. This author could see the night-time launch of the Cassini spacecraft from beside a channel draining the marshland where the spaceport is located. There was plenty of life here—not only harmless vegetation. I had to keep one uneasy eye on an alligator stirring in the greasy water of the channel below my viewpoint. Even this primitive creature, with near ancestors dating back 200 million years, was far in advance of anything that Huygens was to see on Titan!

The main focus of my attention that day in 1997 was the floodlit Titan IVB/Centaur rocket on its launch pad. The rocket was the most powerful then available to space scientists, able to accelerate the massive spacecraft (5.6 m t) effectively on its long journey. The rocket's engines ignited in fiery smoke, and it lifted off into the black night sky, its bright flames illuminating the layers of cloud through which it passed. The smoky trail curved away, over the sea, picking up speed from Earth's rotation as well as from the rocket fuel. Within minutes the rocket had faded from sight.

The spacecraft began a complicated trajectory around the Solar System—twice around Venus, then past Earth, then Jupiter. Its orbit was carefully tuned so that it would pick up speed at each encounter. These so-called "gravity assist" maneuvers shortened the time that the mission scientists had to wait to see the landscapes for which they built the spacecraft. Without the gravity assists they would have had to wait a lifetime—with them a mere 7 years. Cassini arrived at Saturn in July 2004, and on Christmas Day, on its third orbit around the Ringed Planet, it jettisoned the Huygens probe, which it had been carrying across space. Huygens set off to penetrate into Titan's atmosphere and land on its surface. At that moment, Huygens settled on land that was the furthest from Earth that mankind has touched, if only by proxy robotic feet.

Saturn's largest moon, Titan, is the only moon in the Solar System that has a dense atmosphere, mainly of nitrogen, the main constituent of Earth's atmosphere, but also of methane. The action of sunlight on the methane creates a photochemical smog, which hides the moon's surface, so up to the time of the Cassini mission no one knew what the surface of Titan was like. What had been surmised was that the methane atmosphere was not stable and must be continuously replenished from liquid reservoirs on the moon's surface—lakes, perhaps, or marshy land. The very survival of the lander as it touched the surface was in question. Would it topple over on a hillside? Would it find flat, dry land? Would it splash into a sea and sink? Would it squelch into a bog? The landscape of Titan was unknown and the lander's eventual fate uncertain. As I stood at the time of the launch of Huygens on the marshland of the Florida seacoast my imagination failed to envisage the possibility that the probe would find a landscape not unlike the landscape from which it was setting out—it would land on marshland similar to the Florida Everglades over 1 billion km (700 million miles) away.

On January 14, 2005, the Huygens probe successfully entered Titan's upper atmosphere. The angle at which it did so was critical—too steep an angle of attack and the probe might plunge as a meteor into the atmosphere; even if not that steep, the probe could encounter dense atmosphere at too fast a speed and bounce off back into space. Alternatively, too shallow an angle of attack and the probe could shoot through the thin upper atmosphere past its target. Its attitude during its encounter with the atmosphere was critical, too. The probe itself nested inside a protective capsule, its base protected by a heat shield that was presented to the atmosphere through the stabilizing spin imparted to Huygens when it was ejected from Cassini. Friction with the air turned kinetic energy into heat and slowed the spacecraft in its descent. The heat shield on the capsule dissipated heat away from the probe itself.

After they had steered the lander into Titan's atmosphere, the mission controllers had no choice but to wish it good fortune and stand back. Radio data from Saturn takes over an hour to travel to Earth. If the data from the lander as it plummeted towards its destination indicated that it had a problem that the controllers could influence, their command to fix the problem would take more than another hour to get back. In the intervening 2 h, the lander would have crashed. The Huygens lander had to be autonomous. Fortunately—the word belittles the intensive effort that the space engineers had invested in building the spacecraft, but even they would have been anxious during that long wait and wishing themselves good luck—everything worked.

The capsule started its descent through Titan's hazy cloud layers at an altitude of about 1270 km (790 miles). During the following 3 min Huygens had to decelerate from 18,000 to 1400 km/h (11,000–870 mph). A sequence of parachutes then slowed it down to less than 300 km/h (190 mph). For the next 2 h it descended, swinging and spinning under its parachutes, to land on the surface. For the last 160 km (100 miles) of the descent, the protective capsule had dropped off, and the probe's scientific instruments were exposed, including a camera.

Sunlight at the distance of Saturn is diminished to just 1 % of the brightness of sunlight at Earth, and Titan's smog reduces sunlight even further. The illumination of the ground is 1000 times less than terrestrial sunlight (but 1000 times more than the light of the full Moon). So little sunlight penetrates to the ground that solar-electric power cells would have been useless. For the two and a half hours of its descent and, after it had landed, Huygens functioned on battery power alone. Huygens had been sent for 7 years over a distance of 1 billion km to survive and carry out its mission only for as long as the batteries lasted. The least favorable interpretation of the technical specification of the robotic equipment suggested that, after its descent and landing, it might operate for only 3 min. In fact it successfully transmitted data via its link with the Cassini mother craft for half an hour. The data flow was cut off, not by the batteries running out, but by the relay transmitter on Cassini disappearing over the horizon. Huygens itself was heard by Earth-based radio telescopes to be transmitting for even longer, a further 2 h, but with such a faint signal that what it was saying could not be deciphered. After its resounding half-hour success, Huygens died with a 2 h whisper, so far off that it was unintelligible.

TITAN'S LAKE DISTRICT

On its descent Huygens swung gently below its main parachute, spinning as it looked down. At first its video transmissions showed impenetrable haze. Then the ground started to show, a darker mass in the haze. Below an altitude of 60 km (40 miles) the camera started to show the detail of

Fig. 2.2 The surface of Titan. On January 14, 2005, ESA's Huygens probe landed softly on a plain on Titan's surface. The plain was a dry lakebed, with somber scenery in this, the most distant landscape yet pictured. The cobbles are about 15 cm (6 in.) in diameter. They are tumbled boulders, not of rock but of ice, covered with reddish-brown oily chemicals. (Huygens: ESA; image processing by Andrey Pivovarov.) **BB**

the ground. The terrain became clearer below the probe, but the horizon remained foggy. The terrain was hilly, cut with dark, dry riverbeds (Fig. 2.1). Unknown to the controllers back on Earth, Huygens was heading towards a disaster, a landing somewhere among steep hills, where it would topple over. But at low altitudes it encountered a 20 kmph (12 mph) wind. The probe began to drift sideways. The probe moved away from the hills towards a flat plain.

As Huygens touched down, it slid a little and settled down. It had landed on a small rock, slipped off, and dropped on to ground. The ground was soft. It had the same consistency as, on Earth, water-logged gravel, wet sand, oozy mud, or lightly packed, damp snow. The best guess is that the lakebed on Titan where Huygens landed was made of dirty water-ice, weathered from the rocks and cliffs, mixed with reddish-brown chemicals called tholins, made by the action of sunlight on the methane atmosphere, and soaked not with water but with liquid methane. The tholins are representative of the transitional chemicals that, on Titan, bridge the gap between inorganic chemistry and the biochemicals that make life work.

From the lander, the reddish-brown landscape was a view across the lakebed (Fig. 2.2). The immediate landing site was apparently in a drainage channel that led into a lake from the hills nearby. The video images of the descent showed that the lake was fed by numerous river channels, currently dry, wending their way through the neighboring hilly terrain. Distant hills of some isolated islands or a far shore showed faintly on the horizon. Rounded cobbles littered the surface of the sediment.

For an hour or so at the beginning of the mission, Huygens had sampled a single point on Titan, seeing it close up. Since then, over the years, Cassini has used smog-penetrating radar and infrared sensitive cameras to map much of the surface of Titan, building on the detail of the landing site. Titan's equatorial regions have extensive areas of dunes, not sand-dunes but dunes of grains of solid carbon compounds, like the smog particles—soot-dunes. The grains have been blown into dunes by strong winds. The land has few meteor craters—less than 100 appear as definite examples in a recent catalog, fewer than Earth. The largest is 79 km (49 miles) in diameter. This indicates both that craters formed on the higher terrain on Titan's surface have been strongly eroded by its weather and that craters that formed on the lower terrain struck extensive wetlands and the craters were buried. There is some evidence for land that has itself flowed, like lava.

The ground is hilly and irregular, with plenty of natural basins. Hundreds of them are filled by lakes, distributed quite widely over its surface, but only polewards of 50° latitude. Titan's weather acts to dry out its equatorial regions, although there are some shallow ponds, ankle deep, and some swampy regions. These equatorial oases are fed from springs below the surface. There is considerable rain at Titan's poles, which feeds the lakes. The lakes are up to 300 km (200 miles) across. Titan has three large seas that all lie in a restricted area in Titan's north polar region. The largest is Kraken Mare, the largest sea in the Solar System outside Earth. It seems to be quite deep, with few or no islands, but its depth changes through tides induced by Saturn and from season to season.

THE GLINT OF AN ICE-COLD LAKE

Titan's lakes are not bodies of water but bodies of liquid hydrocarbons, principally methane and ammonia. These chemicals are liquid even at the −180 °C (− 290 °F) temperature on Titan. The liquid forms a system of river valleys, estuaries, drowned valleys, and lakes with shorelines, their beaches washed into ridges parallel to the shore as the lake-level changes with the slow march of Titan's seasons during its year of 35 Earth-years. The lakes are fed by rivers, smaller streams merging into larger rivers as they descend from the hilly and mountainous areas. The valley networks are dendritic—branched, like trees—and appear to be very like dendritic river systems on Earth. This structure is indicative of an origin from precipitation. There are dry valleys resembling wadis in desert areas on Earth. These indicate that the valleys are caused by strong episodic flows of liquid. On Earth there are infrequent torrential downpours that scour valleys that then dry out. Some valleys are steep-sided. On Earth we would call them canyons, scoured out by rivers that cut deep through the ground.

Ice floes of frozen methane, water and “air” cover some areas of the lakes. The boulders on the lakebed on which Huygens landed are tumbled blocks of water-ice, moved from there on to the drainage channel by the flow of a stream of liquid methane, fed from the methane rainfall on the hills.

The lakes are depleted by evaporation and filled by rain, in a hydrological cycle similar to the water cycle on Earth. Like Earth's, Titan's scen-

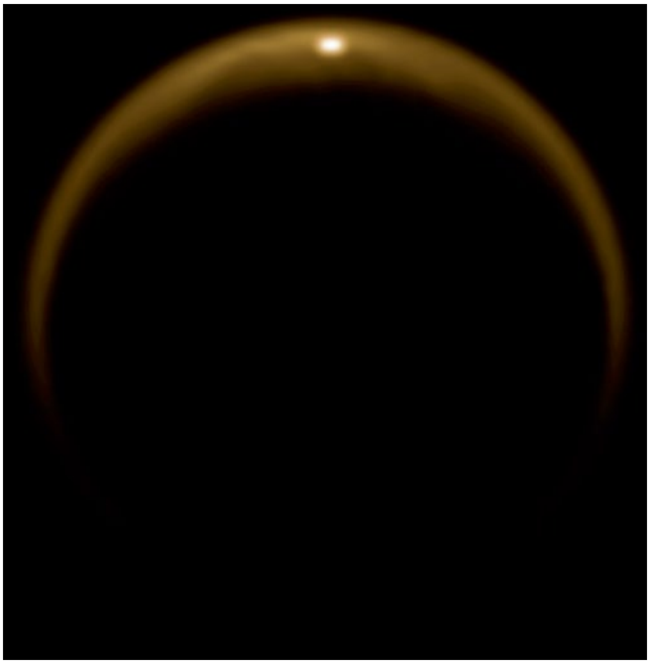

Fig. 2.3 The Sun glints off the surface of Kraken Mare. Sunlight also back-illuminates the atmosphere above and to the side of this lake on Saturn's largest Moon. The image was recorded using infrared radiation, which penetrates Titan's hydrocarbon atmosphere. (Cassini: NASA/JPL/University of Arizona/DLR.) **BB**

ery is in large part the result of erosion by the flow of liquid—not water but liquid methane.

As a result of the lakeland scenery, Titan's and Earth's landscapes are the only landscapes in the Solar System that show one of the most beautiful phenomena beloved by landscape painters—the bright path of the reflected Sun on a lake surface.

In 2009, the northern hemisphere of Titan had been cloaked in winter darkness for nearly 15 years, but the Sun began to illuminate the area again as the moon approached its spring equinox. On July 8, 2009, the Cassini spacecraft, viewing Titan from 200,000 km (125,000 miles), saw something that no one on the science team had expected—a strong glint from the northern polar region (Fig. 2.3). It was the reflection of the Sun from the surface of one of Titan's lakes or seas. Titan's hazy atmosphere is virtually opaque to visible light, and sunlight would not have penetrated to the surface; even if it did, it would not be able to leave the surface. But Cassini sees infrared wavelengths that were able to penetrate through the moon's atmosphere—wavelengths of infrared in the 5 µm range. Katrin Stephan, of the German Aerospace Center (DLR) in Berlin, processed the image and was the first to see the glint. She immediately guessed what it might be: "I was instantly excited because the glint reminded me of an image of our own planet taken from orbit around Earth, showing a reflection of sunlight on an ocean," she said. "But we also had to do more work to make sure the glint we were seeing wasn't lightning or an erupting volcano."

The glint was indeed a reflection from the liquid near the southern shoreline of a lake or sea on Titan called Kraken Mare. Kraken Mare (or the Kraken's Sea—the Kraken is a legendary Norwegian sea-monster) is 400,000 square km in area (150,000 square miles), about the same size as the Caspian Sea. The image showed the backlit atmosphere of Titan, encircling almost the entire strange world. Bob Pappalardo, the Cassini project scientist, conveyed the feeling about Titan that is latent in this seascape: "Thick atmosphere, surface lakes and otherworldliness."

Titan's landscape is diverse and otherworldly, sitting under a somber gloom and a poisonous atmosphere, principally methane but including toxic organic chemicals. Yet Fig. 2.3 is a landscape (really, seascape) in the Solar System that is fundamentally like one of Earth (Fig. 2.4). It is an unsettling combination, with a deeper significance. For Titan is the world in the Solar System that most resembles Earth as it was early in its lifetime. When Earth was newborn, its atmosphere was similar in composition to Titan's. Its surface was rich in carbon compounds, which in the oceans developed into life, such as cyanobacteria—blue-green algae. These algae breathed in the carbon-rich atmosphere and breathed out oxygen. As they thrived, they transformed the atmosphere of Earth, making it rich in oxygen. The landscapes of Figs. 2.1, 2.2 and 2.3 are landscapes of the far world, Titan, but they also have characteristics of our own Earth, far distant not only in space but in time, hearkening back to the landscape just before the dawn of life on our own planet.

Fig. 2.4 The Fighting Temeraire by J. M. W. Turner (1775–1857). The painting (1838) shows how the Sun backlights an atmosphere filled with sea fog, and its light is reflected off the surface of the sea. The right-hand half of this picture is similar to a close-up of the glinting spot in Fig. 2.3. (National Gallery of London: Wikimedia Commons, commons.wikimedia.org/wiki/File:Turner,_J._M._W._-_The_Fighting_T%C3%A9m%C3%A9raire_tugged_to_her_last_Berth_to_be_broken.jpg.)

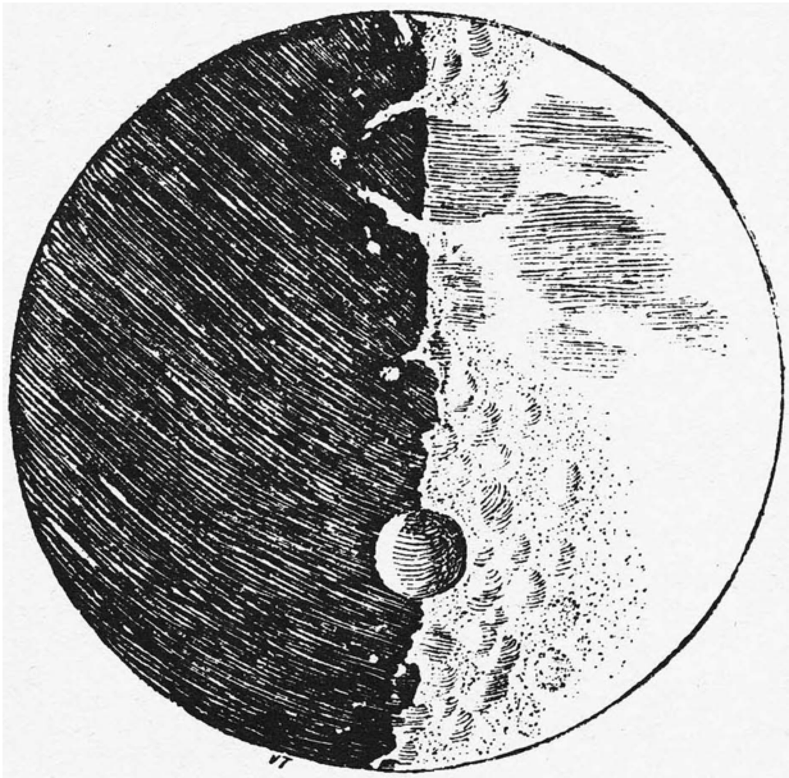

Fig. 3.1 First quarter Moon. Galileo merged several sketches of individual sections of the Moon into this view of its first quarter phase, as seen with the aid of his telescope. It shows a "perfectly round" area of the Moon surrounded by mountains, the first lunar crater distinguished by a human. (Engraving from Galileo's 1610 publication Sidereus Nuncius (The Starry Messenger: Wikimedia Commons, upload.wikimedia.org/wikipedia/commons/7/7b/Galileo%27s_sketches_of_the_moon.png.)

Chapter 3

The Craters of the Lunar Landscape

THE LUNAR LANDSCAPE IMAGINED FROM AFAR

Titan is the furthest other-worldly landscape that we have seen. Our Moon is the closest, so close that some of its scenery was first described over four centuries ago. The Italian astronomer and physicist Galileo Galilei (1564–1642) turned his telescope to the Moon at the end of 1610, and was able to see its features clearly. In his book, *Sidereal Messenger*, he declared that "The surface of the Moon is not perfectly smooth, free from inequalities and exactly spherical, as a large school of philosophers considers with regard to the Moon and the other heavenly bodies, but that, on the contrary, it is full of inequalities, uneven, full of hollows and protuberances, just like the surface of Earth itself, which is varied everywhere by lofty mountains and deep valleys."

With these words, Galileo recognized that the landscape of our own world had counterparts on other worlds—on the Moon and, by inference, other planets. Galileo went on to compare one noticeable feature of the landscape of the Moon with a particular landscape on Earth:

> There is one other point which I must on no account forget, which I have noticed and rather wondered at. It is this: the middle of the Moon, as it seems, is occupied by a certain cavity larger than all the rest, and in shape perfectly round. … It produces the same appearance as to effects of light and shade as a tract like Bohemia would produce on Earth, if it were shut in on all sides by very lofty mountains arranged on the circumference of a perfect circle … walled in with peaks of such enormous height that the furthest side adjacent to the dark portion of the Moon is seen bathed in sunlight before the boundary between light and shade reaches halfway across the circular space.

Galileo was obviously describing a circular lunar crater (Fig. 3.1), comparing it with a region of Earth with which he was familiar, the plain of Bohemia surrounded by mountain ranges. He had seen the crater from above, just as an overflying spacecraft would see a crater on Mars, and he imagined how he would see it as a landscape if he was transported to stand inside the crater.

It is not clear which crater had caught Galileo's attention, because his picture is not quite accurate, the reason being that his telescope had a very narrow field of view. He had to view and sketch a small area of the Moon at a time, assembling the individual sketches into a single picture afterwards. The crater was perhaps one of the craters Tycho or Albategnius, but it was certainly a prominent feature of the Moon as he viewed it in those winter nights of 1610.

Galileo shifted the paradigm of the Moon by describing it as another world, like our own. In previous times, the Moon was regarded as the lowest of the celestial bodies that orbited Earth. All celestial bodies from the Moon upwards were thought to be different from Earth, so much so that there were words, "ethereal" and "sub-lunary," which demarcated Earth from the rest of the universe. Galileo saw that this separation of Earth

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from the Moon was a false dichotomy. Both worlds have landscapes with similar scenery. Indeed, as telescopes improved and astronomers had a clearer and clearer view of the Moon, they described its landscape features, using the familiar terms of terrestrial scenery. The choice of names emphasized how like Earth they thought the Moon to be.

The names given to features of the lunar landscape presupposed that the Moon had large areas of standing water, like Earth's seas. The working language of science at the time was Latin, so the names are mostly in that language (Table 3.1). Many of the presently used terms (most of them approved by the International Astronomical Union, some of them informal) date back to Giovanni Battista Riccioli (1598–1671). The gray patches on the Moon, visible even to the naked eye as the features of the "Man in the Moon," were thought—by pushing the analogy of the surface of the Moon with the surface of Earth a bit too far—to be areas of water. A large, dark gray patch is called *oceanus* (an ocean) and a smaller one *mare* (a sea). An indentation in what would be the shoreline of an ocean is termed *sinus* (a bay). A small, low-lying gray plain could be called *lacus* (a lake) or *palus* (a swamp) fed by rilles. A general area of ground, a geographical region, is *regio*. A depression in the ground became *chasma* (a canyon), *fossa* (a ditch) or *rima* (a fissure). An area especially of hills and mountains between the *maria* can be *terra* (land), and might contain *planum* (a plateau), which could end in a cliff-edge or *rupes*. Hills are *colles* and a ridge is *dorsum*. A range of mountains would be *montes*, and they might end as a headland (a *promontorium*) that protruded into a mare and be cut by a valley (*vallis*). The features are named fancifully, after terrestrial equivalents,

Table 3.1 Planetary geography

Latin term	Feature	Example	Translation
Chasma	Canyon	*Candor Chasma*	
Collis[a]	Hill	*Collis Aristarchus*	
Dorsum (plural dorsa)	Ridge	*Dorsum Arduino*	
Fossa[a]	Ditch	*Fossa Littrow*	
Lacus	Lake	*Lacus Oblivionis*	Lake of forgetfulness
Mare (pl. mares)	Sea (a lava plain)	*Mare Tranquilitatis*	Sea of tranquility
Mons	Mountain	*Mons Piton*	Mount Piton (after a peak on Tenerife)
Montes	Mountain range (the rim of a crater)	*Montes Alpes*	The Alps
Oceanus	Ocean (large lava plain)	*Oceanus Procellarum*	Ocean of storms
Palus	Swamp	*Palus Somni*	Swamp of dreams
Planitia	Low plain	*Planitia Descensus*	Plain of the descent (of the spacecraft *Luna 9*)
Planum	Plain		
Promontarium	Headland	*Promontorium Laplace*	
Rima	Rille (channel)	*Rima Marcello*	
Rupes	Scarp or fault	*Rupes Recta*	Straight scarp
Sinus	Bay	*Sinus Iridum*	Bay of the rainbow
Terra[a]	Land or region	*Terra Grandinis*	Land of hail (northeastern border of Mare Imbrium)
Vallis (pl. valles)	Valley	*Vallis Alpes*	Valley of the Alps

[a] Term not recognized by the IAU

or for people. The tradition to use these terms has been extended in the space age even to newly explored planets such as Mars and Venus, and the moons of the giant planets such as Jupiter or Saturn.

Galileo was the first person to see enough to be able to imagine realistically the landscape of another world, peering through his blurry telescope, describing the scenery of the Moon as if he were actually there. He was followed by centuries of astronomers who devoted their lives to a closer and closer scrutiny of the Moon with more and more powerful telescopes. From the outset their imagination overreached the reality. The lunar landscape owes nothing to water. On the Moon there are no oceans, no seas, no bays, no lakes, rills or swamps. This was becoming clearer and clearer with the scientific study of the Moon, but confirmation waited until the 1960's, when we saw the surface of the Moon from its surface. The Moon is a dusty, rocky desert. The iconic pictures of the lunar landscape are those from the Apollo program of manned landings on the Moon. But, in fact, robotic eyes saw the landscapes of the Moon first. The first pictures from the surface of another world were made in the 1960's by the *Luna 9* and *Lunar Orbiter 2* spacecraft.

THE FIRST PICTURES FROM THE LUNAR SURFACE

The Luna series of spacecraft were derived from a program by the Soviet space agency to investigate the properties of the surface of the Moon. Several initial attempts to make a soft landing on the Moon failed, but in February 1966, the *Luna 9* spacecraft landed intact in the *Oceanus Procellarum* (Ocean of Storms). It returned back to Earth 27 TV images showing lunar scenery in three panoramas.

In the closed world of the Soviet Union there were delays in releasing the pictures, but, intercepting the radio transmissions and looking at their characteristics, scientists at the Jodrell Bank Radio Telescope of the University of Manchester spotted that they used the same standard that was used by newspapers to distribute news pictures. Borrowing a decoding machine from a newspaper, the radio astronomers fed the signal in—and were rewarded by being the first people outside the Soviet Union to view a picture from the lunar surface! The close-up picture (Fig. 3.2), tilted relative to the Moon's horizon, showed the dusty lunar surface, littered with some larger boulders, our first landscape from the desolate surface of the Moon.

Fig. 3.2 The first picture from the surface of the Moon. Luna 9 landed in 1966 on the bleak, dusty plains of the Oceanus Procellarum. (Luna 9: © The University of Manchester's Jodrell Bank Observatory.) **BB**

The first soft landings on the Moon made by NASA were five of the seven landers of the Surveyor program between 1966 and 1968, used to pinpoint possible landing sites for the

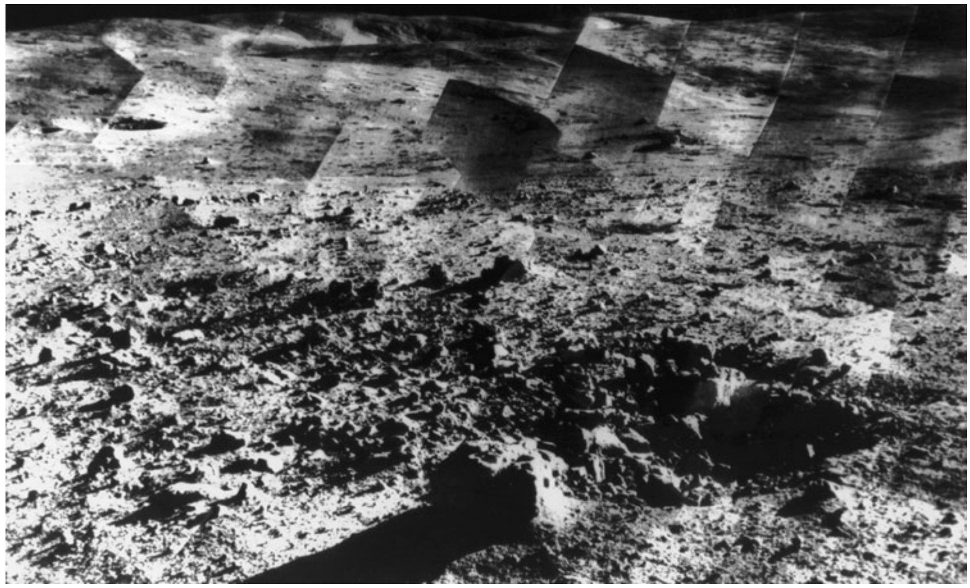

Fig. 3.3 The northern rim of the crater Tycho. Individual pictures from Surveyor 7 obtained in January 1969 have been assembled into a panorama. The large rocky block in the foreground is about half a meter (about 20 in.) across; it stands in a shallow crater about 1.5 m (5 ft) in diameter. The hills on the horizon are about 13 km (8 miles) away. The mosaicking has been created by the pasting together of prints of individual pictures into a montage to form a barren landscape. (Surveyor 7: NASA Image ID 68-H-40.) **B**

manned Apollo program. The Surveyors carried TV cameras of an early technology (vidicons) and were able to sweep over a scene to provide pictures that could be assembled into black and white mosaic landscapes, cutting and pasting paper prints in those un-computerized, pre-Photoshop days (Fig. 3.3). The last spacecraft of the series, *Surveyor 7*, landed in 1969 near to the crater Tycho. Its landing site was chosen with more regard for its scientific interest than the others. The panorama viewed by its TV camera showed a rocky landscape, littered with boulders of a range of sizes, with hills on the horizon. The hills were the rim of the Tycho Crater.

The first landscapes from the Moon represented the ground-truth towards which the remote telescopic views had been reaching. The large circular features on the Moon, first seen through Galileo's telescope, are craters, holes in the ground made by the impact of a meteor or asteroid. The scenery of the Moon has been created predominantly by the impact of meteors and asteroids on to the airless surface. Not only did the impacts make craters, they fractured and pulverized the surface rocks. Excavating a hole, they sprayed dust and boulders above the surface, which littered the ground and lay where they fell.

ONE OF THE GREAT PICTURES OF THE CENTURY

NASA's lunar orbiter program consisted of five spacecraft sent to overfly the Moon to map it in preparation for the Apollo program, in particular to image in detail the 13 candidate sites that had been identified from earlier studies to be possible sites at which Apollo spacecraft could land. As *Lunar Orbiter 2* flew in November 1966 from one possible Apollo site to the next, it had no prime mission to execute, so the spacecraft controllers looked for fill-in projects, as a method of "housekeeping"—keeping the camera mechanism in working order.

In this somewhat unstructured way, in part through serendipity, the lunar orbiter captured a sensational image (Fig. 3.4). *Time* magazine wrote (December 9, 1966): "Except for the black sky in the background, the pho-

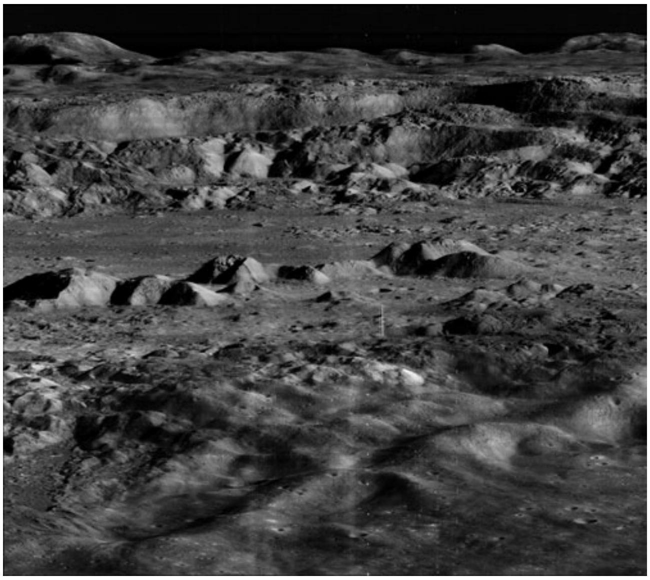

Fig. 3.4 The Copernicus lunar crater, the first planetary landscape. The picture was taken from an altitude of 45 km (28 miles) and looks over the near wall of the crater towards the 1000 m (3500 ft) high mountainous cliffs of the far side, shoved up by the burrowing effect of an incoming, impacting meteor or asteroid. The inner sides of the cliff wall have slumped back in gigantic landslides. Copernicus is about 100 km across and 3 km deep (60 miles × 10,000 ft). Peaks near the center of the crater form a small mountain range, about 500–700 m high and 15 km long (1600–2300 ft high, 10 miles long). These central peaks have bounced back after the impact when the inner walls of the crater rim fell back in. The plains outside the crater (visible in the foreground) are scoured by outflowing debris from the impact, and pitted by numerous smaller craters from debris that was thrown straight up and returned, and from unconnected meteors that fell long afterwards. (Lunar Orbiter 2: NASA Lunar Orbiter Image Recovery Project.) **AA**

tograph might have been mistaken for a composite of the scenic grandeur of Grand Canyon and the barren desolation of the Badlands of South Dakota. But when it was flashed unexpectedly onto a screen at a meeting of the American Institute of Aeronautics and Astronautics in Boston last week, sophisticated space scientists and engineers recognized the terrain immediately. It was a spectacular close-up shot of lunar landscape."

NASA scientist Martin Swetnick was justifiably proud of the picture, boasting that it was "one of the great pictures of the century." Even the *London Times*, then a rather staid newspaper more given to understatement than now, agreed with rare hyperbole that it was "surely the most remarkable photograph ever taken." It was a picture of the crater Copernicus, a landscape with "an eerie character that we've never seen before," according to one NASA insider quoted by *Time*.

Oran W. Nicks, Deputy Associate Administrator of NASA's Office of Space Science and Applications, reported his reaction to the view. It was very similar to Galileo's. He said: "I was awed by the sudden realization that this prominent lunar feature I have often viewed by telescope is a landscape of real mountains and valleys, obviously fashioned by tremendous forces of nature."

Nicks remarked on the un-Earthly clarity of the view, pointing out that it is attributable to the absence of atmosphere. "A photograph from similar altitudes of distant features on Earth would never be as sharp, because of haze."

The clarity and the scale of the lunar features, and the near-horizontal perspective, produced the picture that we would see, were we standing on or near the lunar surface. The picture had an effect that was both objective and emotional. The combination created an impact that marks it as the first planetary landscape in both the scientific and artistic senses of the word.

METEOR CRATERS OF EARTH AND THE MOON

The word "crater" originates from classical Greece as the large bowl used to mix wine and water from which guests would fill their cups to drink. The word was originally used in geology for the mouth of a volcano.

If there is a volcano in a landscape, it is an unmistakable and dramatic feature. Who could overlook a mountain, growing or destroying itself? Who could remain unimpressed by eruptions of gas, ash and steam, gushing flows of liquid rock or fountains of molten lava? Even if a volcano is a quiescent cinder cone, it looms large and dark with hidden power. At close quarters it radiates heat, both radiation absorbed from the Sun by its black ash and lava and heat from the menacing fires below.

On our planet, there are about 1500 volcanoes known on land that have erupted in the last 10,000 years, perhaps as many or even more under the sea. Some volcanoes cover a large area. They may consist of many cinder cones and craters within vast areas of lava, but are fed by a single magma upflow from below Earth that divides upwards and outwards like the branches of a tree. The impact of such enormous complexes of volcanic features on a landscape is immense. Even after billions of years the geological remnants of volcanoes on Earth remain identifiable, even if healed over by weathering—the action of rain, running water, wind erosion and so on.

Meteor craters on the face of the Moon are abundant scars that have never healed. Meteor craters are prominent features of almost all planetary landscapes—the main exception being Earth. We have some meteor craters here on our planet, but they have nearly all healed over. We seem to be living on a different planet. Why is this?

According to the Earth Impact Database maintained by the University of New Brunswick there are only 182 confirmed meteor craters on Earth, and their ages span not thousands of years but thousands of millions of years. Many are very difficult to recognize from the land, as features of the landscape. The list of terrestrial craters ranges up to 300 km (190 miles) in diameter, a scale that is impossible to recognize from the ground. Such craters are "megascopic," too big to be seen by the human eye; they can only be discerned by photography from the air or space, or by large-scale mapping. It is only recently that we have been able to get far enough away from the surface of Earth or have had sufficiently complete maps to see large craters. The typical age of a meteor crater is also a complicating factor. There are plenty of recent volcanoes, but meteor craters are on average much older, and an old crater may be hidden by weathering, erosion, burial processes such as windblown sand or volcanic eruptions, and tectonic deformation or destruction.

Perhaps the best-known meteor crater is the Barringer Meteor Crater in Arizona. It is 1.2 km (0.75 miles) in diameter and 170 m (550 ft) deep, so it is on a recognizable scale in the terrestrial landscape. It is very accessible. This is one of the reasons why it is so well known; there is a road that leads to it from the nearby city of Flagstaff, and there is a visitors' center perched on its rim. The crater is run as a tourist attraction, and hotels in the area are littered with leaflets about it.

If you approach a volcano such as Stromboli in Sicily from the sea, it rises above the horizon long before you are near, and grows and grows, until it looms above you, the upper slopes noticeably foreshortened by the angle of the mountain. In musical terms, the approach is a slow crescendo to a grand theme. The drama of the Arizona Meteor Crater is not apparent until you are right at it, the approach a prelude with a sudden fortissimo.

Fig. 3.5 The Barringer Meteor Crater in Arizona. The edge of the crater has been pushed up above the level of the surrounding plain and shows from outside as a line of low hills (in this view, with the more distant San Francisco mountains on the horizon beyond). The bottom of the crater has silted up with fine wind-blown soil from the surrounding plain, and with material that has fallen from the walls. The walls are wrinkled with gullies made by rainwater and melting snow. At the center of the crater floor, and in places on the walls, are the remains of mine workings, with shafts driven in the early twentieth century into the crater in unsuccessful attempts by geologist Daniel Barringer (1860–1929) to find the meteor, in what proved to be an expensive misapprehension that it was intact and made of valuable ore like iron and nickel. (Photo by the author.) **AAA**

As you drive towards the crater, across the Arizona plain, all that can be seen is a range of hills, gray and low, unobtrusive and unremarkable. When the road reaches the foot of the hills, it bends and slants up the slope of the hillside. Only in the final few meters walk from the car park to the crest of the crater rim does the crater spring into view.

This experience brings to mind the failure of the *Apollo 14* astronauts to realize that they were only 30 m from their destination of Cone Crater and their decision to abandon the search for it because they were running out of time to get back to the landing module (p. 45). As astronaut Ed Mitchell (b. 1930) remarked to CapCom Fred Haise (b. 1933) back in Houston during the *Apollo 14* moonwalk: "This country is so rolling and undulating, Fred, you can be right by a fairly good sized crater and not even recognize it." The crater walls were no more prominent than "undulations."

Standing on the rim of the Arizona Meteor Crater you see the wall in front of you falling away far more steeply than any mountain (Fig. 3.5). At first it is difficult to appreciate the scale, but then you notice the old mine working machinery on the crater floor and the scale gradually comes into focus. You can just distinguish people on the floor, if there are any, and as you sweep over the floor of the crater with binoculars you suddenly see the life-sized cut-out silhouette of an astronaut standing by the fence that stops people straying into the mine workings and coming to harm. It is put there to help you with the scale, but it both reminds you that this is in some aspects a typical lunar landscape and forces you to assess the favorable differences—the blue sky, the vegetation.

The Arizona Meteor Crater is recent, only about 50,000 years old, and retains its characteristic bowl shape, although even a casual look shows how its walls are eroding and the bowl is filling with sand and rocky debris. It is wider and shallower than it was when it first formed. The hills that enclose the crater, as seen from afar, are the crater rim, in part driven up by the pressure generated by the impact, and in part rock from inside the crater folded back in a flap on the crater rim by the blast. Because crater material has been excavated in the explosion and the strata under the surface of the plain have been driven higher by the explosion underneath them, the walls of the crater show precipitous cliffs of rock, with the strata of different colors running horizontally through them, exposing the geology that built up the plain.

Fragments of rock thrown from inside the bowl of the crater, pieces of the iron meteorite, and small iron droplets that have solidified from molten meteorite litter the surrounding plain. Many, perhaps most, of the fragments have been harvested already, and searching for more bits of meteorite is now forbidden. Within the crater the geologist Eugene Shoemaker (1928–1997) found fragments of the minerals coesite and stishovite. These rare forms of silica are made from quartz that has been shocked by a very forceful explosion; apart from nuclear explosions the minerals are associated only with meteor impacts.

A trail leads down into the crater from near the old tourist center, where the approach road turns to run up to the new tourist center (permission needed to descend). The trail cuts down the wall of the crater in an incline that is mostly gentle, but which undulates from time to time as it runs across the many gullies that run down the walls, eroded by rainwater and wind. A blanket of silence comes down as you drop below the crater rim, and on the crater floor it is completely quiet, except for the occasional cry of a hawk circling on the thermal updrafts near the walls; this occasional noise makes the silence more acute. The floor is littered with loose material that has fallen down the inner walls of the crater, with boulders of various colors that have dropped from the different layers of rock and finer soil that has blown into the crater from the surface of the plain. The silence, the warmth and the embrace of the bowl of the crater make this powerful landscape a peaceful place, a long, long way from the moment of its creation in a flaming inferno of noise, explosions, heat and wind as the meteor struck.

On other worlds meteor craters are much more common than they are on Earth, and they are much more significant features of planetary landscapes than of terrestrial ones. Of course this is in part because our approach to the exploration of other planets is by space, so we look down from far away with a megascopic point of view that lets the craters be seen. But it is also true that craters are much more common on other planets.

All planets are affected by the cosmic environment, and meteors from space were about as common near Mars as near Earth. So how come our Earth was so lucky to miss out on this cosmic bombardment? It didn't. The surface of the Moon is pockmarked with craters; there is scarcely any surface without a crater, large or small. Our planet received just as many meteor impacts, but fewer meteors struck Earth's surface because its atmosphere protected it somewhat against impacts, with many meteors burning up or fragmenting into smaller pieces that made smaller craters. More importantly, craters made by the larger meteors were, over time, erased by the weather. The crater walls were eroded by rain and the craters themselves filled by drifting soil or volcanic ash or lava, and by the recycling of the solid surface as its rocks have been thrust down below adjacent tectonic plates. On most other planets there is little or no tectonic activity, and although there may have been volcanic eruptions in the past the activity has died away. There is no rain because there is little or no liquid water. There is little or no atmosphere and little or no weather. Craters persist in abundance on these worlds as unhealed scars! The exceptions are Earth, Venus, Mars, Io, Europa and Titan, the worlds in our Solar System that have significant atmospheres and/or volcanic activity.

ON THE MOON, LIKE THEY FORMED YESTERDAY

The Moon is the world beyond Earth that we know the best. It is our nearest neighbor and the only other world on which people have walked. It is a dry world, dusty and rocky, almost dead. It has no atmosphere, and its surface preserves the record of its entire history, unchanged by any weather. That history speaks of a terrifying bombardment by meteors and asteroids that obliterated the terrain in vast areas of the Moon, puncturing its then liquid interior so that molten lava oozed out into vast plains, thrusting up ranges of mountains in a few brief minutes, creating circular craters with looming, impenetrable ramparts like the forts of giants.

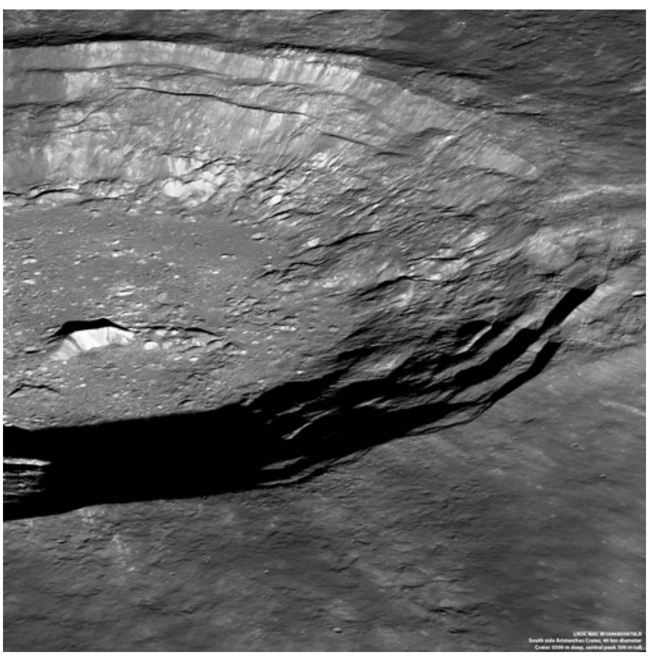

Fig. 3.6 The Aristarchus lunar crater. The Aristarchus Plateau stands on the lava flows of the Oceanus Procellarum, and at its southeastern edge is the Aristarchus Crater, 40 km (25 miles) wide and 3 km (10,000 ft) deep. The picture shows the terraced interior southeastern wall. Features on the wall include dark rocks that have melted and cascaded down into the crater, debris deposits, bright excavated material, and boulders over 100 m (300 ft) wide. (Lunar Reconnaissance Orbiter: NASA/GSFC/Arizona State University M1096850878LR.) **AA**

The impact of a large meteor on a rocky surface like the Moon causes the ground that it hits to surge outwards against the stationary surrounding land, creating an upsurge of mountains that form crater walls (Fig. 3.6). The surge bounces and reflects back into the center of the crater, where, if it is powerful enough, creates a central peak, an isolated mountain (Fig. 3.7), whose rocky structures (Fig. 3.8) may be littered with boulders (Fig. 3.9).

The Moon has no atmosphere and no water, so it has no weather in the conventional sense of the word, although the lunar surface has been peppered by small meteors that have sandblasted the older rocks, creating small craters. Additionally, there is no phenomenon of continental drift on the Moon, no churning of the surface by the motion of tectonic plates. As a result, all the craters made since the Moon formed are still all there, except for a few craters that have been obliterated by a later impact. The lunar craters represent a palimpsest of the 4 billion years of lunar history, a museum of the history of the Solar System, recording impacts both of the smaller, younger ones and the gigantic older craters (Fig. 3.10).

What was the reason for the Late Heavy Bombardment? One theory was that the Sun has a companion star, called Nemesis, in an eccentric orbit with a period of a few million years. On its close approaches, Nemesis disturbs the Oort Cloud of comets, many of which drop down in towards the Sun and cause impacts. This theory has been proposed to explain the apparent periodicity of mass extinctions of species that has been claimed in the record of fossil forms of life over geological time. However, the theory is very controversial, founded on weak statistical data, and not widely accepted.

Another idea to explain the Late Heavy Bombardment is that the rain of projectiles onto the Moon and other inner planets was caused by a collision of two planets in the early Solar System. Maybe this collision was set into action by a disturbance in the Solar System that was caused by an event that coincidentally

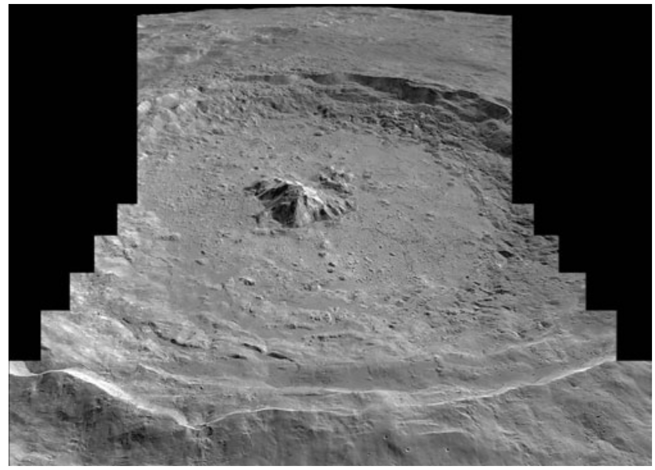

Fig. 3.7 Tycho. One of the most prominent craters on the Moon, Tycho is 85 km (50 miles) in diameter. It is here seen in a montage from the high resolution TV camera of the Selene spacecraft. It is fresh-looking and at the center of a system of rays that lie on top of the lunar surface, so it is relatively young—about 108 million years old, according to dating of ray material gathered by Apollo 17 astronauts. (This may seem a long time ago, and indeed it was, but the age of this crater is only 2 % of the age of Earth. In principle, dinosaurs could have seen this impact.) The impact that caused it melted the lunar rock. Most of the rock was flung out of the crater, coating the surface of the foreground and background of the image. What was left behind pooled back into the crater, making the crater's flat floor. The molten rock cooled stepwise as it sunk down the inside walls of the crater. A bounce in the lunar material after the impact thrust up the central mountain peak. See Appendix 2 in this book for an explanation of the picture shape. (Selene: © JAXA/NHK) **AAA**

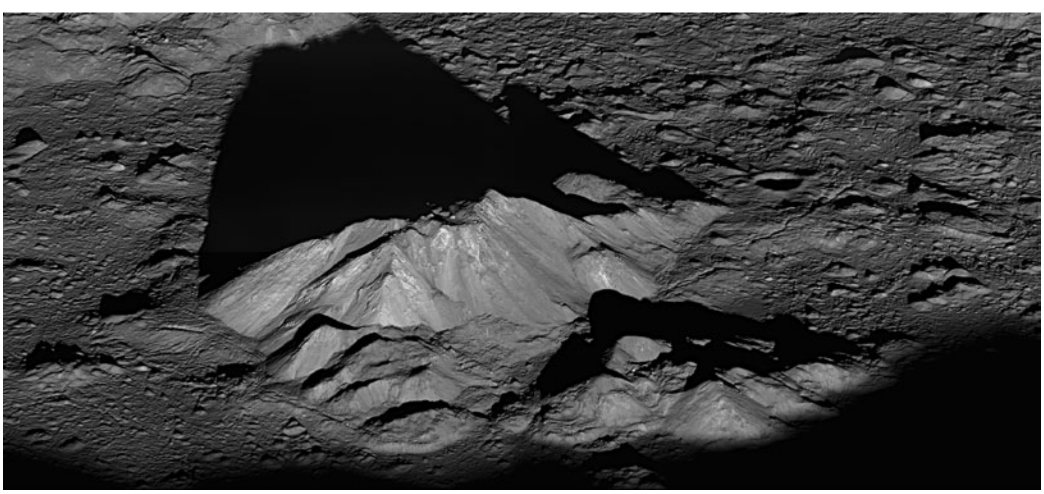

Fig. 3.8 The central peak of the crater Tycho. The mountain is about 15 km (10 miles) wide and 1600 m (5300 ft) high above the crater floor. (Lunar Reconnaissance Orbiter: NASA/GSFC/Arizona State University.) **AA**

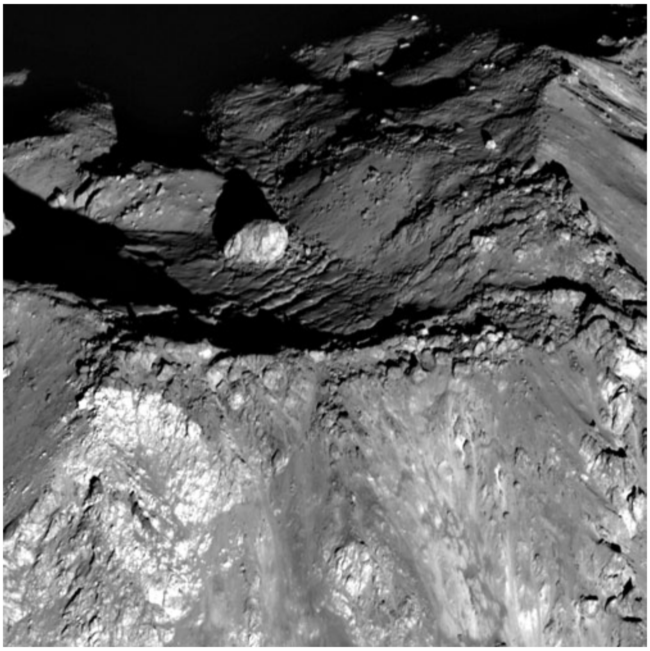

Fig. 3.9 The summit of the central peak of the crater Tycho. The summit is a bowl-shaped depression, containing a boulder about 120 m (400 ft) in diameter. Rocky outcrops on the slopes of the peak are material from below the Moon's surface, which bounced back up at the end of the impact event. (Lunar Reconnaissance Orbiter picture NAC M162350671L,R, NASA/GSFC/Arizona State University.) **AA**

developed in the orbits of two major planets, Jupiter and Saturn. Saturn at one time orbited with exactly twice the period of Jupiter and the same alignment repeated over and over again, building up the same perturbation on the asteroids and causing them to scatter out of their orbit, setting some of them on a collision course.

Other examples of airless worlds that have surfaces that look like the Moon are Mercury, the two moons of Mars, the moons of Jupiter (except for Io, which is resurfaced by volcanic eruptions), the moons of Saturn (except for Titan, which has a thick atmosphere) and the asteroids.

Fig. 3.10 The Apollo 12 Lunar Module, the Intrepid. The Lunar Module was set in a lunar landing configuration shortly after it separated from the Command Module. The photograph was taken by the Command Module Pilot Richard Gordon on Nov. 19, 1969. The Lunar Module, taking Charles (on Nov. Conrad (1930–1999) and Alan Bean (b. 1932) to their landing, was 110 km (70 miles) above the surface. The large, heavily eroded crater occupying a quarter of the picture in the left foreground is Ptolemaeus (164 km, 100 miles, in diameter), and the largest, newer crater on the right is Herschel (40 km, 25 miles, in diameter). (Apollo 12: NASA AS12-H-51-7507.) **AAA**

Fig. 4.1 Comet 67P/Churyumov-Gerasimenko. It was a total surprise as ESA's Rosetta spacecraft approached the nucleus of this comet in 2014 to find that it was dumbbell shaped. But close-up images (this one in January 2015, taken from a distance of 28 km) confirmed what had been expected from Giotto's pictures of Halley's comet: the landscape of its surface shows precipitous cliffs, eroded caverns and outgassing fountains of dust and ice chips propelled into space by gas jets. The landscape is active, rugged and chaotic. (ESA/Rosetta/NAVCAM; Creative Commons licence CC BY-SA IGO 3.0) **AA**

Chapter 4

Ice and Dust Fountains, Rock Piles

FOUNTAINS ON A COMET

The surface of the Moon is dead, a landscape that, after the tumultuous and violent changes of an earlier bombardment, now changes very little and very gradually indeed. By contrast, the landscapes of comets are some of the most violently changing landscapes in the Solar System at the present time. The dynamic nature of comets is signaled from afar by the changes in them that take place as they curve through the sky, tails growing as they approach the Sun, occasionally and unpredictably flaring brightly. Astronomers could only infer the nature of the surface of a comet until the first close-up view of one by the European Space Agency's Giotto spacecraft. It flew by Halley's Comet on March 13, 1986, approaching within 600 km, at which point it suddenly failed, due to an impact by a comet fragment.

To the naked eye, a comet is a bright patch in the sky with a tail curving behind, but this is just the showy part. The main component of a comet is a small, solid body from which the tenuous tail originates. It is hidden within the brightest part of the comet, its head. In scientific terminology, this is called the nucleus of the comet. It is so small that, typically as seen from Earth, it looks just like an unremarkable star. Only by closer inspection would it become obvious that a comet has anything that can be called a landscape.

The nucleus of Halley's comet was what the Giotto spacecraft was sent to take a close look at. It proved to be peanut-shaped, 15 km (10 miles) long, 7–10 km (5–7 miles) wide. Surprisingly, given the white appearance of the comet to the eye, the nucleus is as black as coal. No wonder that this nucleus is so underwhelming to the naked eye! Underneath its solid, dusty crust it is made of ice, principally water-ice, but also dry ice and other gases frozen solid. On the sunlit side, at the time Giotto visited, the comet had three outgassing fountains, jets of vapor spraying dust into space. The dust is what gave Halley's comet its remarkable tail, the streaks of dust reflecting sunlight like streaks of white cirrus cloud in the sky. The tail is a collection of dust particles up to the size of small rocks. One of the pieces, nearly 1 g in mass, hit Giotto and caused it to stop working at its closest approach. The density of the comet, less on average than that of water, indicated that the nucleus is not solid ice. Apparently there are holes beneath the surface, subsurface caves. That could explain its irregular, pockmarked surface. Its deep valleys are exposed holes.

This general picture was confirmed in detail in 2014 when the ESA spacecraft Rosetta imaged Comet 67P/Churyumov–Gerasimenko as it approached the Sun from a considerable distance, before it became very active. The comet's nucleus, overall 5 km in size, was a surprising double shape (Fig. 4.1). It might be that the comet is made from two comets that have jostled together, with loose material gently migrating to the place

P. Murdin, *Planetary Vistas,* DOI 10.1007/978-3-319-15242-4_4

where the two comets touch and fusing into a dumbbell shape. The two main bodies of the dumbbell have precipitous cliffs and eroded caverns.

The general idea of the structure of comets, putting together the evidence from ground-based observations and close-up examination from spacecraft, is that they are dirty snowballs, like one that has been exposed to the sun so that its surface has vaporized or melted, leaving behind a crust of the dirty bits. Sunlight has acted on the crust, making a tarry substance, blackening it further. This is the origin of the black coating.

Halley's Comet orbits the Sun on a long, thin, elliptical orbit, returning to the vicinity of the Sun every 75 years. It has been recorded as returning 30 times, since 240 B.C. Comet 67P/Churyumov–Gerasimenko is similar though its period is much shorter, 6.45 years. Because a comet loses a fraction of its mass every return, it will eventually melt away. Its lifetime will in total be perhaps 1 million years. Because of the progressive and sporadic evaporation, the comet's landscape is transient, a violent surface of subterranean explosions and erupting fountains, like the geysers of steamy sulfurous water in Yellowstone National Park in Wyoming. In both cases, the fountain is triggered by vaporization of ice below the surface. In the case of the Yellowstone geysers the heating of subsurface water is from geothermal heat. These geysers have the reputation of stability and regularity, surrounded by safe boardwalks and erupting to schedule. In the case of the fountains from comets, the fountains are triggered by vaporization of ice by the warmth of the Sun. They are sporadic, bursting out from anywhere on the warm sunlit side.

There is a fictional collection of pictures that gives a good idea what the landscape on the surface of an active comet looks like. *Deep Impact* was the name of a movie released in 1998 about a comet found to be heading towards Earth, and an attempt by astronauts to deflect it by exploding nuclear weapons planted under its surface. ("Deep Impact" was also the name of a NASA mission launched in 2005 that flew alongside Comet Tempel 1, delivering an impactor onto its surface to expose the material below the comet's surface so that it could be seen and analyzed from the accompanying spacecraft and from Earth. The two projects were christened identically by a coincidence.) The movie had two distinguished scientists as "comet advisors," husband and wife planetologists Eugene Shoemaker (1928–1997) and Carolyn Shoemaker (b. 1929). The landscape that the astronauts encountered on the comet is thus as authentic as it might be, given that, up to 2014, there were no actual pictures obtained in such a situation. The Shoemakers put together the scientific evidence, including the Giotto data, to imagine what it would be like to stand on a comet and look around. Since the movie was made there have, however, been a number of close encounters by spacecraft with comets that have added some new details.

What the movie astronauts see as they approach the comet to land is a minefield of rocks trailing the comet, some of them very large. The spacecraft is damaged by collisions with a few rocks. Nevertheless, the

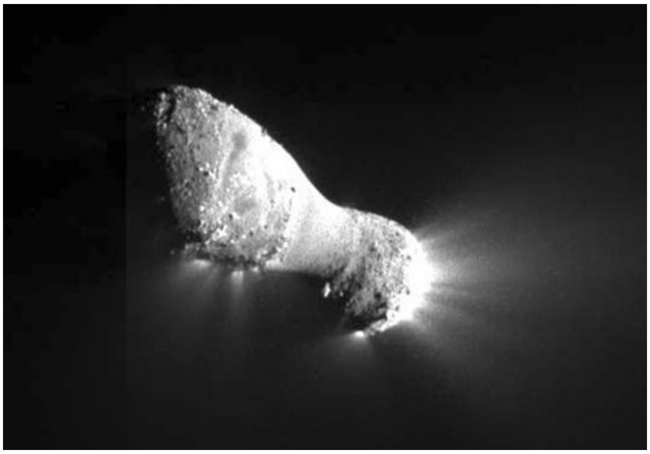

Fig. 4.2 Fountains from a comet. Comet Hartley 2 was viewed by the EPOXI mission from a distance of 700 km (430 miles). The comet's dumbbell-shaped nucleus, or main body, is approximately 2 km (1.2 miles) long and 0.4 km (0.25 miles) wide at the "neck." Jets fountain from two areas of the surface. (EPOXI: NASA/JPL-Caltech/UMD.) **AA**

spacecraft lands and is tethered to the surface by pitons. The astronauts disembark to begin drilling into the comet to place the nuclear weapons. They have been warned that they have less than 7 h before their landing place rotates with the comet into the sunlit side. In the movie, a NASA scientist explains that as soon as the Sun rises, the surface temperature of the comet will quickly rise 350°, creating pressure under the surface that will expel jets of superheated gas in fountains. The astronauts will be working in a field of unpredictable superheated geysers.

The mission does not go smoothly. One of the drills gets stuck, penetrating into a fissure and jamming on the side. The astronauts run out of time. The Sun rises. Fountains of gas do indeed explode unexpectedly up through the comet's surface, one of them erupting full force onto an astronaut and sending him into space, lost. The rest of the crew tumble into their spacecraft and take off back home.

The Deep Impact spacecraft, rechristened the EPOXI mission, went on from Comet Tempel to view Comet Hartley 2, and was able to image outgassing fountains from this comet, lit by the Sun (Fig. 4.2).

BATTERED VESTA

Comets and asteroids are the "minor bodies" of the Solar System. However, this term means only that they are smaller in size that the eight or nine largest planets. It could also mistakenly be read as a suggestion that they are unimportant. Actually, they have some of the most interesting, "other-worldly" scenery of any astronomical landscape, although so few have been inspected by space missions close up that we have to imagine the details from some indistinct clues.

The asteroids are a mixed bunch of solid, rocky and icy bodies. The biggest one in the Main Asteroid Belt is Ceres, the first asteroid discovered in 1801. It is a sphere 930 km (580 miles) in diameter, a third the size of our Moon. Ceres is a sphere because its own force of gravity has completely overcome the structural strength of the rocks of which it is made. Instead of teetering in a random pile, the rocks have settled down under gravity into concentric layers, balancing one on top the other, and plasticized or fused together (depending on depth) into a sphere. This property has given Ceres its designation as a dwarf planet. None of the rest of the asteroids is massive enough for this to have happened.

Some asteroids are extinct or dormant comets—solid bodies that are more icy than rocky; the slumbering ones may wake up from time to time and erupt feebly. The larger ones are more rocky than icy. They are, in a sense, "failed planets." When the planets were being made in the solar nebula about 4500 million years ago, Jupiter formed. It is such a massive body that its force of gravity stirred up the solar nebula around where the planet was orbiting. This prevented the partially built bodies forming here from completely coalescing. As a result numerous nascent planets formed here, but none, apart from Ceres, grew large enough to become a dwarf planet. None grew so massive that each layer within the planet was in equilibrium, balancing stably, one layer lying on the one below. The next largest asteroids are Pallas and Vesta. Each of them is nearly in equilibrium, like Ceres, but the strength of the rocks within plays a significant part in maintaining their shape. Each departs significantly from a completely spherical shape. Pallas and Vesta are about 500 km (300 miles) in diameter, half the diameter of Ceres, a sixth the size of the Moon.

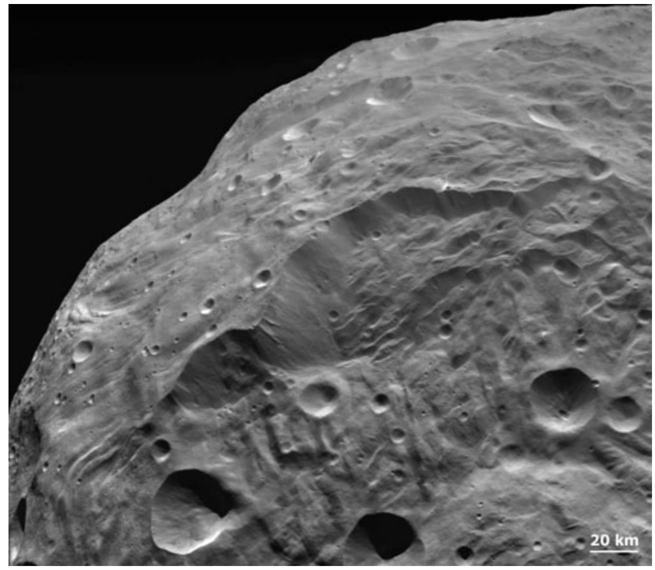

Fig. 4.3 Vesta's near horizon. The Dawn spacecraft obtained this image of the asteroid. In the foreground is a steep scarp with landslides and craters in the scarp wall. The surface of the asteroid is strongly curved. (Dawn: NASA/ JPL-Caltech/ UCLA/ MPS/ DLR/ IDA.) **AA**

Most asteroids are loose accumulations of rock. The individual fragments may have ground together, some even fusing where they touched, but the bits have retained their shape. They heap up like a rubble pile, with spaces between the fragments.

The region inside the orbit of Jupiter where most asteroids orbit is called the Main Asteroid Belt. It was and remains a crowded part of the Solar System, and collisions were inevitable—and still happen. Depending on the size of the approaching asteroid, and its speed and direction of approach, the impacting asteroid might simply dig a hole in its target, remolding the shape of the target somewhat. Or a colossal collision might smash each asteroid into smithereens, creating a spray of fragments. These bits and pieces are the majority of the asteroids in the Main Belt at this time.

The smaller collisions that burrow into the target asteroid have left craters on their surface. Vesta has a crater that was so large that it altered the very shape of the asteroid (Fig. 4.4). Images of Vesta from the Hubble Space Telescope showed that it has a gigantic piece missing at its south pole. The contents of the crater have been scattered into space and orbit the Sun as a family of asteroids called the Vesta family. Other bits were flung further away across the Solar System; from time to time pieces fall to Earth as meteorites. About 5 % of all meteorite falls come from Vesta—known (from the initials of the names of three typical examples) as HED. The link with Vesta comes from their mineral composition, which matches the color and spectrum of the asteroid.

Asteroids are so small that their surface curves away sharply, and landscape features even of the middle distance drop quickly below the

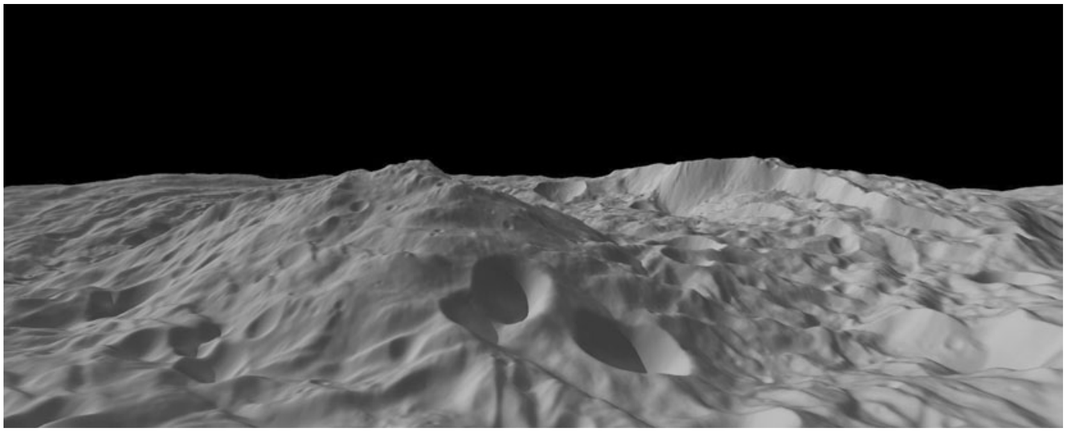

Fig. 4.4 The crater at Vesta's south pole. Imaged by the Dawn spacecraft, the crater is shown here in a picture that removes the overall curvature of the body, as if the giant asteroid were flat and not rounded. This oblique view has been derived from stereo images obtained with a camera aboard the Dawn spacecraft from an altitude of about 2700 km (1700 miles) above Vesta's surface. (Dawn: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI.)
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horizon (Fig. 4.3), even more than on the Moon. The Apollo astronauts remarked on the strangeness of the sense of distance that they felt in their views of the Moon. In part this was because mountains seemed close, with clues as to distance (such as atmospheric absorption or the apparent size of familiar objects like trees) being absent. This was contradicted by the simultaneous rapidity with which mountains curved over the horizon, due to the small size of the Moon. In the same way, and ignoring the effects of fog and other obscuring effects of Earth's atmosphere, if you stand in North America, you cannot see Mt. Everest in the distance, because of Earth's curvature. This is even more apparent with the small size of the asteroids.

Image processing techniques that remove the curvature can produce images that show more distant vistas (Fig. 4.4). An observer on Vesta would not have the same far views, because the distant features would disappear over the curvature of the horizon.

The largest landscape feature on Vesta is its south polar crater is 30 km (20 miles) deep and 460 km (290 miles) across. Considering that Vesta is only 530 km (330 miles) across, this impact came close to breaking up Vesta completely.

ITOKAWA: THE FALCON'S DUSTY PERCH

The asteroid Itokawa was selected as the target of the first attempted sample return mission to an asteroid. A sample return mission is a space mission that attempts to recover samples of the object of the mission and return them to Earth for analysis. The final missions of the Apollo program, *Apollo 11–17,* were sample return missions to and from the Moon. Itokawa was the target of Japan's *Hayabusa* mission. *Hayabusa* means "Peregrine falcon." The spacecraft reached the asteroid in September 2005 and maneuvered into orbit alongside it. Itokawa is a small asteroid, a crooked ellipsoid in shape, only 600 m long and 250 m wide, not massive. Its gravity was too weak to hold the spacecraft in orbit like a satellite, and it had to power itself in flight repeatedly using its rockets for course corrections. The weak gravity was one reason why the asteroid was chosen as a target for the sample return mission—it would be easy for the spacecraft to re-launch itself back to Earth so it would need to carry the minimum of fuel for the return journey.

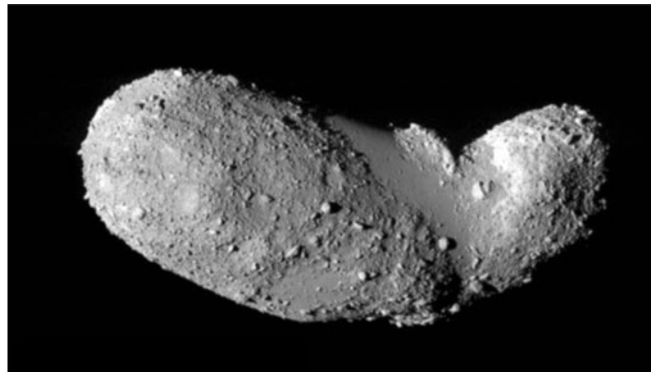


Fig. 4.5 Itokawa, the rubble pile. Littered with rocks, the asteroid has few small craters, which are back-filled with stones and dust. (Hayabusa: Japan Aerospace Exploration Agency, JAXA.) **AA**

The spacecraft carried out remote observations of the asteroid for a month and then in November 2005 attempted to land a small spacecraft called Minerva. The descent was fraught with difficulties. There were technical problems, which caused the spacecraft to make fruitless approaches, plus there was a last-minute problem on the last descent that proved almost fatal. The asteroid proved to be remarkably rocky, and the spacecraft software thought in the descent that it was landing too near an obstacle. It entered a defensive configuration, which meant that the sample-return mechanism failed properly to activate and could not collect material in the manner intended. However, the controllers surmised that the thrust rockets that controlled the descent might have blown dust up into the open collector horn as the spacecraft touched down. So the controllers decided to continue with the mission. The return capsule was sealed and sent home. The return trip was equally fraught with incident, but heroic efforts by the controllers eventually brought the capsule back to Earth in June 2010. As anticipated, the spacecraft disintegrated like an asteroid or fireball on re-entry into the atmosphere, but the capsule survived intact and was recovered at the Woomera range in Australia. The capsule proved to contain over 1000 tiny grains of material from the asteroid.

Because the landing on Itokawa was simply a touchdown, and because of the technical difficulties, no images were obtained of landscapes on the asteroid. However, many images were obtained from the orbiting mother craft. The images were a surprise (Fig. 4.5). The small asteroid is littered almost everywhere with rocks, from big boulders to pebbles, and there are few craters. Those craters that do exist are small. Any meteorites that have impacted on Itokawa have buried themselves in loose material or the craters had been backfilled by the mobility of small stones and dust on the surface. The density of the asteroid proved to be very small and indicated that the asteroid was a loose conglomeration of rocks with large spaces where the rocks do not fit well together. Itokawa is, and looks like, a rubble pile. Its gravity is so weak that the rocks and ores of which it is made have not consolidated. It is representative of a small planetesimal in

Fig. 4.6 The cliffs of Comet Churyumov -Gerasimenko. Towering over 1 km (over 3,000 feet) high, high cliffs bound the valley that divides the two halves of Comet 69P. The cliffs have been sculptured and eroded from the ice-bound surface of the comet. Loosening of the ice by the warmth of the Sun on previous passes of the comet into the inner Solar System has caused boulders up to 20 meters in size to fall from the cliffs and to lie at their foot. They lie in a drift of smooth sandy, snowy material that covers the surface of the neck between the two halves, sprayed from earlier erupting fountains. The image is a mosaic of four taken from a distance of 20 km from the comet by the Navigation Camera of ESA's Rosetta spacecraft in December 2014. (Licence CC BY-SA 3.0 IGO: ESA, Rosetta spacecraft, NAVCAM; additional processing by Stuart Atkinson.)

the very early history of the Solar System that might have grown into a planet if it had accumulated more material.

The dust on Itokawa has a similar composition to meteorite dust. Dust from asteroid collisions, made as one rocky surface grinds against another, permeates the Solar System, throughout its orbital plane, the 'ecliptic.' Interplanetary dust is the medium that reflects sunlight in the phenomenon known as the zodiacal light, a cone of light that shines up from the horizon after sunset, its axis along the line of the ecliptic. In the first hour of a moonless sky, far from artificial lights, the zodiacal light shines like a broad searchlight beam along the zodiacal constellations. The dust falls on Earth, grain by grain, and shows at night as each flies, incandescent, through the air as a meteor. The dust comes from a number of sources, including melted comets and crumbled asteroids.

The landscape from some of the locations on Itokawa will be awe-inspiring (Fig. 4.6). The view from the Muses Sea, the flat area that forms the 'crease' between the two halves of the asteroid, are reminiscent of Yosemite Valley, with steep, high, narrow hills rising steeply from the valley. Parts of the landscape of Comet 67P/Churyumov–Gerasimenko are even more extreme. Vast, jagged cliffs on one half of the double-comet shape overhang smoother areas on the other half and the neck between them. The looming overhangs would likely have fallen if they had formed on Earth, but gravity on the comet is weak, and the strength of the material of which they are made must be enough to maintain them in position. An astronaut walking on the neck of material that connects the two parts of the comet would feel menaced by the landscape and the thought that the overhangs might soon collapse.

EROS: A VALENTINE'S DAY ENCOUNTER

The minor planet Eros was discovered independently in 1898 by Gustav Witt (1866–1946) in Berlin, and, on the same night, by Auguste Charlois (1864–1910) in Nice. It was immediately recognized as the astronomical sensation of the year, on account of its orbit. Up to that point all minor planets lay comfortably in the Main Belt, orbiting completely within the gap between Jupiter and Mars.

The mean distance of Earth from the Sun is called one astronomical unit (AU). The mean distance of Eros from the Sun is 1.458 AU, considerably less than the mean distance of Mars at 1.52 AU. Its orbit is quite elliptical, and it crosses the orbit of Mars. Such asteroids are known as

Mars-crossers, with Eros being the first that was recognized. Its closest approach to the Sun is 1.133 AU, with its closest approach to Earth at 0.149 AU, so it is also a near-Earth asteroid (NEA). Its orbit is likely to evolve quickly with time because of the repeated influence of Mars at each crossing, and it will, sooner or later, become an Earth-crossing asteroid, with the consequent risk that it will impact Earth. It is $34 \times 11 \times 11$ km in size, and if it does hit Earth it will produce a crater that will rival the scale of the Chicxulub Crater, the impact that it is thought by astronomers to have caused the extinction of the dinosaurs. There is a 5 % chance that Eros will hit Earth in the next 100 million years.

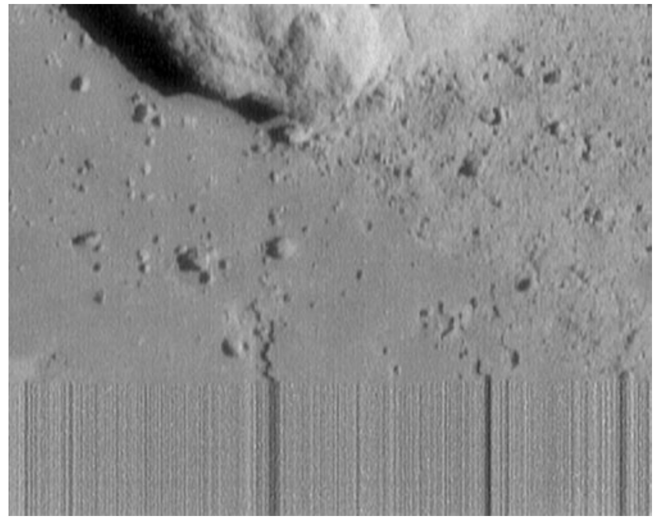


Fig. 4.7 Touchdown! This is the last image of asteroid 433 Eros received from the NEAR Shoemaker spacecraft. Taken from a range of 120 m (394 ft), the image area measures 6 m (20 ft) across. The streaky lines at the bottom indicate loss of signal as the spacecraft touched down on the asteroid during transmission of this image. (NEAR: NASA/Johns Hopkins University, image 0157417198.) **AA**

Eros was visited and examined for nearly a year in 2000–2001 by a space probe, the Near Earth Asteroid Rendezvous-Shoemaker (NEAR-Shoemaker, or just NEAR). Gene Shoemaker (1928–1997) was a geologist whose work on the Barringer Crater in Arizona definitively showed that it was indeed a meteor crater. He studied impact craters all over the world and was killed in a road accident while driving to study a remote meteor crater in Australia. With NASA's flair for public relations, the flight controllers ensured that the NEAR-Shoemaker space probe would meet and join up with Eros by entering orbit around the asteroid on February 14, 2000, St. Valentine's Day. At the end of its mission, the spacecraft was lowered to the surface of the asteroid, touching down on February 12, 2001. The impact was on the scale of a terrestrial fender-bender car crash, as the asteroid is small and its gravity is weak. An astronaut who landed on the surface would weigh 1 ounce there. If his or her exploration of the surface of the asteroid was too exuberant and the astronaut leapt about excitedly, he or she could end up in orbit.

During its descent, NEAR transmitted pictures in real time before it impacted at about 4 mph, sufficient to crush the instruments mounted on the lowest parts of the spacecraft but not to damage what was inside. Its last picture (Fig. 4.7) transmitted prior to touchdown was obtained from a range of 120 m (390 ft), and was truncated in transmission by the impact, but the spacecraft continued transmitting other scientific data for days after its landing, until its mission was declared to be over. Eros was the first asteroid touched by man—at least, by a machine that had been made by man—the second being Itokawa.

Eros is a curious shape, like a curved potato, a tongue or a slipper. Its surface is covered with craters caused by the impact of other smaller asteroids and meteoroids. Apart from one crater, Shoemaker, named after the geologist, the craters are named after various famous lovers, such as

Casanova and Heathcliff; planetologists have had more fun naming these craters than the craters on 253 Mathilde, which are named after the coal fields and basins of the world. The surface of the asteroid is littered with rocks that have been ejected from these craters. In size they range from castle-sized boulders to small pebbles. The smallest pebbles imaged by NEAR in the picture sent from its last transmission from just above the surface were just millimeters in size (Fig. 4.7). There are fewer small craters than expected, so something has been happening to cover them up. Eros is completely without an atmosphere, so the process is not weathering by wind or rain; one thought is that the asteroid shakes when struck by other asteroids and meteoroids, causing landslips on the slopes of hills that bury craters in the valleys below and topple the walls of small craters so that they fill up. In some cases the finer powdery material has separated from the rocks and has flowed into a hollow to make a flat-surfaced area looking like a dry pond. One particular strike about 1 billion years ago produced most of the rocks on the surface, maybe the "ponds," and one of the larger craters, the one called after Shoemaker.

Fig. 5.1 Approaching the Apollo 11 landing site. A perspective color photograph taken from the window of the Apollo 11 Lunar Module, looking west, shows the Mare Tranquilitatis, the smooth undulating area in the foreground, a basin that is the result of a massive crater impact early in the history of the Moon. The landscape looks towards the lunar terminator, the boundary between the sunlit portion of the Moon and the night-time part. The Apollo 11 landing site, Tranquility Base, is near the terminator, just this side of the hills to the right of the center, whose tops are catching the sunlight before the plain below. The landing site is 210 km (130 miles) from the largest crater in the foreground, which is the crater Maskelyne, 23 km (14 miles) in diameter. There are some sinuous valleys that track across the plains, perhaps collapsed lava tunnels, and, in the foreground and left background, the peaks of some old-looking hills protrude in places from the frozen lava "sea" that has flooded into the Mare Tranquilitatis basin and washed up to the surrounding mountains. There are numerous, small, crisp, recent-looking craters scattered across the mare. (Apollo 11: NASA photograph AS11-37-5437) **AA**

Chapter 5

Dusty Plains, Steep Hills and Rugged Lunar Mountains

MAGNIFICENT DESOLATION

Human eyes saw close-up the landscape of another world for the first time in 1969, in the 3-year exploration of the Moon, famous throughout the entire world: the Apollo program. Avoiding mountainous areas such as the region around the Copernicus Crater, the six Apollo landers (*Apollo 11* to *Apollo 17,* excluding the ill-fated *Apollo 13,* 1969–1972) were targeted towards safer, flatter areas to land on. All of them were not far from the equator of the Moon, since this is the easiest zone to approach from Earth, and to escape from if things go wrong. The first landing site, the one for *Apollo 11's* lander, the Eagle, was in *Mare Tranquilitatis* (Sea of Tranquility), one of the lunar "seas"—in reality, like the rest of these misnamed flat, gray areas of the Moon, a dusty plain of basaltic lava. The area for Tranquility Base was chosen because it was a smooth landing site, with relatively few craters and boulders (Fig. 5.1). There were no large hills, high cliffs or deep craters on the approach path that could cause incorrect altitude signals to the lunar module landing radar.

Given the selection criteria, the view of the lunar landscape from the Eagle landing site at Tranquility Base is unsurprisingly flat. But it is also clear that even so, there are undulations in the plain that could well have upset the lunar lander had it encountered one of them. It had been vital that astronaut Neil Armstrong (1930–2012) had been able to seize manual control from the computer and trim the exact landing site as he descended the last few meters onto the lunar surface in 1969. Armstrong told the mission controllers about this immediately after landing: "Hey, Houston, that may have seemed like a very long final phase. The AUTO targeting was taking us right into a football-field-sized crater, with a large number of big boulders and rocks for about one or two crater diameters around it, and it required flying manually over the rock field to find a reasonably good area."

As the Lunar Module landed, its retrorockets blew up dust that partially obscured the view from the windows. That did not make it easy to set down the Lunar Module in the exact right place. The danger of landing in a depression, so small that it had not been mapped from Earth or seen from the reconnaissance passes of satellites above, but deep enough to topple the module over, is apparent from *Apollo 15's* lucky escape a few years later (see below, Fig. 5.8). Armstrong's crewmate, Buzz Aldrin (b. 1930), went on to describe the view from the windows: "We'll get to the details of what's around here, but it looks like a collection of just about every variety of shape, angularity, granularity, about every variety of rock you could find. The colors—well, it varies pretty much depending on how you're looking relative to [the direction opposite the Sun]. There doesn't appear to be too much of a general color at all. However, it looks as though

P. Murdin, *Planetary Vistas,* DOI 10.1007/978-3-319-15242-4_5

Fig. 5.2 The landscape around the Eagle Lunar Module. The horizon is almost flat (curved along the length of the panorama only because of the way individual frames of the panorama have been assembled to cope with distortion in the camera lens). The only feature on the horizon is the low range of the Cat's Paw Hills above the shadow of Neil Armstrong, the astronaut-photographer. These hills are the walls of a complex crater about 2.7 km across, shaped like imprints in the snow where a cat has walked. There are shallow crater to the left and to the right of the lander, under which Buzz Aldrin is working. The shadows in this panorama are inconsistent—the shadows of verticals are not parallel—because the panorama wraps around 360 °. (Apollo 11: NASA photograph JSC2007e045375) **AAA**

some of the rocks and boulders, of which there are quite a few in the near area, it looks as though they're going to have some interesting colors to them …"

Armstrong told Mission Control what he could see (Fig. 5.2): "The area out the left hand window is a relatively level plain cratered with a fairly large number of craters of the 5–50 ft variety, and some ridges—small, 20, 30 ft high, I would guess, and literally thousands of little 1- and 2-ft craters around the area. We see some angular blocks out several 100 ft in front of us that are probably 2 ft in size and have angular edges. There is a hill in view, just about on the ground track ahead of us. Difficult to estimate, but might be a half a mile or a mile."

These hills were the crater walls of the Cat's Paw crater (Fig. 5.2), with a landscape whose underlying structure is similar to the approach to the Barringer Meteor Crater in Arizona (Fig. 5.3).

The scenery on the Moon is nearer than scenery on Earth. The horizon on the Moon is much closer than the horizon on Earth, because the Moon is smaller. The flat lunar surface curves away below the horizon much more quickly than the flat surface of a terrestrial plain, so the views are not so extensive or far-reaching. If a person of average height stands on a plain on Earth the horizon is 5.5 km (2.8 miles) away, on the Moon 2.3 km (1.4 miles). On Earth a mountain 2000 m (6500 ft) high can be seen peeping over the horizon from a distance of 160 km (100 miles); on the Moon it disappears at a distance of 120 km (75 miles).

Determined not to blow his first words from the Moon as he stepped out of the Eagle onto the lunar surface, Neil Armstrong's mind was on the historic moment, not the scenery: "That's one small step for a man, one giant step for mankind."

In his first description of the Moon as he touched it, he was looking down where his feet were going, rather than at the landscape: "The surface is fine and powdery. I can—I can pick it up loosely with my toe. It does adhere, in fine layers like powdered charcoal, to the sole and sides of my boots. I only go in a small fraction of an inch, maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine, sandy particles."

Fig. 5.3 Tracks in the ash. The fossil footprints in volcanic ash at Laetoli, Tanzania, laid down 3.6 million years before the present, belonged to a family of the hominid Australopithecus afarensis. (John Reader/Science Photo Library)

But he soon raised his head to view the landscape: "It has a stark beauty all its own. It's like much of the high desert of the United States. It's different, but it's very pretty out here."

Buzz Aldrin agreed as, twenty minutes later, he followed Armstrong on to the Moon's surface and stood, looking around:

> In every direction I could see detailed characteristics of the gray ash-colored lunar scenery, pocked with thousands of little craters and with every variety and shape of rock … With no atmosphere there was no haze on the moon. It was crystal clear. "Beautiful view," I said … I slowly allowed my eyes to drink in the unusual majesty of the Moon. In its starkness and monochromatic hues it was indeed beautiful. But it was a different sort of beauty than I had ever seen before … "Magnificent desolation."

Searching for a way to express the desolation and the impact of the visit by *Apollo 11,* Aldrin found a flat surface and pressed his boot into the lunar dust. His close-up photograph of his boot print (Fig. 5.4) became the iconic image of the visit—the first steps by a man on another world—and of the landscape around, even though it did not show the human beings or the scenery at all (Figs. 5.3, 5.5).

ON THE EDGE OF THE LUNAR HIGHLANDS

Apollo 9, 10, 11 and *12* landed in areas of the Moon that were much the same as *Apollo 8's* Tranquility Base. After the accurate landing of *Apollo 12,* mission planners were willing to consider landings in smaller, but level, areas within rougher, more interesting regions. *Apollo 13* was targeted to land in the geologically interesting region known as the Fra Mauro formation, made of ejecta from the impact of the huge asteroid that formed *Mare Imbrium* (Sea of Rains). Material from the impact is spread across the whole of the nearside of the Moon, so if Fra Mauro material could be examined and its age determined this would form a layer that would date features older and younger. Perhaps, too, the impact would have brought up very old, very interesting material from deep below the *Mare Imbrium.* The specific landing site was near a young, fresh, 370-m (1200-ft) diameter crater called Cone. The *Apollo 13* mission had to be aborted in its journey to the Moon because of an on-board malfunction, and *Apollo 14* was retargeted to the Fra Mauro landing site (Fig. 5.6).

Commander Alan Shepard (1923–1998) and Lunar Module Pilot Edgar Mitchell (b. 1930) landed the Antares module of the *Apollo 14* mission in February 1971. The astronauts carried out two moonwalks, including one long one that ran radially up to Cone Crater (Figs. 5.6, 5.7). They wanted to see into the large crater, and they collected rock specimens on the way. The samples returned by Shepard and Mitchell to Earth eventually indicated that the *Mare Imbrium* formed 3.85 billion years ago. Their 1.4 km (0.9 miles) journey was arduous as they climbed up the mound on which the crater was situated. They aimed to look into the crater but could not find their way right to the rim. Shepard recorded:

> The mapped traverse was to take us nearly directly to the rim of Cone Crater, a feature about 1000 ft in diameter. As we approached, the boulders got larger, up to 4 and 5 ft in size. And at this time, the going started to get rough for us. The terrain became more steep as we approached the rim, and the increased grade accentuated the difficulty of walking in soft dust. Another problem was that the ruggedness and unevenness of the terrain made it very hard to navigate by landmarks, which is the way a man on foot gets around. Ed and I had difficulty in agreeing on the way to Cone just how far we had traveled, and where we were. We did some more sampling, and then moved on toward Cone, into terrain that had almost continuous undulations, and very small flat areas.

Running out of coolant water for their spacesuits, the astronauts were told to turn back when, unknowingly, they were only 30 m (30 yards) from the rim, unable to see the drop off past the rocky outcrops that intervened, like Saddle Rock (Fig. 5.7). They were not the only explorers in history not to reach their destination, but it frustrated them when they learned that they failed by so small a margin.

Fig. 5.4 Tracks in the dust. Buzz Aldrin's footprint in the lunar dust at Tranquility Base on the Moon, 1969, the iconic lunar landscape. (Apollo 11: NASA photo AS11-40-5878) **AAA**

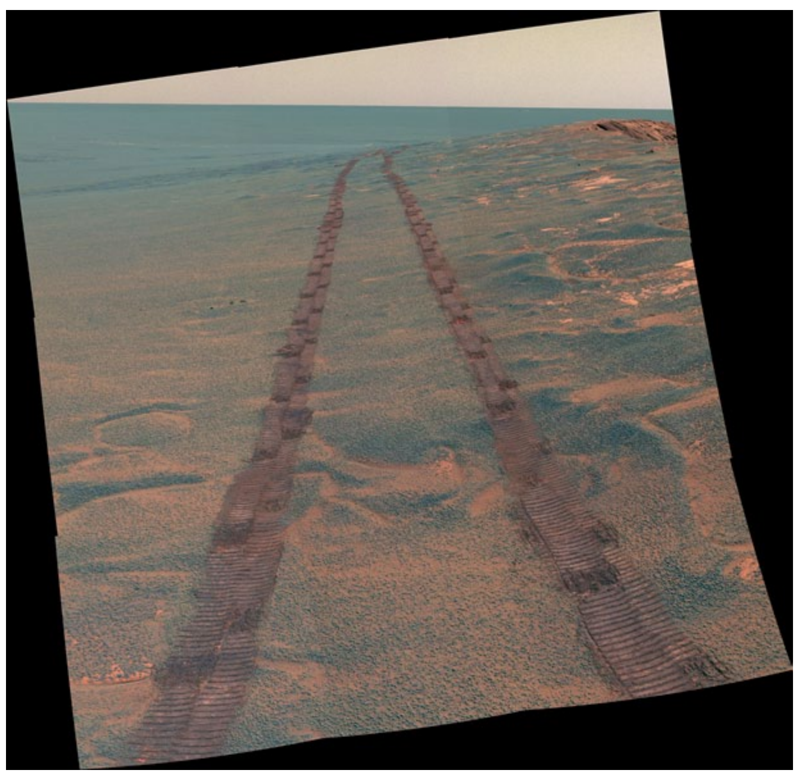


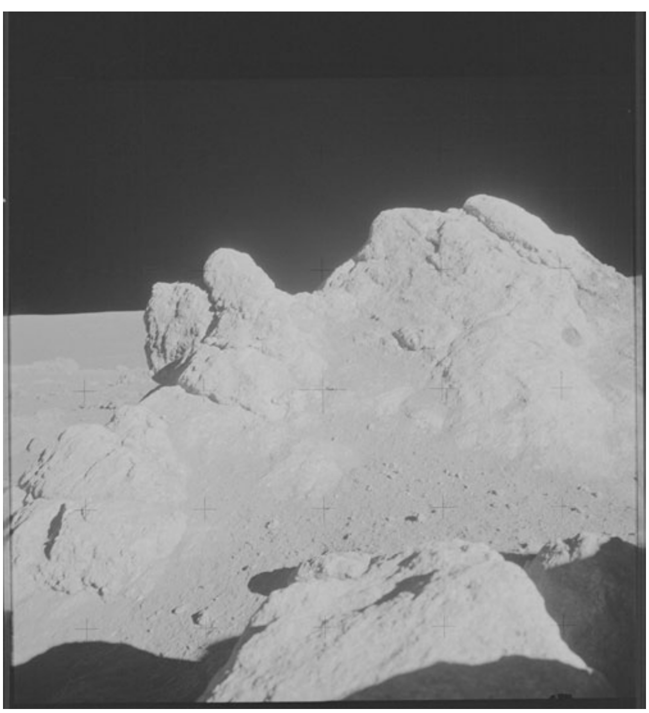
Fig. 5.5 Tracks on the sand. The Opportunity rover looks back on its route across Meridiani Planum on Mars, 2011, towards the crater Endeavour, a proxy human on the Red Planet. (Opportunity: NASA/JPL/Cornell) **AA**

Fig. 5.6 The Apollo 14 landing site. Cone Ridge, the near wall of Cone Crater, in the Fra Mauro region of the Mare Imbrium, is on the horizon under the glare of the Sun. (Apollo 14: NASA photograph JSC1007e045377) **AAA**

WORDS CAN'T DESCRIBE IT

The *Apollo 15* mission landing site was even more adventurous than *Apollo 14's.* The Lunar Module Falcon landed in July 1971 near the Apennine Mountains, which form one of the rims of the *Mare Imbrium* (Sea of Rains). The landing was on a dark plain that intruded into the mountains called *Palus Putredinis* (the Marsh of Decay). The high Apennine mountain closest to the landing site is Hadley Delta, with St. George Crater on its lower flanks and an even higher mountain, Mt. Hadley, nearby. The dark plain is cut by the Hadley Rille, a dry valley. Although the site had been selected as a smooth, safe landing place, dust obscured the view from the windows, and the astronauts found the scenery more difficult to identify than the practice simulations back in Houston had suggested would be the case. Nevertheless Falcon was successfully steered to touchdown by its crew, Commander David Scott (b. 1932) and Lunar Module Pilot James Irwin (1930–1991), coming to rest on a slope, one leg in a small crater, and leaning over at an angle of about 15° (Fig. 5.8). This was uncomfortably close to the tolerable limit of 20°, at which the Lunar Module was in danger of toppling over, as happened to the *Venera 7* lander on Venus. If it had done so the astronauts would not have been able to return to Earth, and would have remained forever on the Moon, in the dead lunar landscape.

Fig. 5.7 Saddle Rock. The promontory at station C1 near the rim of Cone Crater is a jumble of broken rock thrust up by the impact that formed the crater. Although the astronauts did not know it, the horizon a few tens of meters (few tens of yards) away was the rim of their unachieved destination, Cone Crater. (Apollo 14: NASA photograph AS14-68-9450) **AA**



In previous landings, the Apollo crews had put on their backpacks as soon as possible and had immediately gone outside for their first moonwalk. The timing of the flight of *Apollo 15* to the Moon and the landing of the Lunar Module meant that Scott and Irwin had been awake for 11 h, and if they had kitted up for a moonwalk, gone out for the standard 8 h and come back in, they would have been working continuously for 26 h. This would have disturbed their sleep cycle, making them inefficient the next day. As a result, the plan was to work inside the Lunar Module, to sleep, and then to go outside for the first time. However, they also wanted to prepare for the EVA

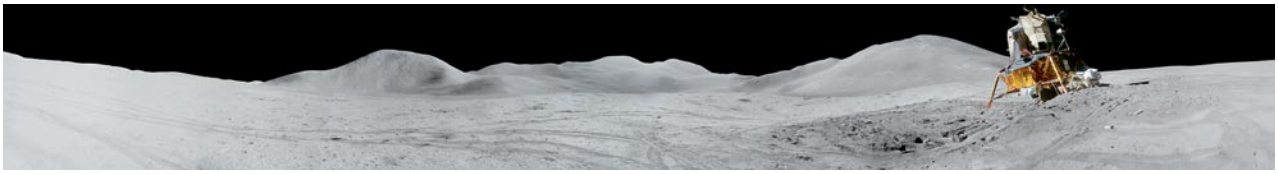


Fig. 5.8 Apollo 15 landing site. The Lunar Module Falcon leans at 15° on the slope of a hill near a small crater. One of its legs is actually in the crater. Left to right in the background is the mountain called Hadley Delta, Mount Hadley itself, and the Swann Hills. Moon buggy wheel tracks crisscross the dusty plain. (Apollo 15: NASA photograph JSC2007e045379) **AAA**

(extra vehicular activity), by carrying out a site survey, in particular to see where they could drive the Moon buggy. This was the first Apollo landing to use a motorized vehicle, formally named the lunar roving vehicle (LRV), to explore the lunar surface. They put on helmets and gloves for what was labeled a "stand-up EVA." They opened the overhead hatch of the Lunar Module and Scott stood with his head and arms outside the spacecraft, like an exultant partygoer standing up through the open sunroof of a limo or the Desert Fox scanning the horizon from a scout car. He braced himself in the opening, taking pictures, with a clear view all the way around the horizon.

Scott described the scene for the geologists back in Houston (his words transcribed and edited slightly for clarity):

> Let me start at 12 o'clock, in the west. On the far, distant horizon, apparently across the rille, I can see—just about our 1 o'clock, now—a very large mountain. All of the features are very smooth—the tops of the mountains are rounded off. There are no sharp jagged peaks and no large boulders—it's a gently rolling terrain, hummocky. The ridge line across the rille seems to be slightly lighter, with some white marks from craters—recent craters, apparently. Bennett Hill also has a lighter-colored albedo. One face of it—that facing the Sun now—is almost completely white. As I come around to my 2 o'clock, the horizon is really the Northern Complex. I can see the craters Chain, Icarus and Pluton—they are very rounded, subdued craters. It looks like the southern rim of Pluton is on the same level as our location here. The northern rim is somewhat higher. I'd say—distances are difficult—but maybe 50 m higher. I can see the scarp on the other side of the north rim of Pluton. All of it very flat, smooth, and gently rolling. The inside walls of Pluton are fairly well covered with debris; fragments up to, I'd estimate, maybe, oh, 2–3 m. Irregular distribution; no layering; just sort of scattered around. As I look on around to the north, Mount Hadley itself is in the shadow, although I can see the ridge line on the top of Mount Hadley. It too is smooth. I see no jagged peaks of any sort. And, as I look up to Hadley Delta, itself, I can see what appears to be a sweep of linear features that curve around from the western side of Hadley Delta on down to the Silver Spur down there. I see nothing that indicates any flow downhill on Hadley Delta—nothing like a landslide, only some subtle changes in topography. There's one bright, fresh crater right next to St. George on the eastern side which is almost white; and it's got an ejecta blanket about a crater diameter away.

Later Scott commented on the unearthly clarity of the view:

> When people say, "What was it like?" I can't tell them what it's like, because there's nothing on Earth that compares with it. There's no way to describe it in any terms I've ever found. … I've never read anything that can adequately describe how well you can see. It's crisp, and it's clear, and it's distinct, and it's definitive. … It's so

> clear that you really get fooled. It looks like you can reach out and touch it, because the image is so sharp. On Earth, when you're used to looking at mountains, even, they're far away and your mind sets that scale. We've been doing that for thousands of years. And, all of a sudden, people go to the Moon and the atmosphere isn't there and their scaling goes away. There's no way for your mind to use the experience, the hook, that's in the back of your head. Now you're looking at this crystal clear, crisp kind of scene that's a totally new experience—from the eyes to the brain. It's a remarkable thing, and I've never found any words that can describe it.

The *Apollo 15* astronauts spent 3 days on the lunar surface over the course of which they took the Moon buggy to Hadley Rille. Hadley Rille is a lava tube. A lava tube is a valley in the ground along which molten lava has flowed, deepening the channel, lining it with solidified lava and making it steep-sided. When the *Apollo 15* astronauts visited Hadley Rille they found its rocky sides hidden under dust and softly rounded at the rim and along the floor, but nevertheless very steep. Later, Irwin wrote of the approach to Hadley Rille in the Moon buggy:

> From the top of this ridge we could look down into and across Hadley Rille. We were amazed at how huge Hadley Rille was. We could look down about 1000 ft and across to the far wall at least a mile away.... Looking to the south along the edge of the rille that faces to the northwest, I could see several large blocks that had rolled downslope three quarters of the way to the bottom. Soon I could see the bottom itself—very smooth, about 200 m wide, and with two very large boulders right on the surface of the bottom. "It looks like we could drive down to the bottom here on this side, doesn't it?" Dave asked hopefully. And he actually wriggled over and found a smooth place that sloped from St. George's Crater into a gully that dropped to the bottom of the rille. "Let's drive down there and sample some rocks." "Dave, you are free to go ahead. I'll wait right here for you," I told him. I reasoned that we might have made it down and back, but if we had driven to the bottom, and something had happened to the machine, we'd never have been able to get out.

The two astronauts returned to Hadley Rille on the third day of their explorations for another look:

> After crossing terrain that has the aspect of rolling sand dunes, we came upon a striking view of the far side of the rille. We parked near the rim of the canyon. We both marveled at the layering in the far wall. These patterns may represent successive lava flows that formed the surface of the basin of the lunar "sea." There were shadings of gray into brown, different textures and patterns. Remember, this canyon is 1000 ft deep and about 4000 ft from rim to rim. CapCom nervously asked how close we were to the edge of the rille. Actually, we were about 50 m away.

On the second day, the two men drove into the mountains and found a rock that proved to be 5.15 billion years old (Fig. 5.9). It became known as the Genesis Rock, after a reporter misheard the word "pyrogenesis" in connection with it (a pyrogenic rock is one that has been produced by intense heat):

> The going was rough, but it suddenly smoothed out as we drove onto high ground near the Apennine Front. We could look ahead and see craters splattered right up the slope of Mount Hadley Delta. The driving improved as we moved along the front. "Boy, that's a big mountain!" Dave exclaimed when we got Hadley Delta framed squarely ahead of us. The soaring height of the mountains of the Moon,

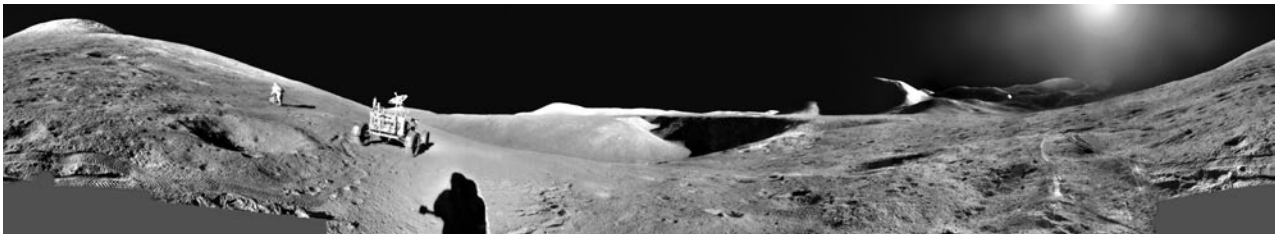


Fig. 5.9 Hadley Rille and the Genesis Rock. James Irwin took the photographs that have been merged into this panorama. He is standing on the edge of the Hadley Rille, his back to the Sun. Beyond the Moon buggy, David Scott examines a boulder on the slopes of Mount Hadley Delta. Earth shines above the hills on the right hand lunar horizon. (Apollo 15: USGS, NASA) **AA**

> from the base up, seemed to us to compare with Everest and other great mountains of Earth. Spur Crater was a real gold mine. As soon as we got there we could look over and see some of this white rock. Immediately I saw white, I saw light green and I saw brown … [The white rock] was lifted up on a pedestal. The base was a dirty old rock covered with lots of dust that sat there by itself, almost like an outstretched hand. Sitting on top of it was a white rock almost free of dust. From 4 ft away, I could see unique long crystals with parallel lines, forming striations.

LAST STEP FROM THE MOON

The last landing on the Moon, in 1972, was *Apollo 17,* the most scientifically driven of the Apollo missions, its landing site the most daring. The landing site was in the Taurus-Littrow Valley on the edge of *Mare Serenitatis* (the Sea of Serenity). *Mare Serenitatis* is a large lava-filled crater, surrounded by a wall of hills and mountains made of buried rock that had been pushed up through the Moon's surface by the impact of the asteroid that created it. Some of the hills collapsed back and left valleys that run radially through the crater wall. The southeastern crater wall of *Mare Serenitatis* is called the Taurus Mountains, and the Taurus-Littrow Valley is one of the radial valleys that run through them, near the Littrow Crater. Soon after the *Mare Serenitatis* basin was formed, lava welled up from the Moon's interior, filling the basin and being pushed up to the surface through the fractures inside the basin walls. Forced into narrow channels, some of the lava sprayed up in fountains, the cooling droplets making glassy beads that fell to the basin floor.

The variety of geology in this area was the main reason why the Taurus-Littrow Valley was selected as the landing site. To exploit this feature, NASA selected a geologist, Harrison (Jack) Schmitt (b. 1935), as the Lunar Module pilot who would land the Challenger module there, with Mission Commander Eugene ("Gene") Cernan (b. 1934), who has the distinction of having been the last man on the Moon (up to now). The precise landing site was on the valley's central axis, flanked on one side by the Northern Massif and the Sculptured Hills, and on the other by the Southern Massif, near to a group of small craters, the largest of which, at a 600 m (2000 yards) diameter, being called Camelot (Fig. 5.10).

Fig. 5.10 The Apollo 17 landing site at Taurus-Littrow Station 5. Fractured rocks litter the Camelot Crater, the depression in the foreground. Just beyond the crater, astronaut Schmitt, below the North Massif, is walking towards the buggy; the Sculptured Hills are on the right. (Apollo 17: NASA photograph JSC2004e20304) **AA**

Buzz Aldrin described the *Apollo 11* landscape as "desolation." The *Apollo 17* astronauts described their landscape as "breathtaking" and "magnificent." After his return to Earth, Schmitt described his view of the landscape from the Challenger module, just after it had landed:

> My first view out of the right-hand window, looking northwest across the valley at mountains 2000 m high, encompassed only part of a truly breath-taking vista and geologist's paradise. Only later, when I could walk a few tens of meters away from the Challenger, did the full and still unexpected impact of the awe inspiring setting hit me: a brilliant sun, brighter than any desert sun, fully illuminated valley walls outlined against a blacker than black sky, with our beautiful, blue and white marbled Earth hanging over the south-western mountains.

Indeed one of the most majestic panoramas within the view and experience of humankind is the valley of Taurus-Littrow. The roll of dark hills across the valley floor blends with bright slopes that sweep evenly upwards, tracked like snow, to the rocky tops of the massifs 2000 m above. The valley does not have the jagged youthful exuberance of the Himalayas, or of the layered canyons of Colorado, or of the glacially symmetrical fjords of the northern countries, nor even of the now so-intriguing rifts of Mars. Rather, it has a subdued and ancient majesty. And we were there and part of it.

Both men felt awed by their location: "Absolutely incredible," said Cernan as he stepped out and looked around. "This is an epic moment in my life."

Schmitt and Cernan made three expeditions out from the landing site to forage for geologic samples, traveling to collecting points in a little buggy. They left their footprints and buggy tracks in the dust—they are still there (Fig. 5.11). At their various stopping places, Cernan made a series of pictures used to produce panoramic landscapes. The *Apollo 17* Moon buggy racked up 35.74 km (22.3 miles) in its roving over the Taurus-Littrow site. This was the record for a drive on the surface of another world for only a year, surpassed by the Russian *Lunokhod 2* rover, which, according to estimates based on the tracks it left in the lunar dust, toured 39 km (24 miles) of the Moon in 1973. (Both records were beaten in July 2014 by the Opportunity rover on Mars; see Chap. 6.)

Although there are a number of geological processes that have helped shaped the Moon, the surface rocks are limited in their variety. The maria are composed mostly of dark basalts, which form from rapid cooling of

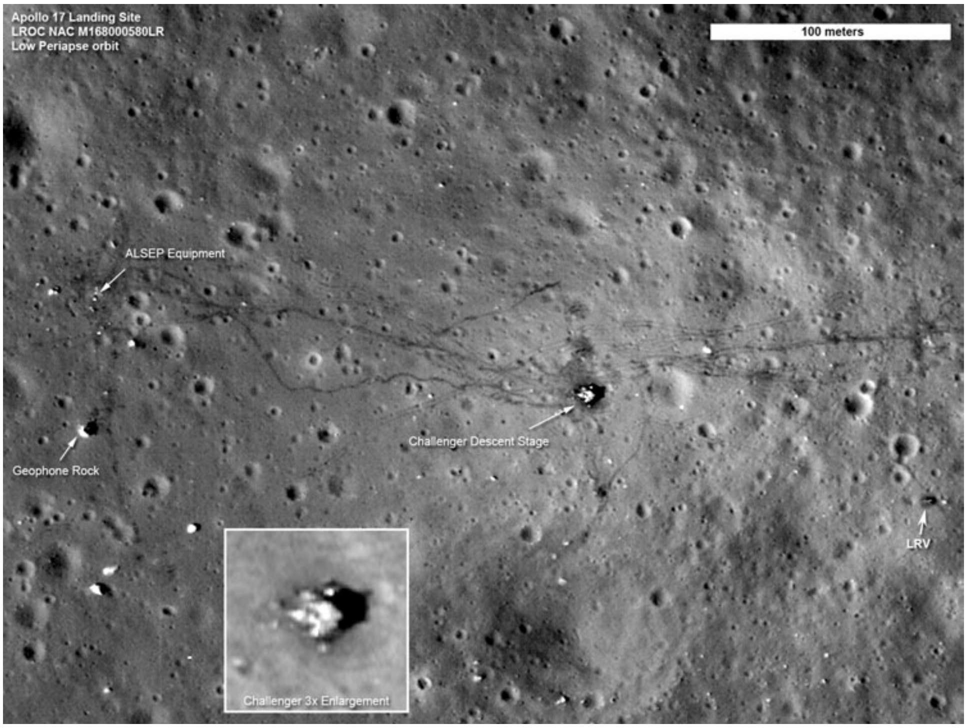


Fig. 5.11 Tracks on the Moon. Footprints and buggy tracks on the Moon at the Apollo 17 site were still visible in 2011, 40 years after the astronauts had left, even looking down from a height of 25 km (15 miles). The lower part of the Challenger module is still on the Moon, with the Moon buggy parked on the right edge of the picture (just below the center). (Lunar Reconnaissance Orbiter: NASA Goddard Space Flight Center/ASU) **AA**

molten rock generated by massive lava flows. The mountainous areas around the maria are called the highlands, and their rocks are mostly anorthosite, which is a kind of lighter colored rock that forms when lava cools more slowly than the basalts do. Breccias are fragments of different rocks compacted and welded together by meteor impacts; they are found in both the maria and the highlands. These rocks are thus all fundamentally similar in chemical composition, and their colors are limited to various shades of gray. It is rare to find a colored rock on the Moon, and the color pictures taken by the astronauts are not much different from black and white photos. A significant exception to the lack of color was an orange rock, selected by Schmitt for return to Earth. At 4400 million years old, this rock is the oldest ever brought back from the Moon.

It is thought that the reason that the Moon is so homogeneous lies in its origin. Soon after the formation of the Solar System the proto-Earth collided with another planet, jaywalking errantly across the paths of the other planets. This theoretical planet, Mars-sized, has been called Theia, after the mythological Greek Titan who was the mother of Selene, the Moon goddess. The bulk of the two proto-planets, including both their iron cores, merged to form Earth. The iron sank to the core of the newly enlarged Earth, and the more rocky material rose to the surface of the planet and settled into layers, disturbed only later by upwelling liquid volcanic material. The surface of our planet became highly variegated from place to place. Debris from rocky crusts of the two proto-planets was flung into orbit around Earth after the collision and accumulated, all mixed up, into the Moon. The Moon was too small to layer the material to the same degree as Earth had and had no iron core to generate significant volcanic activity. Its material remained homogeneous, like floor sweepings.

It is very difficult to judge distances on the Moon. *Apollo 15* astronaut Dave Scott described how all the crews had problems. The difficulty, he said, is that there is nothing familiar with which to judge scale.

> There are no trees, no cars, no houses. And, as an example, we all know what size trees are in general. There are no trees, and there's nothing in the landscape that has any familiarity. There's no hook. So, when you look out there, you see boulders but you really can't tell whether it's a large boulder at a great distance or a small boulder nearby. If it's very nearby, it's easy because you can run out along the ground and start calibrating your eyes (because of changing parallax). If you're looking close to the LM, you know what 3 or 4 in. are. But, as you start going out, you start losing your perspective because there's nothing to measure out there. And that's why everybody had these problems. On Apollo 14, they kept going and going (thinking they were getting close to the summit of Cone Crater Ridge). It's because you just can't tell. There's no atmosphere, so there's somewhat of a difference in terms of how you see distances. There's a magnification effect of sorts. It's a very interesting phenomenon that everybody gets fooled on these distances. You try to visualize based on what you know the distances are. We sort of knew how far Pluton was and I sort of guessed at what the boulders were, but that was a real guess. It becomes a real problem in those situations in which you don't have anything that you grew up with, in a sense.
>
> Manmade tracks help you a lot. Once you have some rover tracks you can start seeing things. As an example (Fig. 5.12), up on the side of Hadley Delta, looking back at the Lunar Module, boy! It looked small!—without haze, it looks closer and smaller than it really is. But knowing how big the LM really is gives you a scale of how far away it is. Five or six kilometers. And when you're on the Moon, boy, that's a long way away.

Gene Cernan of *Apollo 17* commented on the same thing. After landing, and while waiting for Mission Control to complete its assessment of the condition of the landing module, he was pinpointing the landing site by reference to landmarks. He estimated that they were 200–300 m from the rim of the crater Camelot. In fact, the near rim of Camelot was about 800 miles due west of them. Later he commented on this in a section of the transcript of his radio transmission back to Houston:

> This was typical of the problems you had judging size and distance on the lunar surface. Everything looked almost an order of magnitude (factor of ten) smaller than it really was. Certainly two to three times smaller and a lot closer than it really was. You had no telephone poles, no roads, no houses, no buildings to really judge distance by. Everything you looked at, you'd almost say, "Well, it's just out there a few 100 ft," but it was probably a mile away. A boulder that looked like it was 4 or 5 ft tall might be a mile away and be 30 ft tall. You learned very quickly that you had no good way to judge distance or size. Of course, after enough times of underestimating things you sort of recalibrated your system. You said, "I know it looks like so and so, but it's probably so and so." And even when we drove places, it didn't look like it was that far, but we kept driving and driving and driving before we got there. So, I'm not surprised that I was off by a factor of three here.

In the *Voyage of the Beagle*, Charles Darwin (1809–1882) remarked on the same problem while traveling in 1835 in the Andes:

> Travelers having observed the difficulty of judging heights and distances amidst lofty mountains, have generally attributed it to the absence of objects of compari-

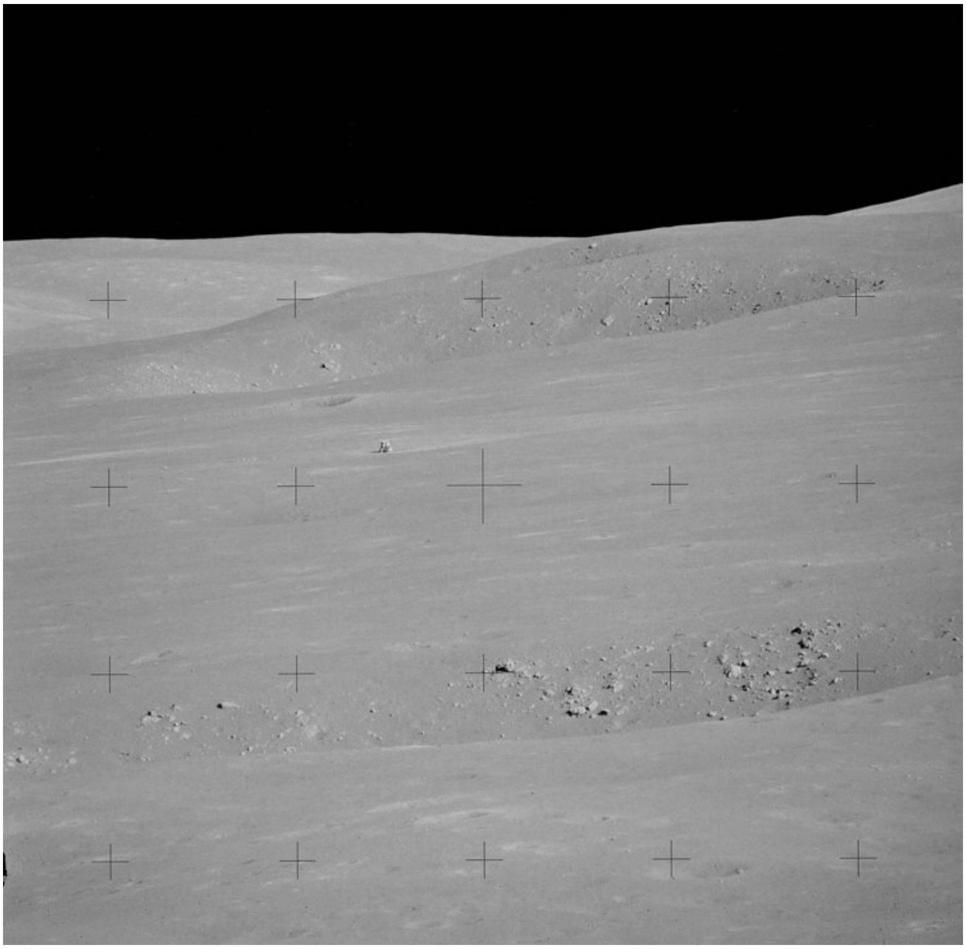


Fig. 5.12 From Apollo 15. Astronaut Dave Scott's favorite photograph of the whole mission is a telephoto shot of the landscape, looking towards the North Complex in the background across the crater Dune in the foreground, with a cluster of boulders at its rim that have been excavated from deeper layers by the impact. As he returned to Earth in the orbiting module, Scott described this view as the most impressive from the 3 days he spent on the Moon: "It shows the Lunar Module from the side of Mount Hadley Delta, and, in the background is the crater Pluton. If you look at how small the LM is, you get an appreciation for how giant that crater is." If the Lunar Module was not there the craters and hills could seem almost any size. In addition the lack of any haze in the more distant hills reduces any impression of distance. (Apollo 15: NASA photograph AS15-84-11324) **AA**

> son. It appears to me, that it is fully as much owing to the transparency of the air confounding objects at different distances, and likewise partly to the novelty of an unusual degree of fatigue arising from a little exertion—habit being thus opposed to the evidence of the senses. I am sure that this extreme clearness of the air gives a peculiar character to the landscape, all objects appearing to be brought nearly into one plane, as in a drawing or panorama.

As Darwin says, it is the clarity of South American mountain air that compresses the distance scale. On the Moon there is no atmosphere at all. No dust intervenes between the observer and the distant horizon, no water droplets, no air molecules. As a result there is nothing along the line of sight to deflect sunlight and cover what lies behind with an overlaid dazzle. On Earth, this helps to indicate distance (Fig. 5.13). In the

Fig. 5.13 Chalets at Rigi (1861), by the Swiss painter Alexandre Calame (1810–1864). Calame specialized in paintings of Swiss Alpine scenery. Not only do familiar structures in terrestrial landscapes give visual clues as to their distance, the progressive blue haze produced by aerosols in our atmosphere shows the depth of the vertical layers in the landscape, one by one. (National Gallery, London: Wikimedia Commons, commons.wikimedia.org/wiki/File:Chalets_at_Rigi.jpg)

desert of the American Southwest, as in the Andes, where the air is clear, where you don't have any salt and moisture, distances are hard to judge. It is different in the eastern region of America or in Europe, where the air tends to be hazier. Haze helps to judge the distance. When artists are painting landscapes they use the lightness of haze to give depth to the picture (see Chap. 10).

As Neil Armstrong pointed out, Moon rocks are a jumble of rocks of all shapes and sizes. This adds to the difficulty of judging distance. Not only are there no familiar objects to give a sense of scale, there is nothing to distinguish one size of rock from another. The kind of distribution in which one range is the same as another except for a multiplicative factor is called "self-similar." In practical terms this means that if you look at a sample of the rocks and then look at a subsample through a magnifying glass or through the wrong end of a telescope, it is difficult to distinguish which view is which. The view has no natural scale. Cover up the astronaut standing by Tracey's Rock in the panorama (Fig. 5.14) at *Apollo 17* Station 6, so as to lose the scale, and the gigantic boulder shrinks to a more normal size. The picture could almost be a beach with sandcastles in the background.

Fig. 5.14 Apollo 17 Station 6. To the left the Sculptured Hills, to the right the South Massif, with the East Massif more distant between them. Foreground is Boulder 2, dwarfing geologist-astronaut Schmitt. It rolled to its present position down the slope at the right. The flat, sloping face of the boulder pointing directly at the camera is covered with fine dust, which Cernan sampled. As he left the station Cernan thought about writing his daughter's name with his finger in the dust, as lunar graffiti, but, under the pressure of the mission schedule, he could not go back and had lost the opportunity. This anecdote, retold back in Houston, gave the rock its name: Tracey's Rock. (Apollo 17: NASA photograph JSC2007e045387) **AAA**

SHADOW PLAY

The atmosphere of Earth obscures distant mountains and provides a sense of distance that is absent on the Moon. The atmosphere provides also a source of both delight and light. The sky changes in a kaleidoscope of color and illuminates the landscape, additionally to the much brighter light of the Sun, in a way that cannot exist on the Moon and which contributes to the otherworldliness of landscapes.

On Earth, sunlight dominates over the light of the sky. But if direct sunlight is cut off, the effect of the illumination of scenery by the sky becomes apparent. Startlingly red colors suffuse the landscape on Earth in the period immediately after sunset, as the red and orange sky shines down on the land.

These effects are the direct result of the existence of the terrestrial atmosphere. The molecules of air scatter sunlight, but clear air scatters the blue colors of the solar spectrum more than the red. When the Sun is illuminating those lower reaches of the atmosphere all its blue light is scattered, and direct sunlight is red, giving the red and orange colors of clouds, dust particles and water droplets that produce spectacular sunsets on Earth.

The Moon has no atmosphere, so these specular effects do not exist in the lunar landscape, and the sky is black. But there is another subtle effect in the lunar landscape that shows the Moon has no atmosphere. On Earth, if, at times of strong direct sunlight, you stand in a shadow, you cannot view the Sun, but you can look up to the blue sky. Of course, the Sun does not shine directly into a shadow. However, the blue sky does (Fig. 5.15). This means that shadows in terrestrial landscapes are not black, as one might unobservantly believe, but blue, as artists know. The pictures of Claude Monet (1840–1926) show this well (Figs. 5.16, 5.17).

On the Moon there is little light from the sky, because there is no air to scatter sunlight. There is direct light from the Sun, and much weaker light from Earth and the stars. As a result, lunar shadows are deep black (Fig. 5.18).

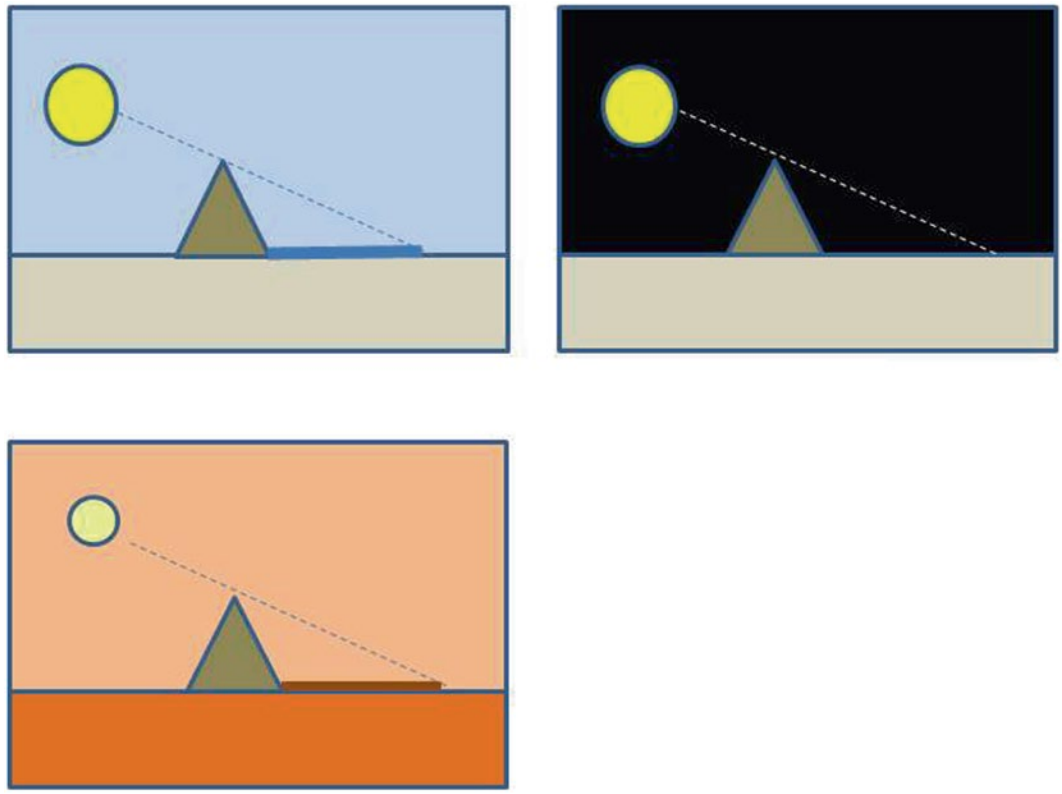


Fig. 5.15 Shadows on Earth, the Moon and Mars. No point within the shadow cast by the Sun on the ground is illuminated by sunlight but is illuminated by the light of the sky. On Earth the sky is blue (or, at sunset, red), on the Moon it is black, on Mars orange, and the ground in the shadow takes on the respective hue

On Mars the shadows are illuminated by the yellow or orange light of the sky (Fig. 5.19). The Opportunity, Spirit and Curiosity rovers carry a special device to quantify this. A color reference chart is mounted on each rover's casing, in view of its camera, arranged with the color palette in segments around a central post or gnomon like a sundial (see Figs. 2 in FM or 10.2). The sundial casts a shadow and alters the color of the sectors across which it falls. This data is used for calibration purposes to make realistic, or otherwise control the color balance of, Martian pictures.

'GARDENING' ON THE MOON

Because there is no atmosphere on the Moon, there is no weather (in the ordinary sense of the word) to consolidate dust into soil, or to wear down rocks by the action of rain or the abrasion of wind. There is little or no earthquake or other tectonic action to grind one rock against another. However, any dust that does form lies there forever. The dust on the Moon has thus accumulated over billions of years. Where is it from?

The surface of the Moon is unprotected against small falling meteorites, and the large craters are, in the majority, the result of impacts on the surface by a rain of meteorites that took place about 500 million years after

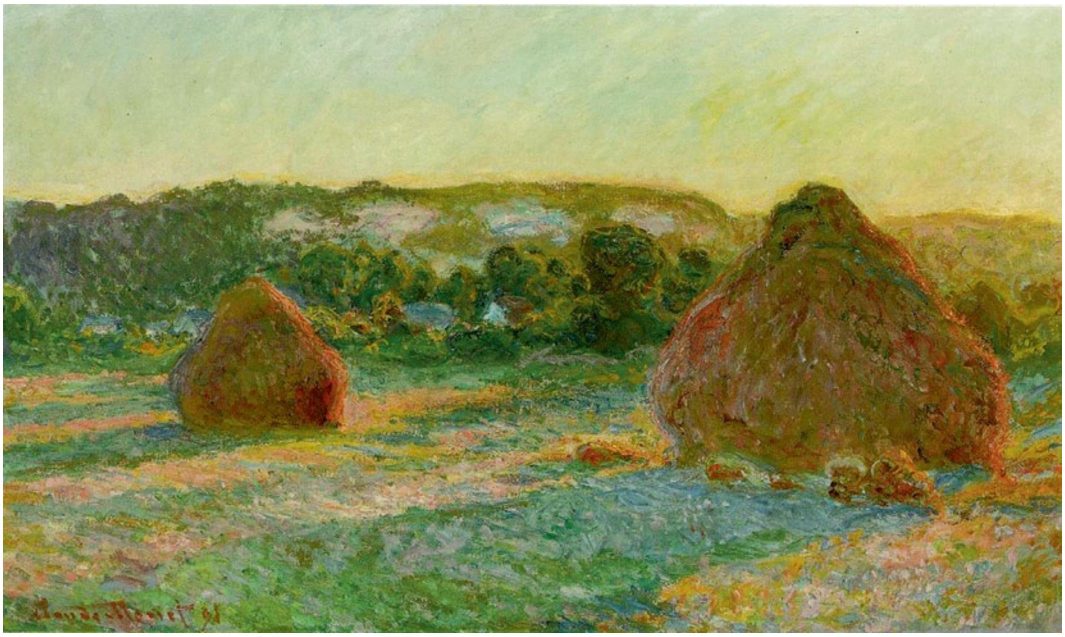


Fig. 5.16 The painting Wheatstacks (End of Summer). Between 1888 and 1891 the French impressionist painter Claude Monet (1840–1926) made a long series of more than 25 paintings of haystacks in fields near his home in Giverny in France, as a series of studies of the colors of the scene under the changing seasons and atmospheric conditions. During the day, the strong light of the Sun and the weaker light of the sky both illuminate the ground, but only the blue sky casts blue light into the shadow of the haystack. (Art Institute of Chicago: Wikimedia Commons, commons.wikimedia.org/wiki/File:Wheatstacks_(End_of_Summer),_1890–91_(190_Kb);_Oil_on_canvas,_60_x_100_cm_(23_5–8_x_39_3–8_in),_The_Art_Institute_of_Chicago.jpg)

the Moon was formed—the event known today as the Late Heavy Bombardment. It is thought that the meteors of that time were a mixture of asteroids themselves and fragments from asteroid collisions that filled the Solar System with rocks. Most of the rocks have by now fallen onto solid bodies in the Solar System, or found their way into two parking zones (the Asteroid Belt and the Kuiper Belt), where they are generally stable. But some still break free from time to time and rove across the orbit of Earth, and some rocks get formed by further, more recent collisions of lesser magnitude between smaller asteroids. The Moon, Earth and other worlds still receive impacts of rocks that have originated from events early on in the history of the Solar System and similar later collisions. The fall of a meteor on the Moon's surface is unhindered by any atmosphere. When a very small meteor hits Earth it burns up in the atmosphere, but on the Moon it digs a small hole

Fig. 5.17 The painting Grainstack (Sunset) (1891). When the Sun has moved just below the horizon it no longer illuminates the ground, but the orange evening sky does. There is a weaker shadow on the ground from the brighter sky around where the Sun has set. The sky at the zenith is bluer. The ground in the shadow is illuminated by sky that is in part blue and in part orange. (Museum of Fine Arts, Boston: Wikimedia Commons, commons.wikimedia.org/wiki/File:Claude_Monet_-_Graystaks_I.JPG)

Fig. 5.18 Black shadows on the Moon. Astronaut Harrison H. Schmitt is standing next to a huge split boulder during the Apollo 17 mission. This picture was taken in 1972 by astronaut Eugene A. Cernan. (Apollo 17: NASA AS17-140-21496) **AAA**

Fig. 5.19 Cape York near Endeavour Crater. The orange-brown sky of Mars shows above the "Kirkland Lake" rock field. This sky illuminates the shadows in the rock with an ochre color. (Opportunity: NASA/JPL/Cornell: P2541) **AAA**

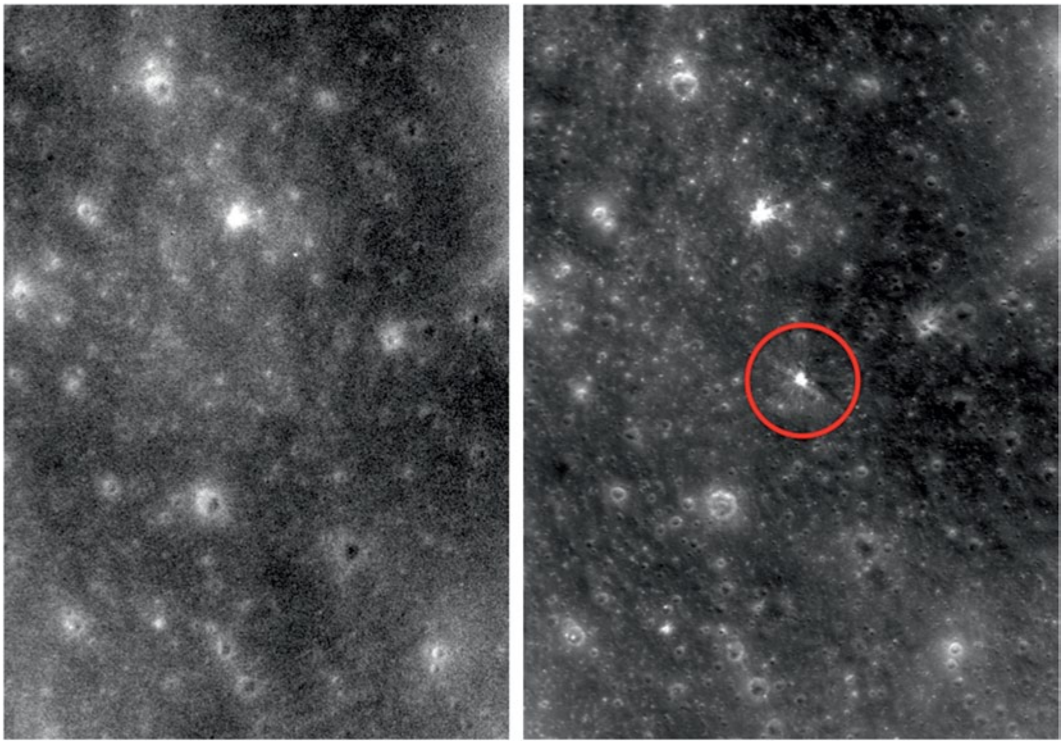


Fig. 5.20 New crater on the Moon. Since this crater, imaged in September 2009 by NASA's Lunar Reconnaissance Orbiter, is not visible in images from the *Apollo 15* mission (August 1971), it had to have formed sometime in the last 40 years. The new crater is only 10 m (about 10 yards) across, and was made by a meteor (or asteroid—pretty much the same thing—or comet, perhaps) about 0.5 m (20 in) in diameter, and perhaps half a metric ton in mass. It is surrounded by fresh, bright ejecta from below the Moon's surface. Meteors this size fragment and entirely burn up when they strike Earth's atmosphere. Only 10 kg (22 lbs) of an 80-metric ton meteorite that struck Earth's atmosphere in 2008 was recovered in the Sudan after an extensive search. All meteorites can strike the surface of the airless Moon with full force. (Lunar Reconnaissance Orbiter image M108971316L: NASA/GSFC/Arizona State University; and Apollo 15: NASA photograph AS15-9527) **AA**

or chips a bit of rock off the rock it hits. When a larger meteor hits Earth, it may not all burn up, but friction with the atmosphere slows it down, and it lands without much of an impact. It may make a shallow dent in soft ground. But on the Moon such a meteor will land at full speed and make a considerable crater. On the Moon, the impact splatters pieces of the meteorite and the lunar surface over large distances, including boulders, rocks and dust.

A further source of dust is weathering of the rocks by solar heating. The day/night change of temperature on the Moon is 100 °C (200 °F), and surface rocks are repeatedly heated and cooled. This cracks the surface layers of the rocks into flakes and dust.

Weathering is still happening. Meteors still strike the lunar surface (Fig. 5.20). The processes slowly churn over the lunar dust, a process known as "gardening." It is not known precisely for what reason, but boulders still tumble down mountain slopes. It may be that they are dislodged by a direct hit from a small meteorite, striking with unhindered speed, or they may move when some of their mass wastes away in the thermal cracking process, and pick up momentum due, simply, to gravity. They certainly

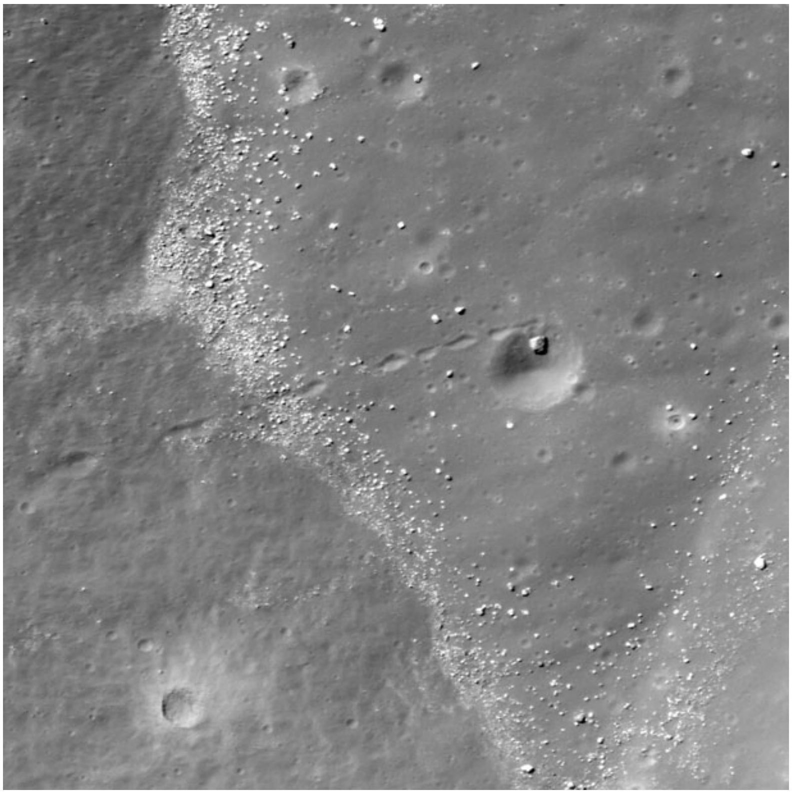


Fig. 5.21 Hole in one! A 10-m diameter boulder on the Moon bounced as it rolled downhill from left to right, its trajectory intersecting a 60-m (65-yards) diameter crater, where it dropped in, plowing into loose material on the slope of the crater wall and coming to a stop, like a golf ball dropping into its cup. Numerous other boulders litter the plain nearby. (Lunar Reconnaissance Orbiter: NASA/GSFC/Arizona State University M122597190L) **AA**

leave tracks in the dust (Fig. 5.21). Tracey's Rock at *Apollo 17* Station 6 obviously does not belong where it lies (Fig. 5.14), and in fact its track in the dust can be traced back one-third of the way up the massif from which it fell and rolled downhill to its present location. Schmitt's geological interest in the boulder was that it represents a sample from a place high on the hill that was otherwise inaccessible. The Lunar Reconnaissance Orbiter is mapping boulders that have rolled downhill and might be of interest to geologists who will explore the Moon in the future.

It has to be said that some of the descriptions of the landscape from the Apollo astronauts are metaphorically one-dimensional. This is understandable. The astronauts are communicating the geology and concentrating on what to do next on their highly pressured mission. The wife of one astronaut said that the Apollo astronauts were typically taciturn: "Most of them are fighter pilots," she said. "They communicate in single phrases. Ask them what it was like on the Moon and they might say something like 'Very interesting.'"

The very brave men who have so far stood on the Moon were not only warriors, they were space pioneers, trained not as poets but as engineers, with the very job of starting to make living in the planetary landscape mundane. Buzz Aldrin commented, in words that are more sophisticated than the self-deprecating thought that they express, "We weren't trained to smell the roses." He went on: "Neil and I were both military guys, pilots who were accustomed to keeping our feelings reined in. We couldn't dally; we had a job to do, a mission to accomplish."

In distancing themselves from involvement in the lunar landscape, the astronauts were the reverse of romantic, but they were certainly conscious of the pivotal moments in space exploration in which they participated. Neil Armstrong's first words from the Moon are often quoted; less well known are the last words from the Moon, the wordy sentiments enunciated by Gene Cernan: "As I take Man's last step from the surface, I'd just

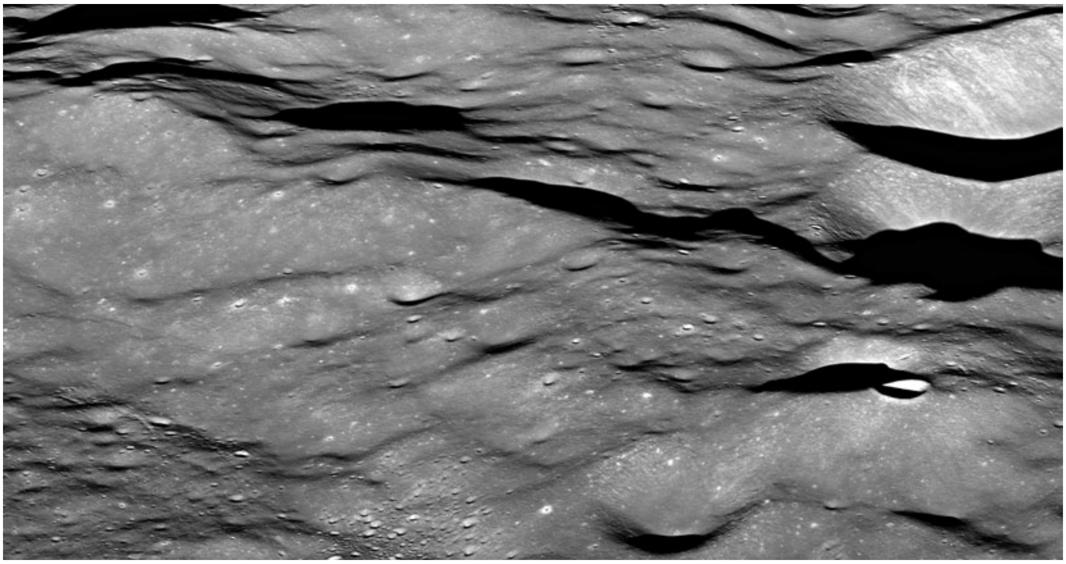


Fig. 5.22 The hills around the crater Vertregt J, 17 km (11 miles) in diameter on the right hand edge of the picture, are typical of the lunar highlands. Their contours are chaotic, they are rounded in profile, and they are pocked with numerous small craters left by recent meteor impacts. This crater is on the far side of the Moon, near the large Aitken Crater at the Moon's south pole, never visible from Earth. (Lunar Reconnaissance Orbiter: NASA/GSFC/Arizona State University M149411489) **AA**

like to say what I believe history will record: that America's challenge of today has forged Man's destiny of tomorrow. And as we leave the Moon at Taurus-Littrow, we leave as we came and, God willing, we shall return, with peace and hope for all mankind."

No one has yet been to the other worlds of the Solar System. Their landscapes are still literally otherworldly, as we will see in the rest of this book.

LUNAR HIGHLANDS AND MARIA

Most mountain scenery on Earth was created over periods of millions of years by the slow crunch of one tectonic plate against another, the mountain ranges being pushed up as wrinkles like a carpet rumpling as it slides slowly into another on a polished wooden floor. Mountain scenery on the Moon (Fig. 5.22) was created not in millions of years but in minutes by the collision of a meteor or asteroid, forming a crater, shoving surface material rapidly outwards to make walls in a single event rather than a long process. In the early history of the Moon, the impacts came quickly one after another, walls overlapping, newer walls pushing over previously existing walls, creating a chaotic jumble of low mountains that now form the lunar highlands.

Structured mountain ranges also exist on the Moon. Completely circular mountain ranges, or circular arcs, persist around the most recent meteor impacts—we call them craters. Small craters have low walls, but large craters have higher walls—all that material from inside the crater has

Fig. 5.23 The Sinus Iridum ("Bay of Rainbows") is a lava plain, a circular crater basin some 250 km (150 miles) in diameter, that overlaps the Mare Imbrium (foreground). A little over half of its circular crater wall remains complete, and is the Montes Jura mountain range, extending 350 km (220 miles) from the Promontorium Heraclides (left foreground) to the Promontorium Laplace (on the right horizon). The heights of the Jura mountains increase from 1000 to 3000 m above the plain (3000–10,000 ft) from Heraclides to Laplace. This landscape, a single TV frame from high definition TV, was made from a height of about 100 km (60 miles). (Selene: © JAXA/NHK) **AA**

to go somewhere! The largest craters are the lunar maria. These craters are so large that they are termed basins, not craters. The dividing line is put at 250–300 km (150–200 miles) in diameter. The circular arcs of the crater walls around maria curve gently. They look like mountain ranges on Earth and are given their names—Apennines, Alps, Juras, Caucasus (Fig. 5.23). These mountains are high, produced by large asteroids and their height seems especially high by contrast to the flat lava plains that fill in the large craters that result.

EARTHRISE OVER THE LUNAR LANDSCAPE

Apollo 8 was the first manned spacecraft to leave low Earth orbit. It was led by the Mission Commander Frank Borman (b. 1928), with crew James Lovell (b. 1928) and William Anders (b. 1933). They took off from Earth on December 21, 1968, and a few hours later left their relatively safe orbit around Earth to venture into interplanetary space, towards the Moon. Anders says that when the trajectory was explained to him, he gave some thought to the odds. "I figured we had a one-third chance of success, a one-third chance of a survivable accident and a one-third chance of not coming back." Lovell didn't let himself address the problem: "If you worried about whether or not you were coming home, you wouldn't go in the first place."

As they embarked on their epic journey, the crew of *Apollo 8* set up the start of a series of "firsts" in space exploration. They were the first people to go far enough away to be able to look back to see Earth as a planet in its entirety. But their attention was primarily in front of their spacecraft. Their trajectory took them towards the Moon, and 61 h after launch, they entered lunar orbit. A few hours after that, they passed behind the Moon, out of communication with Earth, on their own in space. As they continued their orbit, under the control of the force of gravity of another world, they became the first people to see the Moon's far side.

They orbited the Moon several times, gazing down on its surface. They were the first people to see, with their own eyes, a planetary landscape, in the definition of "an expanse of scenery that can be seen in a single view," the landscape of another world. From a height of 100 km (300,000 ft), they skimmed in their spacecraft over the surface of the Moon, seeing its light-colored mountains, its darker dusty plains (which Galileo and other astronomers in history had interpreted as seas or oceans) and its craters. The landscape lay before them in perspective, stretching out towards a horizon, as if they were terrestrial explorers standing on a tall mountain peak, looking over lands newly discovered. What they saw was natural cosmic scenery, essentially in the same composition as a landscape painting, taking a high panoramic point of view across the land.

There were marked differences between the view that the Apollo astronauts had of the landscape of the Moon and typical terrestrial scenery. The Moon is much smaller than Earth and the horizon was curved by its spherical figure, not straight. The sky above the ground was the black of space, with nothing—no air, and therefore nothing suspended in it like clouds or dust—to obscure the view and reflect haze. The ground itself was bare, with nothing growing. The rocks were shades of gray, no strong colors. No water sparkled under the incessant sunlight. The entire world was strangely homogeneous, unnaturally still.

Although the rocks themselves were not brightly colored, as on Earth the variety of their shapes did show evidence of their origin and the effects of erosion over time. Lovell described to Mission Control, back on Earth in Houston, TX, the landscape that he saw out of the window of the Lunar Module: "The Moon is essentially gray, no color; it looks like plaster of Paris or sort of a grayish beach sand. We can see quite a bit of detail. The Sea of Fertility doesn't stand out as well here as it does back on Earth. There's not as much contrast between that and the surrounding craters."

Lovell paused, searching for the words to describe the strangeness of what he was seeing: "The craters are all rounded off. There's quite a few of them, some of them are newer. Many of them look like—especially the round ones—look like they were hit by meteorites or projectiles of some sort."

The passage from lunar night to lunar day is a spectacular event that makes apparent the subtle colors in the Moon's scenery. Here it is described by Jim Irwin as the *Apollo 15* spacecraft approached its target:

> We cannot see any light on the Moon's surface. You look out, and there is a dark object looming up, a big mass in the darkness of night. You have no concept at all of its features because of this blackness….[W]e see a very thin crescent Moon in front of us. Despite the delicacy of the shape, we get the impression that the Moon is very big. We are silent as we coast to the Moon … All of a sudden we come from darkness into daylight. You are at the Moon! It hits you just like that. It is the most beautiful sight to look out and see this tremendously large planet. You'd never guess that the Moon would be that big, even though you've seen all the pictures. But here you are seeing it with your own eyes for the first time. It is staggering. You can barely see the curvature of it. You are coming round and moving not too fast, at medium speed, and you cross the terminator, which is that line between darkness and night. The surface of the Moon is a dark gray, gunmetal gray. It looks like molten lead that has been shot with BBs. It doesn't look real, it looks like clay. First it goes from black to dark gray. Since there is virtually no atmosphere on the Moon to diffuse the light, there is a very distinct line between darkness and light. As the reflected sunlight get brighter the gray turns to brown, light tan and almost white, directly underneath the Sun. So you have this constantly changing beauty and color as you go round the Moon.

Although the same view must have been available to them three times before, because they were gazing directly down at the lunar surface, it was not until the fourth orbit of the *Apollo 8* astronauts crossing the face of the Moon on Christmas Eve 1968 that they noticed Earth rise over the lunar horizon in front of them. Technically, Earth does not rise as seen from the Moon, because the Moon is locked into position and, from a given position on the Moon, Earth is always in the same place in the lunar sky. For example, as seen from the position that is central on the Moon's face, Earth is always overhead. But as seen from a spacecraft cruising around the Moon, skimming the surface from behind the Moon to the front, towards Earth, Earth rises.

The sound quality of the available recording of the conversations in the module is not very good, and there have been disputes as to who said what, or who actually took the first picture of the same or subsequent similar scenes. It seems to have been Borman who was first to notice Earthrise: "Oh my God! Look at that picture over there! Here's Earth coming up. Wow, is that pretty!" Borman reached for his camera. Another crew member, maybe Anders, chuckled as he joked about their strictly defined to-do list: "Hey, don't take that, it's not scheduled." Borman took a black and white picture and asked whether Anders' camera was loaded with color film. Anders loaded the camera with a color film that Borman handed him, and snapped several Earthrise pictures, not sure of the correct exposure. If this account is accurate, it was Anders who captured (Fig. 5.24) the first iconic manmade picture of a planetary landscape. Borman also took a version of the image, describing it in his autobiography as "One of the most famous pictures in photographic history—taken after I grabbed the camera away from Bill Anders."

Anders' picture was released by NASA under the title *Earthrise*. It was reproduced as a *Time* magazine cover with the title *Dawn*, and as a U. S. postage stamp, and it was selected by *Life* magazine as one of its

Fig. 5.24 Earthrise over the Moon. The first picture made in 1968 by human beings of a comic landscape. (Apollo 8: NASA William Anders photograph 68-HC-870) **AAA**

"100 Photographs that Changed the World." Later Lovell explained the contrast between the lunar landscape and Earth: "Up there, it's a black-and-white world. There's no color. In the whole universe, wherever we looked, the only bit of color was back on Earth … .It was the most beautiful thing there was to see in all the heavens. People down here don't realize what they have."

Anders has also commented on the color contrast between the Moon and Earth: "As we came around the back side of the Moon, where I had been taking pictures of craters near our orbital track, I looked up and saw the startlingly beautiful sight of our home planet "rising" up above the stark and battered horizon. It was the only color against the deep blackness of space. In short it was beautiful and clearly delicate." The blue color is a distinctive feature of our atmosphere (see Chap. 9) and, when 4 years later, *Apollo 17* brought back a photograph of the full Earth that NASA released under the name Blue Marble, the phrase "blue planet" became both a literal description of Earth and by extension a metaphor for its ability to support life, including us.

At the time that Anders took the original picture, the lunar orbiting module was passing over the crater called Pasteur, but the lunar landscape at right angles to the downward direction, in the foreground of the photograph and on the Moon's horizon, is too foreshortened to be easily identified. Lovell's general description of the lunar surface fits. Earth forms the distant background with the lunar horizon in the middle background and the lunar surface is stretching out in perspective in the foreground.

Apollo 8 circumnavigated the Moon and, looking out of the window of their cramped spacecraft, its astronauts saw Earthrise. The astronauts who actually landed on the Moon saw Earth even more obviously positioned in the context of the lunar landscape, with a complete hemisphere of black sky above their horizon. This emphasized how small Earth was. Russell ("Rusty") Shweickart (b. 1935), the Lunar Module pilot on the *Apollo 9* mission, never at first hand experienced what he so eloquently described after talking with his fellow astronauts, in a lecture called "No Frames, No Boundaries":

> And a little later on, your friend goes out to the Moon. And now he looks back and he sees Earth not as something big, where he can see the beautiful details, but now he sees Earth as a small thing out there. And the contrast between that bright blue and white Christmas tree ornament and the black sky, that infinite universe, really comes through, and the size of it, the significance of it. It is so small and so fragile and such a precious little spot in the universe that you can block it out with your thumb. And you realize that on that small spot, that little blue and white thing, is

> everything that means anything to you—all love, tears, joy, games, all of it on that little spot out there that you can cover with your thumb. And you realize from that perspective that you've changed, that there's something new there, that the relationship is no longer what it was.

We can get a taste of this powerful, emotional reaction from the "Earthrise" photograph. We know that we are in this picture, on the surface of Earth, too small to see, isolated in our tiny planet in a vast universe. Our planet is manifestly limited in its capacity, and fragile, and we are all on it together. American poet Archibald MacLeish (1892–1982) wrote about the view in *The NY Times*: "To see Earth as it truly is, small and blue and beautiful in that eternal silence where it floats, is to see ourselves as riders on Earth together, brothers on that bright loveliness in the eternal cold—brothers who know now they are truly brothers." In his book, *Earthrise: How Man First Saw Earth*, historian Robert Poole (b. 1957) says that "It is possible to see that *Earthrise* marked the tipping point, the moment when the sense of the space age flipped from what it meant for space to what it means for Earth." The adventure photographer Galen Rowell (1940–2002) called *Earthrise* "the most influential environmental photograph ever taken." The picture composition has an enduring quality and has been repeated, when possible, by all subsequent lunar exploration spacecraft.

Fig. 6.1 Mars, as seen by the Hubble Space Telescope at its closest approach to earth in 2005. A dust storm right of center obscured the land underneath. Clouds fringe the polar caps. (HST: NASA, ESA, and the Hubble Heritage Team, STScI/AURA.) **AAA**

Chapter 6
The Rocky Landscapes of Mars

Galileo in 1610 was the first person to view Mars through a telescope, in the same frenzy of astronomical discovery in which he discerned the landscape of the Moon (Chap. 3). But Mars, though larger than the Moon, was much further away, and all that Galileo could see was that it had a disc. He could discern no features. During Galileo's lifetime, however, in 1636, the Italian lawyer Francesco Fontana (1580-c.1656) used a self-made telescope to glimpse an indistinct spot, which changed its appearance in such a way that he inferred that it was being carried around by the planet's rotation. In 1659, telescopes had improved to the extent that permanent details on the Red Planet could be identified. The Dutch astronomer Christiaan Huygens (1629–1695) was able to see in 1659 a shadowy gray-green triangular feature now known now as *Syrtis Major.* It was repeatedly recognizable, brought into sight each time the planet rotated, and Huygens was able to estimate the length of the Martian "day" as 24 h, like Earth, an estimate only 37 min short of the modern value. This permanent feature was the first indication that there would be a landscape on Mars.

The Italian-born French astronomer Giovanni Domenico Cassini (1625–1712) made further progress. In 1666 he saw a white cap over the south pole of Mars. By the beginning of the eighteenth century, in 1704, the French-Italian astronomer Jacques Philippe Maraldi (1665–1729) had been able to see that the size of the polar caps varied throughout the Martian seasons, as if they were ice caps like Earth's. The dark features were interpreted as "seas," like the gray lunar maria.

The seasonal changes in the polar caps were confirmed by William Herschel (1738–1822) in a careful paper that he presented to the Royal Society of London in 1784. Herschel visualized the polar Martian landscape as an ice field. "The analogy between Mars and Earth is," Herschel wrote, "perhaps, by far the greatest in the whole Solar System.… If then, we find that the globe we inhabit has its polar regions frozen and covered with mountains of ice and snow, that only partially melt when alternately exposed to the Sun, I may well be permitted to surmise the same causes may probably have the same effect on the globe of Mars; that the bright spots are owing to the vivid reflection of light from the polar regions; and the reduction of those spots is to be ascribed to their being exposed to the Sun."

Herschel noticed a thin white and blue line on the edge of the disc of Mars that he interpreted as an atmosphere, and observed what he took to be "clouds and vapors," which from time to time obscured the Martian surface or stood out as temporary white areas over the red. He articulated the growing realization that Mars had a "considerable but moderate atmosphere, so that its inhabitants probably enjoy a situation in many respects similar to ours."

The maps drawn of Mars by different astronomers at different times differed in their clarity, as if sometimes obscured by clouds or fogs. French astronomer and science popularizer Camille Flammarion (1842–1925)

P. Murdin, *Planetary Vistas,* DOI 10.1007/978-3-319-15242-4_6

wrote that "the details of a globe seen from the distance of Mars through two atmospheres are always vague and excessively delicate. There can be no single drawing which gives a rigorous and exact representation of Mars as it would appear to an observer close to the surface." The red areas on the surface of Mars were identified as continents, while the dark areas were seen to have various colors reminiscent of expanses of water: blue, green and blue-green. The dark areas were, in a word, lakes and seas, and were named accordingly by a succession of Mars observers: "Delambre Sea," "Dawes Ocean," "Schiaparelli Lake," and so on. Some mottled areas were viewed as swamps. "These aqueous stretches," wrote Flammarion, "appear to be in a different physical state from our own seas: less dense (?), less liquid (?), or covered with viscous fogs (?)." Attention focused on the hydrology of Mars, its landscapes interpreted accordingly. As Mars was mapped in finer and finer detail, the "enigmatical variations" were given definite form as continents, seas, gulfs and bays.

The finest telescopic views of the Red Planet (Fig. 6.1) have been made by the Hubble Space Telescope, orbiting above one of the atmospheres that lie between the surface of Earth and the surface of Mars.

The idea that Mars had a landscape similar to our own took hold. Taking advantage of times when Mars was closer to Earth than usual so that its disc was larger and its features clearer, the Vatican Observatory astronomer Angelo Secchi (1818–1878) drew detailed representations of Mars in 1869. His sketches included two wide, dark, linear features on the surface that he referred to as *canali*, which is Italian for "channels," but which, literally translated into in English, can suggest artificial construction.

The word "canal" when used about Mars reverberated in 1877 when the Italian astronomer Giovanni Schiaparelli (1835–1910) produced a detailed map of the planet, which showed numerous *canali*, many more than two thin, linear features that crisscrossed the "continents." He gave them names of famous rivers on Earth, such as the Nile, the river Indus and the Oxus. In mapping Mars, the "clear analogy [of Mars] with Earth," Schiaparelli wrote, as well as "brevity and clarity, compel us to make use of words such as island, isthmus, strait, channel, peninsula, cape, etc." Although he wrote with proper skepticism that the *canali* "may be designated as canals, although we do not know what they are," Schiaparelli's *canali* were fine, straight and sometimes doubled. The existence of such a complex geometrical network implied that the canals were the result of work by intelligence. Flammarion imagined the circumstances and the landscape in which the network would have been constructed: "…while we quietly observe these continents and seas slowly carried across our vision by the planet's axial rotation and wonder on which of these shores life would be most pleasant to live, there might be at the same time thunderstorms, tempests, social upheavals and all kinds of struggle for life… Yet we may hope that, because the world of Mars is older than ours, mankind there will be more advanced and wiser."

The “channels” resembled manmade canals, which could be used to redistribute water across the planet.

The *canali*, though relatively thin, were rather wider than the water in a terrestrial canal would be. This was explained by the idea that Martian canals carried water that irrigated the areas that flanked the canals, as happens in Egypt alongside the Nile. The Nile itself is straight in some sectors, and the irrigated area either side is thin, so it formed a model for Martian canals.

This vision of Mars set the trend for the investigations that followed, particularly those carried out by the U. S. businessman Percival Lowell, who founded the Lowell Observatory near Flagstaff, AZ, in time to investigate Mars in 1894, when the planet was particularly close to Earth, and in the subsequent decades. He published highly successful books about life on Mars, including maps with over-detailed networks of canals. This encouraged the idea that Mars was inhabited by advanced beings. Lowell developed the notion of Mars as an arid, dying world. Its inhabitants could be trying desperately to stave off its desertification. The idea that they were looking for an exit to colonize the landscapes of a more fertile planet, such as Earth, inspired H. G. Wells’ novel *War of the Worlds* (1898) and numerous imitators.

In 1894, Lowell and his assistants drew over 900 pictures of the markings on Mars, with a complex network of canals that intersected at spots, which were at first called “lakes.” But when the overall picture of the Martian landscape was radically altered by Lowell, their name was altered to “oases.” An important series of thirteen measurements was made by Lowell’s colleague William Pickering (1858–1938), who attempted and failed to determine the polarization of light from the surface of the “seas.” When unpolarized light—sunlight, for example, with an equal mixture of vertical and horizontal polarizations—reflects off a water surface, like a lake, the horizontal polarization is reflected more than the vertical polarization, so the reflected light is not polarized. Pickering could not detect this polarization and concluded that the dark areas were not standing water.

Lowell transformed the mental image of the Martian landscape from one in which there were areas of natural standing water to one in which Mars was dry, except for the water locked up as ice at the polar caps and distributed across the otherwise arid surface of the planet by an irrigation system of artificial canals. Lowell interpreted the dark markings as areas of semi-desert vegetation. Lowell saw changes in color of the dark areas that correlated with the change in size of the polar caps, as if the vegetation freshened from melt-water in the Martian spring carried to the intermediate and equatorial regions from the poles by canals. He imagined the Martian landscape:

> … [I]t follows that Mars is very badly off for water, and that the planet is dependent on the melting of its polar snows for practically its whole supply… as a planet grows old, its oceans, in all probability, dry up, the water retreating through cracks and caverns into its interior. Water thus disappears from its surface, to say nothing of what is imprisoned by chemical combination. Signs of having thus parted with its

> oceans we see in the case of the Moon, whose so-called seas were probably seas in their day but have now become old sea-bottoms. On Mars the same process is going on, but would seem not yet to have progressed so far, the seas there being midway in their career from real seas to arid depressed deserts; no longer water surfaces they are still the lowest portions of the planet, and therefore stand to receive what water may travel over the surface. They thus become fertilized, while higher regions escape the freshet and remain barren. (Lowell 1896)

The general areas of the Red Planet, Lowell imagined, were like the desert areas around Flagstaff:

> The ochre regions… seem to be nothing but ground, or, in other words, deserts. The pale salmon hue, which best represents in drawings the general tint of their surface, is that which our own deserts wear. The Sahara has this look; still more it finds its counterpart in the far aspect of the Painted Desert of northern Arizona. To one standing on the summit of the San Francisco peaks and gazing off from that isolated height upon this other isolation of aridity, the resemblance of its lambert saffron to the telescopic tints of the Martian globe is strikingly impressive. (Lowell 1910)

Both the lower and the higher regions of Mars, Lowell thought, were flat and practically free from mountains. This was the reason why canals were able to run in a complex network of straight lines, making no deviations. This was not a definitive and unanimous conclusion, however. Terrestrial canals respond to undulations in the landscape much less prominent than mountain ranges. But additional evidence about the absence of mountains came from observations of the limb of Mars. The limb of a planet is the edge of its disc as seen in a telescope, the line where the surface of the planetary globe disappears from view over the horizon. The limb corresponds to the places on the globe where there is a horizontal view across its surface. According to Lowell's observations, the limb was almost perfectly smooth, less rough in proportion to the size of the planet than the skin of an orange. Mountains would be brought from time to time to the limb by rotation but were never seen.

The Martian landscape, Lowell thought, was that of an arid featureless plain with shallow undulations, alternately low semi-desert and higher desert areas, a flat, barren landscape interrupted from time to time by artificial canals and oases. In 1907, science writer E. T. Brewster was unequivocal in reporting Lowell's picture of the Martian landscape:

> Our nearest planetary neighbors ought to know their flat and sea-less world far more completely than the children of men know theirs. In fact even our own maps of the Martian surface have no tantalizing blank spaces at top and bottom, while, thanks to the nearly complete annual melting of its snowcaps, the poles of that other world are as familiar to the inhabitants of both as are the regions between. A mountain on Mars a quarter of the height of unknown peaks in Alaska and Antarctica or on the Roof of the World would have been seen years ago. A few miles of perpetual ice prove to be a more impassable barrier than sixty millions of empty space.

Close-up views of the Martian landscape from the Space Age, which for Martian exploration began in 1971, showed how far from reality Lowell's imagination had taken him. The desert regions are there, but there is no vegetation, no canals and no water, flowing or standing. And, far from being totally flat, Mars has mountains that dwarf any on Earth. Lowell could not see mountains on the limb of Mars because they were obscured by its atmosphere and dust held in its lower regions. Similarly, as they orbit, astronauts in the International Space Station see the limb of Planet Earth as a smooth, continuous curve.

In actual fact, the highest Martian mountains are not only higher than a quarter of the height of the mountains of Alaska, Antarctica or the Himalayas, but higher than three times the height of the highest of those terrestrial mountains.

THE GIANT VOLCANOES OF MARS

High volcanoes on Mars were the first landscape features recognized on that planet, apart from large-scale colored features that could be seen by ground-based telescopes. Two white polar caps are readily visible from Earth as are olive green, brown and ochre areas on its generally orange surface. From close by, spacecraft have seen more detail.

Mariner 9, which reached Mars in November 1971, was the first spacecraft to enter into orbit around another planet. The pictures that it relayed back were at first very disappointing. A dust storm was in progress, covering the whole planet and obscuring everything, except the south pole. But, as the dust settled, the mission scientists noticed four black spots that appeared. They referred to them informally at first as Groucho, Chico, Harpo, and Zeppo, after the Marx brothers. The black spots were the tops of four high volcanoes, protruding above the dust.

Something similar had, in fact, been noticed by the Italian astronomer Giovanni Schiaparelli (1835–1910). In 1879, Schiaparelli named this region *Nix Olympica,* or Snows of Olympus. It had a white radiance that Schiaparelli thought might be snow on a mountain, which he fancifully named after the Greek mountain, Mount Olympus. Moreover, Schiaparelli noticed that this region was visible through dust storms and guessed that it might be high. The whiteness turned out to be due to white clouds that form around the top of the mountain.

Olympus Mons stands 24,000 m (79,000 ft) above the surrounding plain. The base of the volcano totals 1500 km (900 miles) in diameter when the profile of the mountain is smoothly continued out from the top of the scarp cliffs to include the so-called "aureole" (or halo) of wrinkled terrain that surrounds the mountain (Fig. 6.2)—something to do with outflowing rock that has seeped from the volcano onto the surrounding plain. This titanic volcano truly deserves its dramatic designation, being named after the mountain home of the gods of classical Greece.

When the first Martian explorers approach Olympus Mons, they will see it from a great distance across foreground ridge lines in the aureole. As they get nearer it will appear as a monumental feature of the landscape. In shape it stands like a circus marquee, with the scarp making near-vertical walls about a third as high as the summit (Figs. 6.3, 6.4). If the explorers approach in the cold of a Martian morning they might see the lower flanks of the volcano hidden behind frosty cloud, but its peak will stand above the cloud tops, perhaps trailing a stream of cloud downwind. Inside the near vertical scarp, the flanks of the volcano slope gently upwards. Olympus Mons is a shield volcano formed by the gentle outflow of successive waves of molten lava.

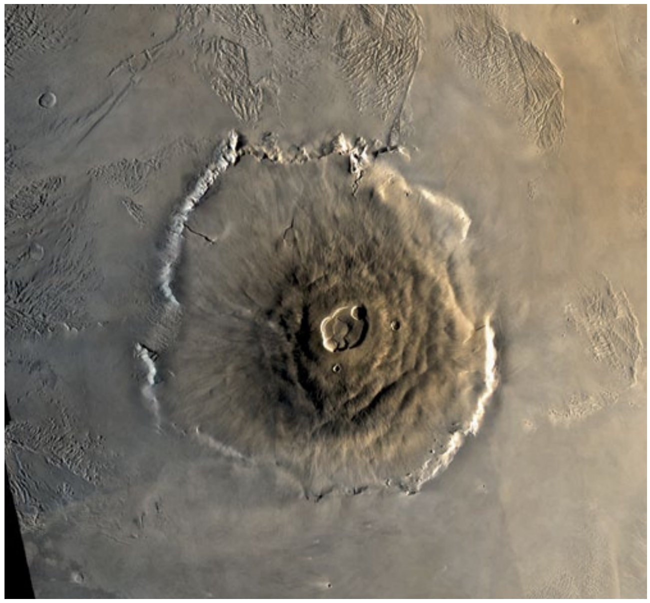


Fig. 6.2 Olympus Mons, seen from directly overhead. There is a multiple caldera at the top of the mountain. The caldera was a source of molten lava that flowed out in successive waves that left a stack of layers like a pile of pancakes, or of the shields from which the term "shield volcano" derives. The mountain is surrounded by an outward-facing scarp 550 km (340 miles) in diameter, say the size of England or Arizona, and several kilometers high. Beyond the scarp is a moat filled with the outermost waves of lava that has flooded out from the volcano. There are one or two small impact craters on the volcano's flanks. That is rather few, and indicates how the volcano was active relatively recently, covering up the traces of earlier meteoric impacts. (Viking Orbiter 1: Jody Swann/Tammy Becker/Alfred McEwen, U.S. Geological Survey; MH20N133–735A.) **A**

If the Martian explorers reach the summit they will see into the complex of six overlapping calderas at the peak (Fig. 6.5). These are not vents from which lava erupted in a fountain. They are like the calderas of the Kilauea volcano on the Big Island, the result of the collapse into pits of areas in the partly solidified roof of a deeper chamber of magma that welled up from below, overflowed from the summit and then sank back; if the magma had hardened at the surface, it became unsupported and collapsed while the liquid magma drained back into a vast chamber below.

In the record books, Mt. Everest is listed as the highest mountain on Earth. Its summit is 8000 m (24,000 ft) above sea level, but only 4000 m (12,000 ft) or so above the Tibetan plateau on which it stands. The highest volcanoes on Earth are in the mountains of the Andes and rise almost to 7000 m (23,000 ft). The largest mountain on Earth is Mauna Kea in the Big Island of Hawaii, which is only 4200 m (13500 ft) above sea level but 10,000 m (33,000 ft) high above the seafloor on which it stands. Olympus Mons on Mars is more than twice as high as this. The Big Island is actually five volcanoes that form one complex, but,

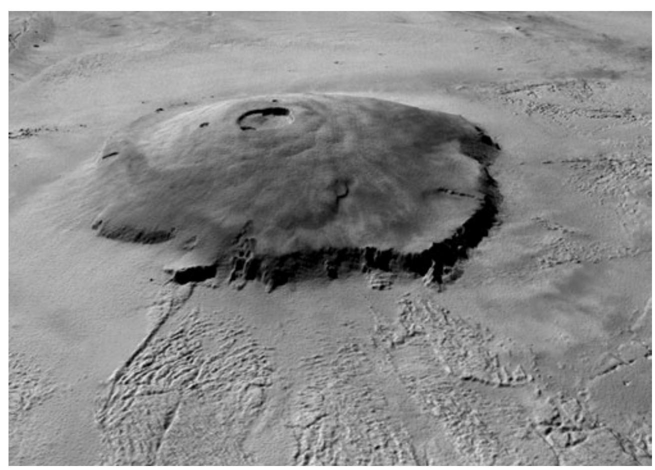


Fig. 6.3 Olympus Mons. The image shows the escarpment, rising abruptly for several kilometers from the surrounding plain and sloping up more gradually to the summit. In the foreground, the extensive plains are wrinkled with an "aureole" of gigantic ridges and blocks, which extend up to 1000 km (600 miles) from the summit like petals of a flower. The explanation for the origin of the aureole deposits is unclear, but they appear to be landslides from the volcano, and may have been altered by subsequent glaciers. Vertical scale in this image has been exaggerated by a factor of about 10. (Mars Express and Mars Orbiter: NASA/MOLA.) **BBB**

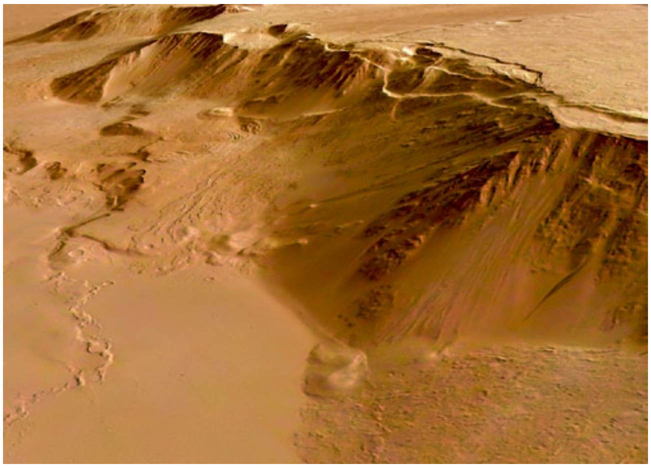


Fig. 6.4 Olympus Mons, on Mars. Perspective view of the eastern scarp of the volcano Olympus Mons, showing massive landslides that have slipped onto the plain below. This landscape has been made from a map of the surface of Mars generated by a stereo camera and stored as a computer file. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **BBB**

treating them as a single entity, the mountain that makes up the Big Island averages 100 km (60 miles) in diameter at sea level and perhaps twice this at the base. Olympus Mons is more than twice this again at the base of the scarp that cuts off the mountain (Fig. 6.2).

The overall range of the relief of Mars (height difference between highest mountain and deepest canyon) is 37,000 m (120,000 ft), twice the value of the range of heights on Earth. The enormous size of Olympus Mons and the other Martian volcanoes is a consequence of the low gravity of Mars and the absence of plate tectonics. On Mars all the volcanic material accumulates on the same stationary spot over an upwelling source of magma. On Earth, the volcanic material builds a series of volcanoes in a row on a moving tectonic plate, as in the Hawaiian Islands. The westernmost islands are made from the older volcanoes, now extinct; the easternmost island, the Big Island, is still an active volcano.

In various observations made from 2003 to 2010, astronomers claimed to have detected traces of methane in Mars' atmosphere. Although doubt has been cast on the reality of this observation by the failure in 2013 by the Mars Curiosity rover to detect methane in a chemical analysis, made on the surface, of Martian air, it had already been suggested that the meth-

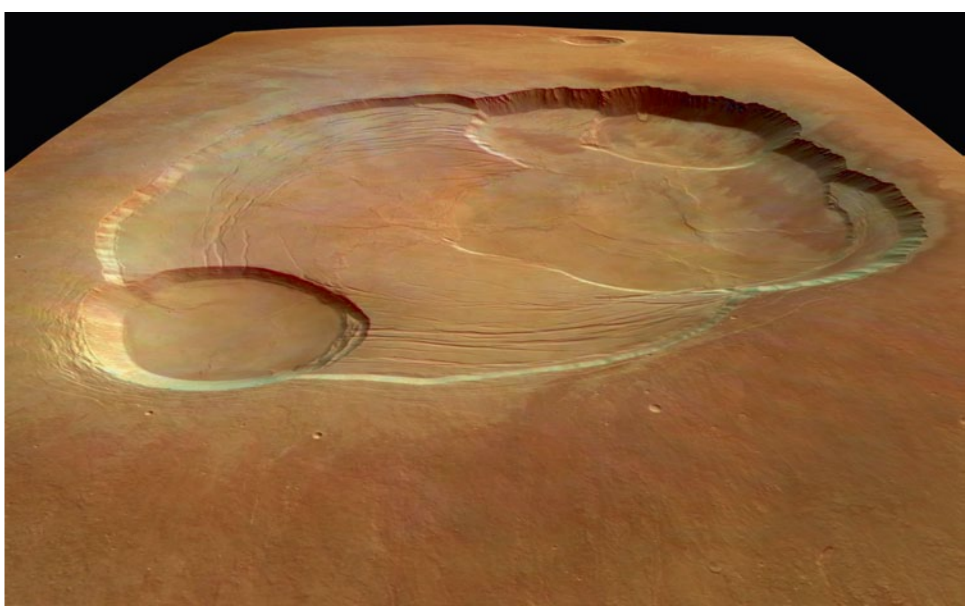


Fig. 6.5 The craters on Olympus Mons. ESA's Mars Express provided this perspective view of the multiple caldera atop the volcano. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **BBB**

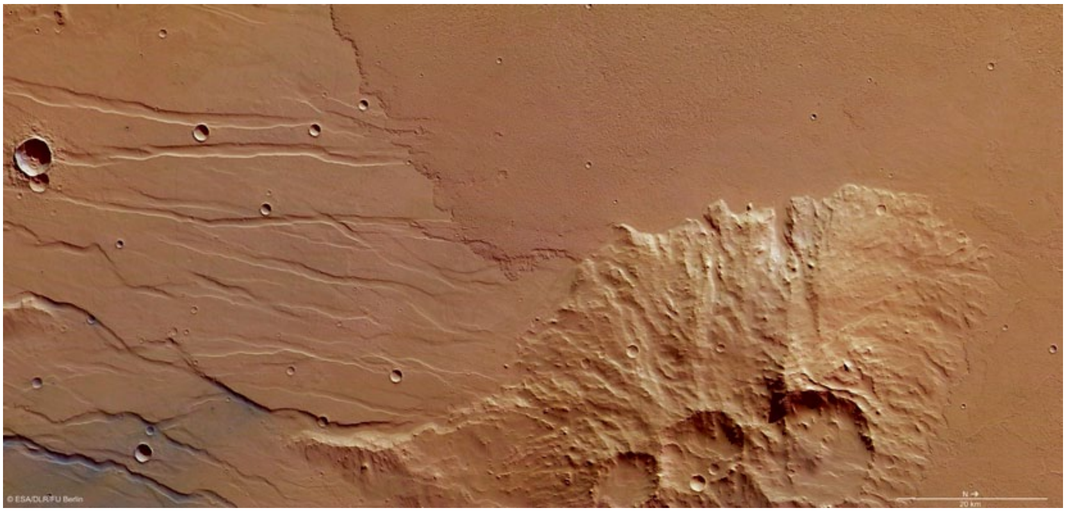


Fig. 6.6 Ghost craters. Daedalia Planum is a plain that lies south-southeast of Arsia Mons, one of the four largest volcanoes on Mars, with a base of diameter of 350 km (200 miles) and a height of 14 km (45,000 ft). The plain is covered with solidified lava flows that originated on Arsia Mons. In this image there are two lava flows that have divided around an area of older, high terrain, one of them (on the right) considerably younger than the other. Not only is it deeper and lying above the older flow (on the left) but also there are fewer craters in it, and therefore fewer meteors that have struck it. In places, the left-hand lava in particular shows earlier meteor craters that are now almost completely hidden—so called "ghost craters." (ESA/DLR/FU Berlin, G. Neukum.)
BBB

ane concentration was patchy, and Curiosity may simply be in an unlucky place. One exciting possibility is that the methane has been produced by bacteria living in niche environments, perhaps caves below the Martian surface. Another is that there is some residual volcanic activity somewhere on Mars. Some of the slopes of volcanoes on Mars are so devoid of meteor craters that they may have been laid down as little as a few million years ago (Fig. 6.6). It is plausible that volcanoes may erupt again on the Red Planet. But no volcanic activity has ever been seen. By contrast volcanoes erupt all the time on one body of the Solar System—Io, the innermost large moon of Jupiter.

THE HEALING SCARS OF MARS

The question whether there is life on Mars is a question with, as yet, no firm answer. There are niche environments where the conditions might be favorable to the existence of life, but all the evidence that has been produced in attempts to show that life exists or has existed on Mars is equivocal. There is certainly not much life there at this time, and certainly no human life. But on Mars there are (as of this writing in 2014) two small, proxy human explorers, two robotic tourists who arrived in 2004 and 2012.

The first of these robots is Opportunity, a small six-wheeled roving vehicle, the size of a golf cart, with an appealing appearance a bit like a John Deere tractor, sized for a kitchen garden.[1] The Opportunity rover has cameras like eyes on a mast, held as high as a human head above the ground,

[1] We mean no disrespect in this comparison. Both John Deere tractors and the Mars exploration rovers are wheeled, stable vehicles that move over and reach out to irregular ground and were designed by talented engineers for reliable functionality without much of a margin in their design for dressing up.

looking around and taking pictures, looking somewhat as if it came from a science fiction movie. Opportunity has a character something like the robots R2-D2 and C-3PO in the *Star Wars* films and has gathered a wide circle of fans who follow her every move. By default, the rover decides what it wants to inspect closely, plotting out the safe route there and finding out what it is; of course the mission scientists back on Earth, closely following the route and the data, can direct the rover to what they think is interesting, too. For more than nine years, Opportunity has traveled over 30 km (15 miles), has rolled around, its controllers choosing day by Martian day where to go and what to look at, and retrieving picture postcards of the landscape.

NASA's Opportunity rover takes its power from solar arrays on its back, storing electricity in batteries for use when the panels are dusty or when the Sun is shining weakly, for a short day or not at all—during the night, during dust storms, or during the winter. The rover tours and works hard on her wide-ranging sightseeing program during summer days, but she concentrates on survival during the freezing winter. In the weak winter sunlight she tries to keep warm on a Sun-facing slope until the spring, not straying much from her selected, sheltered spot, investigating sites only in the immediate area, carrying out monitoring programs, for example of the weather and Mars' rotation, that would have no continuity if they were carried out while the robot was traveling about.

Opportunity arrived at Mars on January 24, 2004, when, in an enclosed lander capsule, tetrahedral in shape, she separated from the parent spacecraft in which she had been traveling for eight months. At 5 km/s (12,000 mph) the lander entered the Martian atmosphere with an aeroshell cover in the forward direction, rubbing against the atmosphere, taking the heat, slowing the capsule down. The lander reduced speed to 0.5 km/s (1000 mph) until it was safe to open a supersonic parachute without it ripping off its anchoring. The lander descended through the Martian atmosphere on the parachute to a height of 2500 m (8000 ft), while it measured how fast it was traveling downwards and sideways, for correction by rocket thrusters. The sideways drift was so small that the onboard computer decided not to attempt to improve matters in that respect. Two dozen interconnected airbags inflated, surrounding and getting ready to protect the rover from the impact of the lander as it dropped on to the ground. The lander fired retrorockets to control the descent speed almost to zero, scattering Martian dust. At a height of about 10 to 15 m (30–50 ft) above the ground the parachute released its load and drifted slowly away from the impact point, clear of the lander. It would have been a catastrophe if the parachute had drifted down directly on the lander and blanketed it into immobility. Cut free, the lander plunged to the ground. Cushioned inside the airbags, it bounced more than a dozen times, rolling by chance, at the last moment, over the edge of a small, 22-m (70 ft) diameter crater, into which it dropped. The crater has since been named Eagle, the term in golf for a two-under-par-three hole-in-one, as well being the name of the U. S. national bird.

Opportunity was at that time in the lander surrounded by the inflated airbags, looking a bit like the Michelin man. The airbags were deflated and dragged back into the lander, out of the way. The rover sat a while and thought about which way was up. The tetrahedral lander opened one of its side panels, choosing the one that levered the lander over onto its base, so everything was now more or less upright. It opened two more panels, and spread out on Mars like a three-petal flower; mission controllers adjusted the petal angles so that the lander was trimmed to be exactly upright. Opportunity deployed her solar panels and charged up her batteries, extended the mast on which her camera is located and erected her antenna so she could communicate with Earth. She had a good look around and sent her first pictures home. Mission controllers chose which petal to drive the rover down from the lander. It had taken Opportunity seven Martian days to complete the landing formalities after touchdown, and she rolled down onto the Martian soil on the *Meridiani Planum* on January 31.

Opportunity has a pair of navigation cameras (Navcams) as well as two panoramic scientific instrument cameras (Pancams) on her mast, to select interesting places to go, plot the route there and take pictures to analyze the geology she finds. She travels forward at a maximum speed of 5 cm/s, although 1 cm/s is a more typical speed because everything is oriented to not getting the rover into a dangerous state or stuck. On a good day, she travels perhaps 100–150 m (100–150 yards), the record being 200 m (200 yards). To help avoid obstacles that might jam her wheels or tip her over, Opportunity has two sets of stereo, hazard-avoidance cameras (Hazcams), mounted front and aft. Every 10 s or so Opportunity uses the onboard computer to analyze the Hazcam images to look for problems, and decides how to steer around them, unless she comes across a particularly challenging case, in which case she asks for guidance from mission controllers.

Opportunity is the rover in one of a pair of NASA missions called Mars Exploration Rover-A and -B (MER-A and MER-B). The other rover is called Spirit, which landed on Mars in the same way in the same year but got stuck in sand and expired in 2010. The planned duration of both missions was 90 days, but they lasted much longer than planned. Opportunity's primary program of scientific studies of Martian minerals was executed well before that time limit in the crater into which she had, by chance, rolled when she landed.

The mission scientists were jubilant that the Opportunity rover had landed in a crater. For geologists, craters serve the same function for their work as seacliffs, canyon walls or mountain bluffs do on Earth. They give access to a variety of minerals that had been below the surface of the planet and are now exposed at the surface by the impact (Fig. 6.7), minerals that have been created over a range of geological epochs.

Cornell planetologist Jim Bell, the Principal Investigator for the scientific cameras in the MER missions, had wanted for this reason to land in part of the *Valles Marineris*, to see the exposed canyon wall. This was ruled out because of the unknown effects of the winds around the canyon

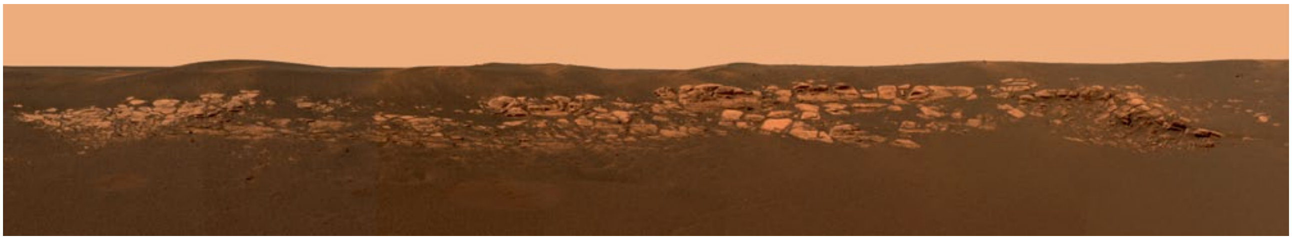


Fig. 6.7 Eagle Crater. The Opportunity rover's view, looking up to the Martian sky over the walls of the crater, which is about the size of a school classroom. The first picture by Opportunity of the inner side of the crater walls showed a rock outcrop about 10 cm (4 in.) thick about 10 m (10 yards) away. The rock had been deposited during the geological history of Mars and proved to be layers of minerals that formed in flowing water. (Opportunity: NASA/JPL/Cornell.) **AA**

walls. Would they cause the parachute to veer and to crash its precious cargo against a cliff? "The safest places to land were often the flattest, most 'boring' sites with the least compelling scientific potential…" complained Bell, but fortunately this turned out not to be so for Opportunity's landing site on *Meridiani Planum*.

In fact, the first view (Fig. 6.7) that Opportunity had of her landing site was a layered stratum of rock about 10 m (10 yards) away, exposed below the lip of the crater. She did not even have to search out her first target for investigation. Many of the minerals that Opportunity found here and nearby had been formed in water. The rocks of the landing site had been formed probably in shallow waters near the shore of a salty Martian lake during the planet's warm and wet epoch, much the same environment that is found now on Earth in salt lakes (Fig. 6.8). This was exactly what the scientists hoped they would find.

Both Mars exploration rover missions operated much longer than planned, but Spirit got bogged down in soft soil after 5 years. As it turned out, Opportunity has operated 100 times longer than her nominal mission. The engineers who built her estimated that she might be able to travel for 500 m (500 yards), but over her eight years she has been able to investigate a variety of sites during a trek of more than 30 km (20 miles) from her landing place.

In her sightseeing tour between Eagle Crater and its next primary destination, Endeavour Crater, Opportunity has toured several craters of increasing size. After slipping on loose sand on her first attempt at too steep a route, she successfully climbed up out of the Eagle Crater on March 22, 2004. While Opportunity was inside the Eagle Crater, her view was that of the walls of the crater, its rim and the sky above.

Unlike in Arizona's Meteor Crater the silence would not have been pierced at all by the cries of hawks. Nor would there have been much wind to disturb the stillness there, beneath the shelter of the crater walls. In any case, the buffeting of the wind and its noise on Mars is less noticeable than on Earth because the density of air is less. Additionally, there is no vegetation, no twigs or leaves to rustle together. If you could survive on Mars without a spacesuit you would hear almost nothing. This is a rare experi-

Fig. 6.8 The Scapegoat, a painting by Holman Hunt (1827–1910). Hunt painted this landscape (1854) at Oosdoom (the Biblical Sodom), on the margin of the salt-encrusted shallows of the Dead Sea, taking great pains to render the landscape in a naturalistic way. The mountains beyond are those of Edom, a region in the southern part of Israel. The scene is clearly terrestrial, not only because of the animal and the skeletal remains in the deposits on the shore of the lake but also because of the clouds and their shadows, and the large Moon. But although the color of the hills owes something to twilight effects, it is primarily due to the mineral content of the rocks, as on a barren planet without vegetation or other living things. Indeed, on the frame Hunt quotes the biblical text about the scapegoat in which it is banished to a "land not inhabited." The location is one that, of all the landscapes on Earth, most resembles the conditions under which the rocks of the Meridiani Planum were laid down on Mars. (The Lady Lever Art Gallery, Port Sunlight: Wikimedia Commons, commons.wikimedia.org/wiki/File:William_Holman_Hunt_-_The_Scapegoat.jpg.)

ence on Earth, although rumor has it that you can hear almost nothing while walking in rocky deserts near the Wise Observatory near Mizpeh Ramon in the Negev Desert of Israel, and in the Atacama Desert on the way to the European Southern Observatory at Paranal in Chile. In these deserts there is almost no vegetation with leaves that can rustle. Few insects live there, and there is no buzz of passing flies and bees. Birds are rare, and the sky is silent of their calls. The loudest noise a visitor might hear is the hiss of the pulse of blood in his or her ears, modulated by heartbeat. Of course, on Mars it is impossible to survive without being in a sweaty spacesuit, your head enclosed in a helmet, the sound inside being your breathing and the rustling of the fabric. It would not in practice be the natural experience that you can get in a wilderness in the terrestrial environment in which you belong. On Mars we are unavoidably aliens.

Once outside the crater, Opportunity gained her first sight of her surroundings, the *Meridiani Planum*, a flat plain of rock covered with sand at various depths, from loose grains on rocky outcrops to deeper drifts in hollows and depressions. On such a uniform plain, some things stand out as unusual, and in its 30 km (20 miles) trip between Eagle Crater and Endeav-

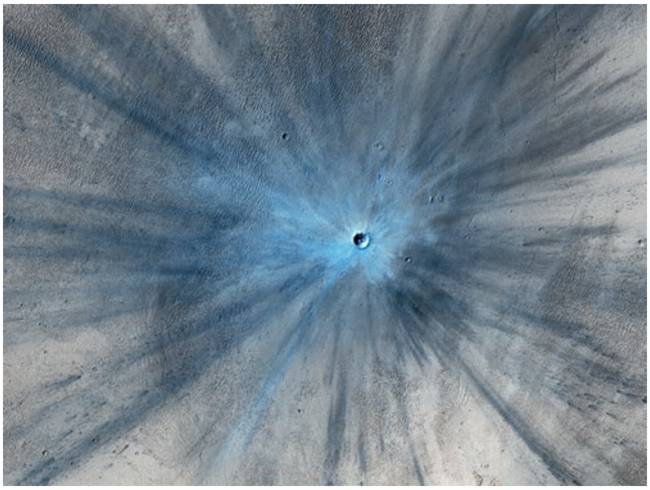


Fig. 6.9 A dramatic new crater on Mars, freshly produced in 2010–2012. The red dust of the Martian surface has been blasted away, leaving bluer bare rock (its blue color here much exaggerated). Broken rock was tossed outward as far as 15 km (9 miles). (Mars Reconnaissance Orbiter: NASA/JPL-Caltech/Univ. of Arizona.) **BBB**

our Crater Opportunity detoured when she saw strange rocks. Half a dozen of them turned out to be meteorites, fallen to the surface of Mars over the recent past at speeds too small to make craters and to shatter. Meteors are striking Mars even in the present day. One struck the surface of Mars sometime between July 2010 and May 2012, creating a new crater 30 m (100 ft) in diameter and spraying broken Martian rocks in all directions, the impact blowing away surface dust (Fig. 6.9). This is one of a number of fresh craters on Mars. Before-and-after imaging that brackets their appearance suggests that meteor impacts produce 200 craters at least 4 m (13 ft) in diameter on Mars per year at the present time.

Terrestrial landscapes are strewn with meteorites, too. The Nullarbor Plain in Australia is one such place. It is a limestone and sandstone plain of flat, rocky slabs, red or gray, on which iron meteorites stand out dark and gnarled. Meteorite collectors use hang gliders to skim over the surface, looking down for large collectible specimens. Opportunity creeps along the surface of Mars much more slowly but does not have to look through scrub and bushes that hide the rocks behind.

Opportunity passed by Fram Crater in April and then spent some time at the 132-m diameter Endurance Crater (May to December 2004). The initial view was breathtaking, according to Steve Squyers, the Principal Investigator for the Mars exploration rover mission.

The far western wall dominates the scene. The wall is a precipice along much of its crest, and if the images don't lie, there are segments, meters high, that are so steep they overhang. Crags and pinnacles dot the crest, and long ribs of rubble extend down from it towards the crater floor. The lower walls of the crater are steep and forbidding, wide swaths of featureless sand studded at irregular intervals with rounded, oddly perched boulders. On the floor of the crater is a spectacular dune field, the undulating crests like frozen waves in the images.

Squyres' thoughts immediately turned to the practicalities of maneuvering the rover on the crater edge. "These cliffs are the kind of thing that Opportunity could fall off and die if we screw up." Opportunity scouted carefully around the crater to look for a good way in, pawing the ground with her wheels to get a good idea of the grip that they had on these rocks. It took ten days to edge in to the crater down the slope, where she was able to gaze up at the impressive Burns Cliff in the western crater wall (Fig. 6.10). She found it difficult to creep up close enough to the cliff on the slippery, sloping bare rock at its base. The cliff proved to be made of entirely horizontal strata, which had never been pushed sideways and

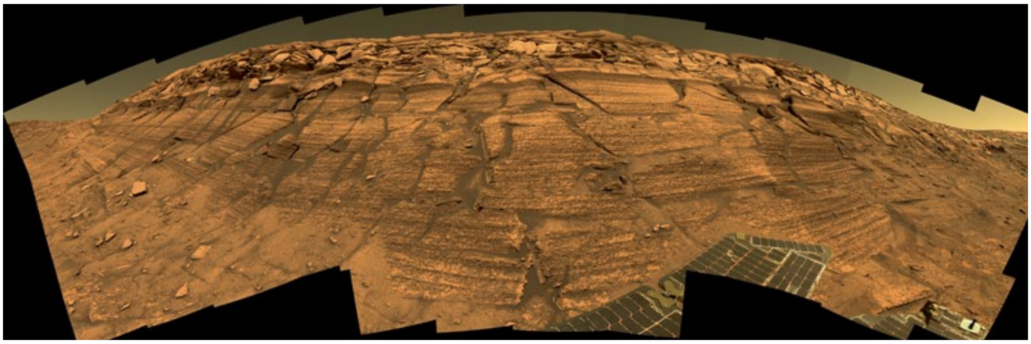


Fig. 6.10 Burns Cliff in Endurance Crater. The rover was close up to the cliff, in order to examine its rocks closely, so the cliff seems to bulge outwards in the middle. In reality it curves in a gentle hollow shape. The cliff is made of close-knit strata, probably due to windblown sedimentary layers of sandy material, although there is also the possibility that the rock was deposited, layer by layer, in water. (Opportunity: NASA/JPL/Cornell.) **AA**

folded by tectonic forces. Unlike on Earth (Fig. 6.11) there has been little or no tectonic activity on Mars.

Opportunity's next target was the beautiful Victoria Crater. The crater's edges are deeply scalloped with crumbling bays (Fig. 6.12) between hard capes. Opportunity explored this crater from September 2006 until August 2008, inching her way about a quarter of the way around the rim, easing her way into the crater at Duck Bay (Fig. 6.13). The crater is named after the ship in which Magellan circumnavigated the world, and features of the crater were named after places that he visited.[2] The precipitous cliffs, like Cape Vincent, with its stratified layers, would not be out of place in terrestrial scenery (Fig. 10.18). They are of course exposed through meteor impact, not water erosion or tectonic faulting.

[2] In February 1520, viewing a large hill behind Cape St. Mary in what is now Uruguay, someone in Magellan's crew is reputed to have exclaimed 'Monte vide eu.' (I see a mountain, in a mixture of Portuguese dialects), giving a name to Uruguay's capital city. South of that, Magellan stopped at Bahia de los Patos (Bay of Ducks), an unidentified location named after the abundant penguins that his crew found there and misidentified.

Fig. 6.11 San Andreas Fault, California. This view is clearly terrestrial. Not only is the sky blue but the strata are folded, crumpled by tectonic forces as the Pacific plate and the North American plate collide. Strata on Mars, like those exposed at Burns Cliff, remain horizontal, except perhaps on volcanoes, since Mars has no phenomenon of continental drift. (Bernhard Edmaier/Science Photo Library.)

Fig. 6.12 The Victoria Crater. Imaged at a somewhat oblique angle from the HiRise camera on NASA's Mars Reconnaissance Orbiter, the crater is small, some 750 m (2500 ft) in diameter. Its rim is distinctively and beautifully scalloped, the gullies caused by wind erosion and downhill movement of crater wall material. The dark streaks that run out from some bays (especially prominent at the top of the picture) are made by material that has been lifted from the crater walls by the wind and blown out of the crater onto the plain. Boulders that have fallen from the crater wall litter the floor near the walls, and the central area of the floor is covered by sand dunes from material that has fallen and blown in. The widest gulley on the rim, near the bottom of this picture and a small, "ghost" crater plus two very small craters, is Duck Bay, which was visited by the Opportunity rover from September 2006 to August 2008. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona.) **A**

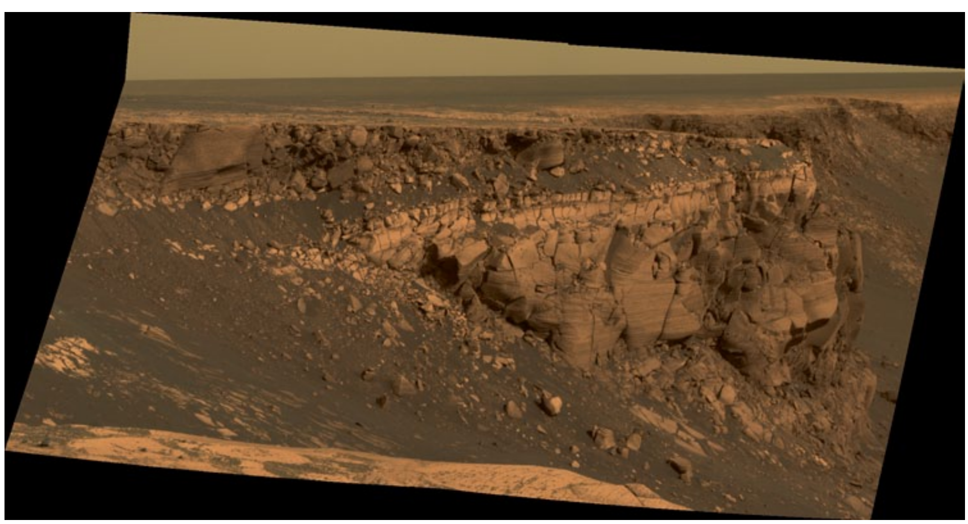


Fig. 6.13 Cape Vincent in Victoria Crater. This image from Opportunity is a view across Duck Bay to Cape St. Vincent, one of the many promontories in the walls of the crater. The crater walls are highly stratified (compare William Dyce's Pegwell Bay, Kent—a recollection of Oct 5th 1858, Fig. 10.18), with material at the top of the promontory made of a layer of loose, jumbled rock and solid bedrock below. The bright band of blocky rock that is visible around the entire crater between the loose surface layer and the solid rock below represents what used to be the surface of Mars before the incoming meteor made the crater. The strata of rock were laid down by the wind-drifting sand in a dune sea. (Opportunity: NASA/JPL/Cornell.) **AA**

Victoria is 750 m (2500 ft) in diameter with low hills on its rim. It is a Martian version of the slightly bigger Meteor Crater in Arizona. Its floor is covered with a lacy network of dunes, sandy material that has blown into the crater, piled into a complex pattern by the motion of the Martian air over the crater and the irregular hills of its rim.

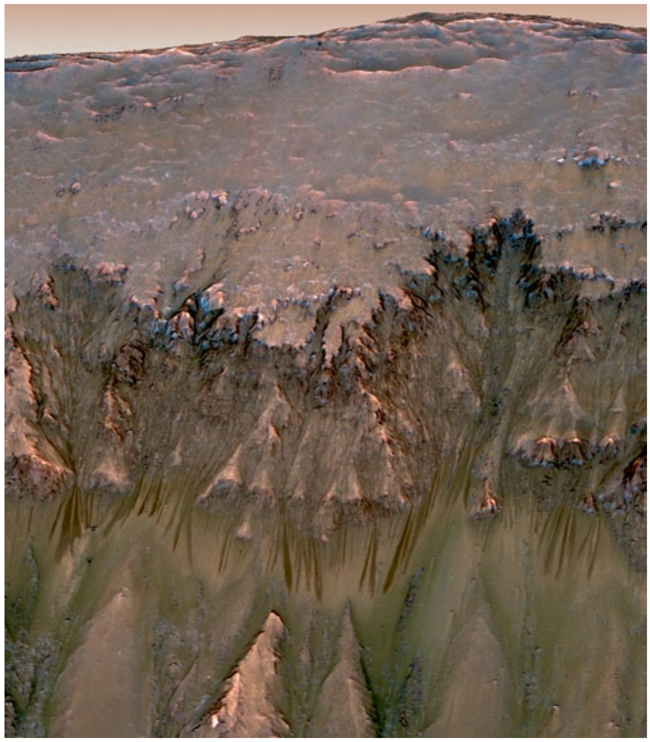


Fig. 6.14 Newton Crater. The Sun-facing walls of the Martian crater are scalloped like the crater Victoria, with overhangs of strata from the upper layers on the crater rim. These strata are being undermined by flowing, briny water, revealed in this picture as dark, finger-like streaks that drain down the sloping walls at the bottom of the picture during late spring and summer. They fade in winter and return during the next spring. The salts in the water lower the temperature at which water freezes and maintains the water as liquid during summer. The streaks are about 1 m wide and hundreds of meters long, and they drain down the centers of wider deeper gullies that have been eroded first by the wind and then by flowing, icy soil—small glaciers. The picture has been made by combining 3D models with an exaggerated full-color image from the HiRise camera on the Mars Reconnaissance Orbiter. The viewpoint is that which would be seen from a helicopter inside the crater at about the ground level of the plain outside. (Mars Reconnaissance Orbiter: NASA/JPL/LPO.) **BBB**

The gullies around the crater's edge have been cut by wind erosion, and it is 150 m (500 ft) wider now than when it was first made, but 50 m (160 ft) less deep. Eventually it will be filled back in to become a shallow depression in the Martian plain. The Martian wind is gradually healing the scars left on its surface by the cosmic bombardment of meteors.

In some craters on Mars the gullies that run down the crater walls have been enhanced by the flow of small glaciers, which have left piles of moraine on the crater floor, rumpling up the loose material at the bottom of the walls. This might have happened several times in a succession of ice ages on Mars over the past few million years (Figs. 6.14, 6.15).

These channels of water originate in icy mud that underlies the surface of Mars. The presence of this water was first revealed in the scenery of Mars, around what are called "splosh cra-

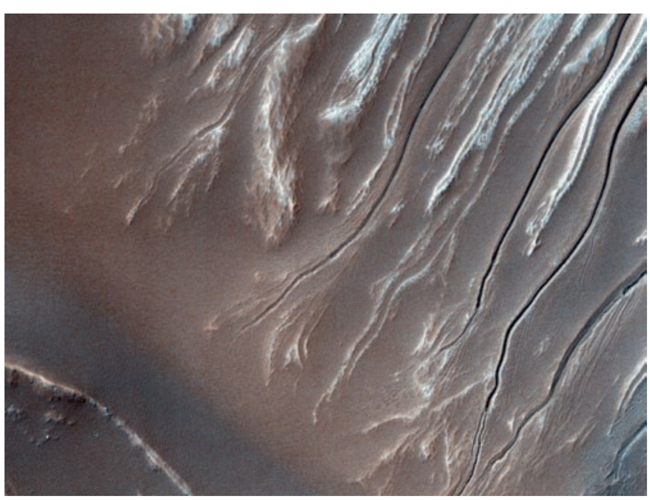


Fig. 6.15 Avire Crater. Avire is a tiny crater located inside the Newton Crater. Like its larger cousin, Avire has thin, deep gullies cut into its walls, seen here from above. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona). **A**

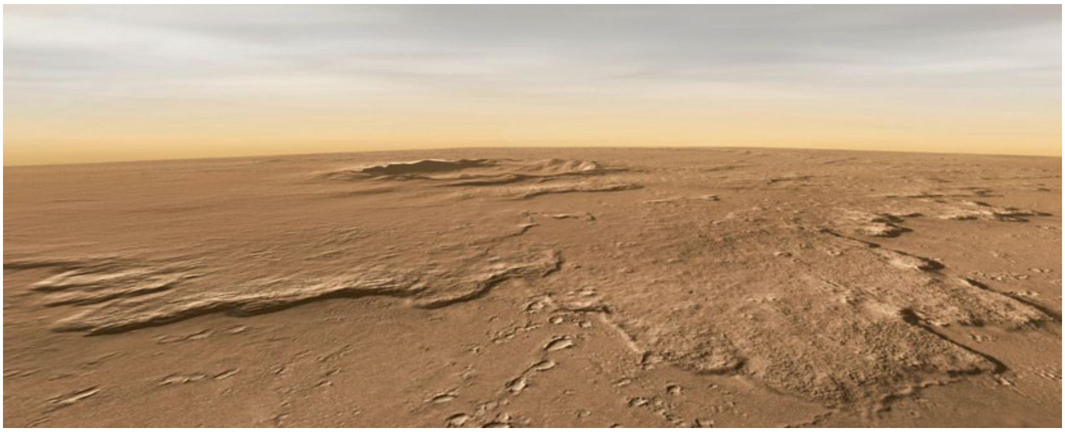


Fig. 6.16 Lobate structures. Petals of rocky debris encircle a fresh crater on Mars, called Tooting. The impact of the meteor that formed the crater fluidized the icy soil on Mars at the time the impact occurred, sending out a blast wave of surging debris that reached up to 30 km (20 miles) from the impact. It left a plateau around the crater that ranged from 5 to 120 m (15–200 ft) in height, leaving an abrupt scarp where the debris ground to a halt (foreground). This perspective monochrome image has no height exaggeration. (Mars Odyssey Orbiter, MOLA laser altimeter and Thermal Emission Imaging System: NASA/JPL/Arizona State University, R. Luk.) **A**

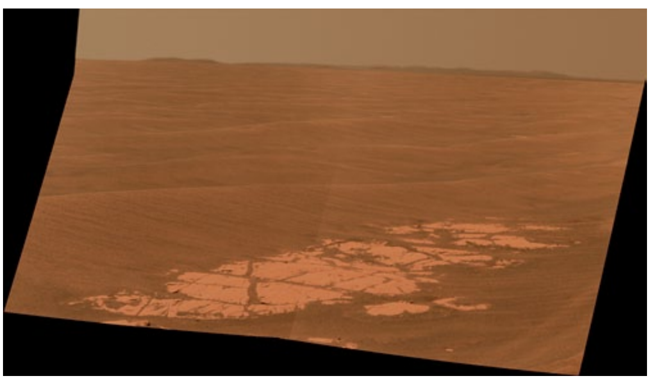


Fig. 6.17 The Endeavour Crater on the horizon. The west crater rim is seen (left of the picture) at a distance of 13 km (8 miles) in April 2010. Hills on the right are from a crater, Lazu, which is 35 km (21 miles) away. Compare with the panorama of the Apollo 11 landing site, Fig. 5.2, and the view of the Cat's Paw hills, which are also crater walls. (Opportunity: NASA/JPL-Caltech/Cornell University.) **AA**

ters." They are surrounded by so-called lobate structures. These are ranges of hills in the form of petals (Fig. 6.16). When a meteor impacted on the surface of Mars to form the crater, its heat melted the ice under the surface, creating a surge of icy mud that flowed outwards to create the "petals."

Opportunity set off from the Victoria crater in September 2008 on a 3-year march to visit the Endeavour Crater. The crater came in sight about half way through the trip, as low hills on the horizon (Fig. 6.17) like the view of Arizona's Meteor Crater from the approach road. The hills were in sight from sand dunes and flat rocky outcrops, across which Opportunity was able to sprint. Eventually the rover reached the crater rim (Fig. 6.18) and could see into its shallow bowl (Figs. 6.19, 6.20) (Fig. 6.21).

CANYONLANDS

The exploration of Mars began with a *Mariner 4* flyby in 1965 that lasted a few hours. It recorded 21 images of the Red Planet's cratered old surface and transmitted them back to Earth over the next 2 weeks. Six years later, in 1971, the *Mariner 9* spacecraft was sent to Mars, entering orbit around the

Fig. 6.18 Looking over the rim. Opportunity's arrival at "Spirit Point" gave it its first views into the Endeavour Crater on Aug. 9, 2011, across a small crater, Odyssey, on the rim. (Opportunity: NASA/JPL-Caltech/Cornell/ASU.) **AA**

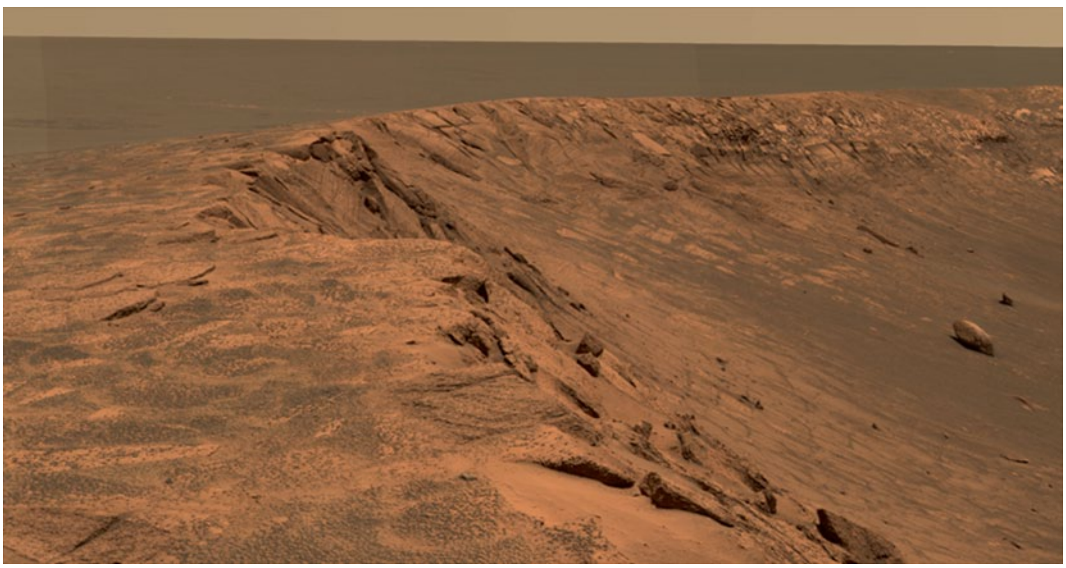


Fig. 6.19 The view along the rim of Endeavour Crater. (Opportunity: NASA/JPL-Caltech/Cornell/ASU.) **AAA**.

Red Planet for a sustained look. It discovered the eponymous *Valles Marineris* (Mariner's Valley), a huge canyon system, the largest in the Solar System, 600 km (379 miles) wide and 7 km (23,000 ft) deep, which extends 4000 km (2500 miles) east-west along the Martian equator. The volcanoes of the Tharsis Province, including Olympus Mons, are at the western head of the canyon.

The size of the canyon of the *Valles Marineris* is huge, and the landscape views across it are astounding (Figs. 6.22–6.24). Imagine standing on the rim of the Grand Canyon in Arizona. Widen the canyon from its current value, about 40 km (25 miles) at its widest, making it more than ten times wider, also at its widest point—about as wide as the entire state across which the Grand Canyon runs. Make it three times as deep as its present value of 1800 m (6000 ft). Turn the canyon so it runs north-south and move it to lie along the entire 3700 km (2300 miles) length of the Mississippi River, from Illinois to the Gulf of Mexico. As the Grand Canyon actually is, it could be hidden in a corner of the *Valles Marineris* canyon

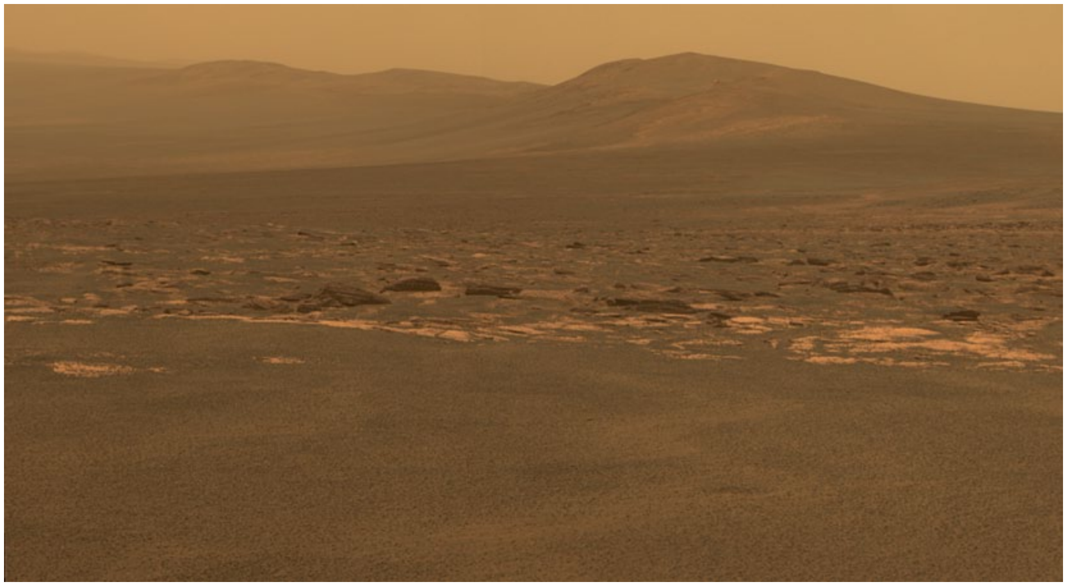


Fig. 6.20 The interior of Endeavour Crater. The view across the crater shows a rocky landscape, with sand dunes. The far wall of the crater curves away to the right. (Opportunity: NASA/JPL-Caltech/Cornell/ASU.) **AA**

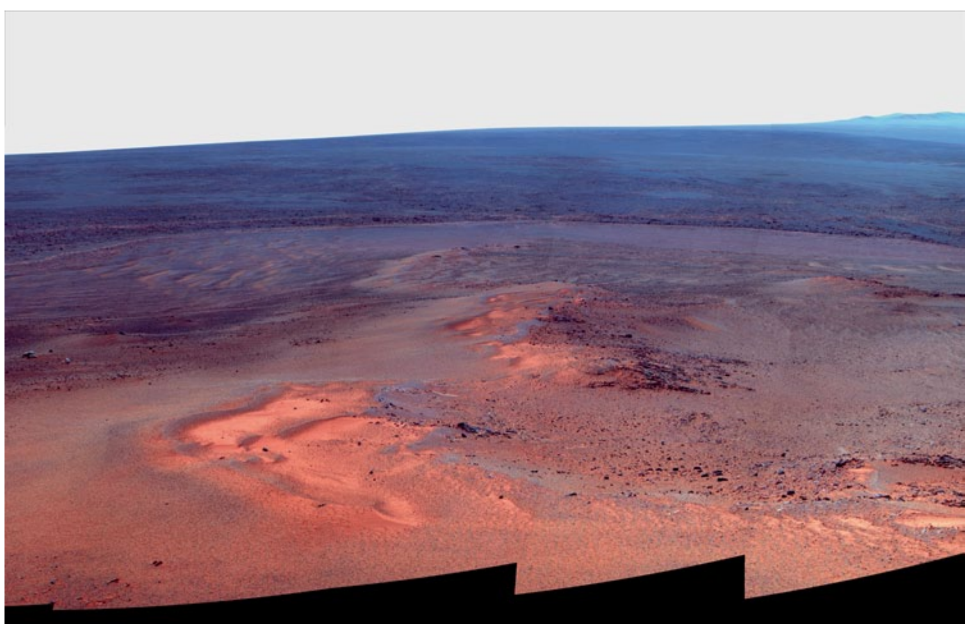


Fig. 6.21 The sand dunes of Endeavour Crater. In 2012, the Opportunity rover looked across the crater from a high, rocky outcrop called Greeley Haven on the rim of the Endeavour Crater, 20 km (12 miles) across. The floor of the crater is domed upwards with deep sand dunes in the foreground and mid-field. The northern edge of the Cape York segment of the rim of Endeavour Crater runs parallel to but just outside the left edge of the picture and curves to the right across the upper half of the scene, about 10 km (6 miles) away. This image, which shows about a third of the crater interior, combines exposures taken by the Pancam camera mounted on the rover through three filters, one blue, one green and one infrared, so the colors are exaggerated, and the view is not what would be seen from here by a human being. The blue color in parts of the scene is from "blueberries" (discussed later). (Opportunity: NASA/JPL-Caltech/Cornell/Arizona State University.) **B**

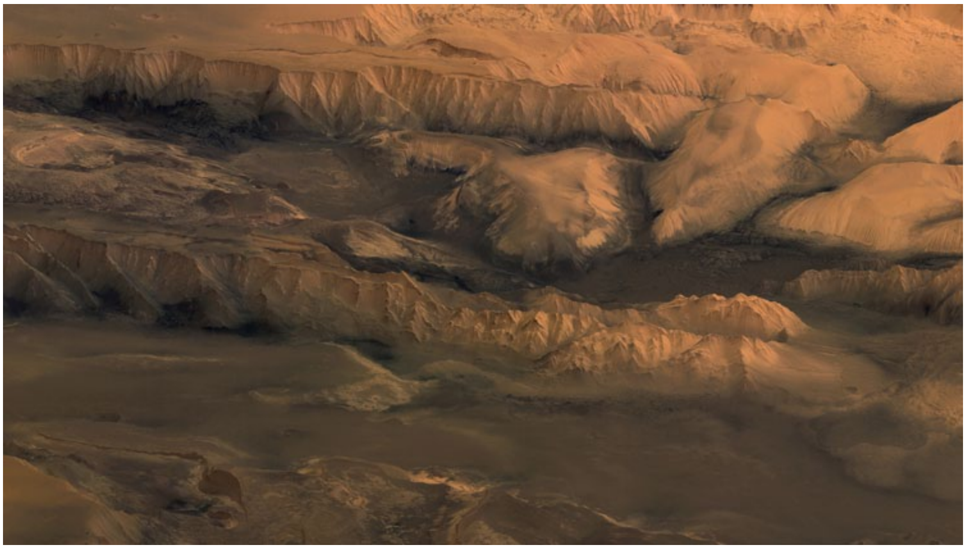


Fig. 6.22 The central section of the Valles Marineris. The view is a landscape as if seen from a point hovering in the sky above the surrounding highlands in the middle of the Valles Marineris, looking from south to north. Three parallel valleys run east-west here: Melas Chasma, Candor Chasma and Ophir Chasma, each about 200 km (125 miles) wide. The steep cliffs in the background and center are about 5000 m (16,000 ft) high and show traces of intense erosion. The remains of massive landslides can be seen at the foot of the mountains. How this enormous structure on the surface of Mars was formed is still unclear. The vertical topography shown has been exaggerated to look twice as high in proportion as in reality. The colors are a good approximation to the real colors. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **A**

system. Stretched and made more complex, as has been described, in all three dimensions, the Grand Canyon would then be a rival to the *Valles Marineris*.

The *Valles Marineris* is thought to be the result of massive volcanic upthrusting of the Tharsis Province at its western end. The Tharsis Province is an area of vast volcanoes (see pp. 73-75). The upwelling caused such great

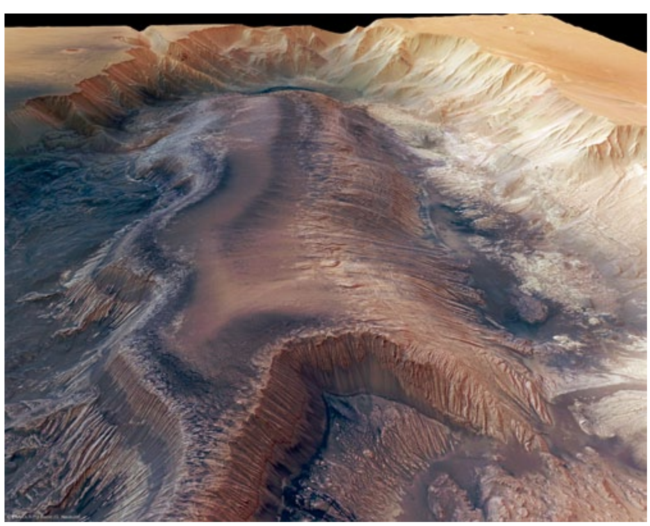


Fig. 6.23 Hebes Chasma. This completely enclosed valley, almost 8000 m (26,000 ft) deep, is located in the north of the Valles Marineris region. Its steep sides are layered, and many landslides have brought down material from the cliffs into the valley floor. There is a flat-topped mountain, or mesa, in the center of the valley, which reaches up almost to the level of the surrounding plains. It is made up of numerous rock layers stacked on top of each other. It is not known whether the strata are sediments from a lake, wind-blown sediments or volcanic rocks, but the successive layers have been exposed by erosion. Other instruments on Mars Express have revealed water-bearing minerals such as gypsum in some areas of Hebes Chasma. Significant quantities of water once existed here. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **A**

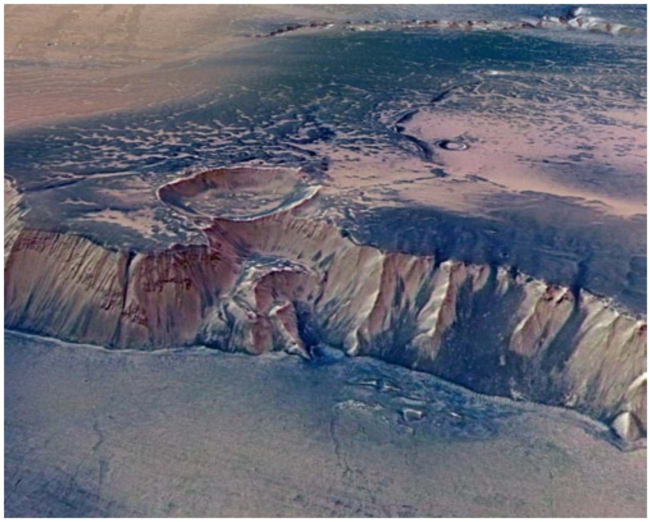


Fig. 6.24 Grander canyon. An impressive cliff, up to 4000 m (13,000 ft) high, is located in the eastern part of Echus Chasma, north of Valles Marineris on Mars. The canyon is 100 km long and 10 km wide (60 × 6 miles). Apparently, sometime after the canyon was formed, a meteor impacted on the plain near the cliff tops, weakening the wall of the canyon and causing it to collapse to the canyon floor. The canyon was once one of the largest lakes of water on Mars. The lake's shoreline formed a beach along the bottom of the cliffs. The lake's contents flooded out of the canyon and carved the impressive but more shallow Kasei Vallis, which extends more than 3000 km (1800 miles) to the north. At some later time, lava flowed in the valley, leaving an extraordinarily smooth floor. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **A**

stress in the Martian surface that it split in radial cracks along the equator, like the heave of ground below a water or gas leak. It is a gigantic rift valley and is probably still opening further. Large volumes of water or ice melt water were also at work, removing rocky material from the cracks, undermining cliffs, causing the surface to cave in.

VAST DRY PLAINS

When a space probe is landed on the surface of a planet it is more or less inevitable that it lands well away from impressively large landscape features, especially early on in the exploration of a planet, when the uncertainties of how accurately a probe can be targeted are high (for example, due to a lack of knowledge about the atmosphere and how it will affect the probe's passage downwards). As a result the first landers on Mars were targeted into some of the vast plains. The first landers on Mars were the Viking landers, which gently lowered themselves onto the surface by slowing down with retro-thrusters. Their landing sites were chosen to be safe to land on, and had no large rocks or hills within the landing zone. As a result the Viking landscapes were monotonous and almost featureless. The plain was gently undulating and strewn with chunky angular rocks (Fig. 6.25). Sand had been blown around the rocks, or in some cases it has been blown out from under rocks so that they stand on a small pillar of sand, like a golf ball positioned on a sandy tee. At Lander 1 site the sand was thick enough to lie in some places in dunes. Over the time that the landers were operating it was possible to see some slight alteration of the distribution of the sand, eroded by the wind, but the surface of the sand is mostly quite stable because it is crusty, the sand particles cemented together by mineral deposits brought up from below, dissolved in water that evaporated at the surface. Mars is covered by a freeze-dried brown desert.

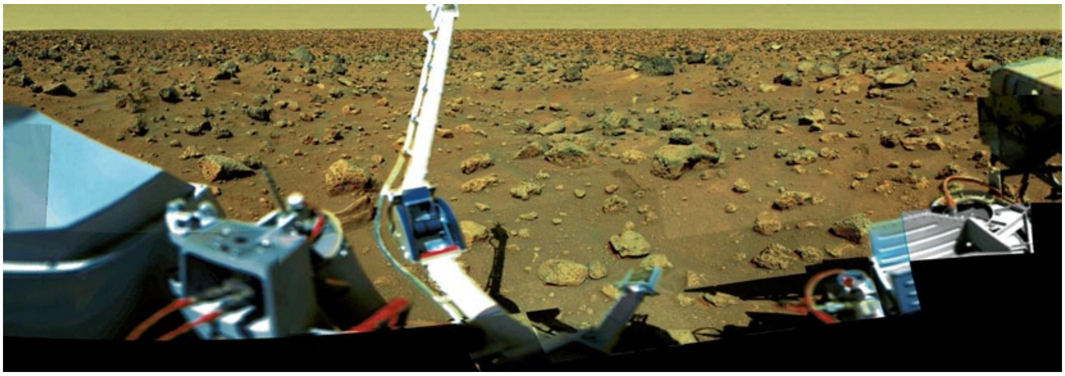


Fig. 6.25 The rocky plains of Mars. This image was acquired at the Viking 2 lander site with camera number 1. Some parts of the lander are visible in the foreground and to the left and right. The rocks are angular fragments from the Martian bedrock sprayed out from the impacts of meteorites in the area around and scattered onto the plain. They are all very similar in color and composition because they all come from the same type of bedrock. Some rocks have been weathered more or less than others, so they do show some regions on their surfaces that are different shades. Between the rocks are drifts of sandy soil, blown here in dust storms. This image has had its colors balanced to approximate what would be seen if the Martian surface materials were on Earth. The onsite view would be redder, illuminated by light reflected from fine-grained red dust in suspension in the air. (Viking Lander 2: NASA and Edward A. Guinness, Washington University in St. Louis.) **AA**

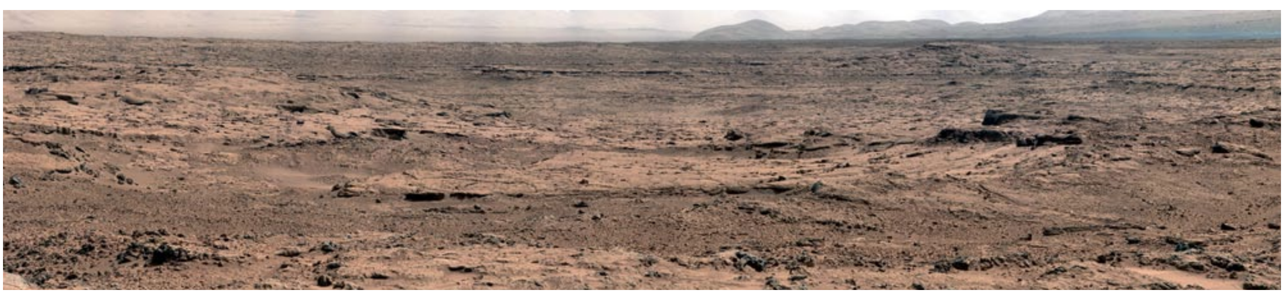


Fig. 6.26 The view from "Rocknest." In the center is the shallow rock-strewn crater called Point Lake. Beyond is the Glenelg Intrigue; its name is palindromic, as well as the name of a feature in Yellowstone National Park and a Scottish village, and the Curiosity rover will visit the location twice (once coming, and once going). The mountains on the horizon rising to the right are the Mount Sharp hills, the scientific destination of the rover, and beyond them, a lighter gray, the inside precipice of the far wall of the Gale Crater. The image has been white-balanced to show what the rocks and soils in it would look like if they were on Earth. (Curiosity Rover: NASA/JPL-Caltech/Malin Space Science Systems.) **AAA**

The Curiosity rover landed in 2012 inside the Gale meteor crater, and its flat floor proved to be, as expected, broken by the meteor impact (Fig. 6.26), as well as littered by rocks and sand. The rocks and sand are pink, basaltic lavas with a high concentration of iron. Weathering of the bedrocks in the thin Martian atmosphere produces minerals such as rust. This is why Mars is the Red Planet.

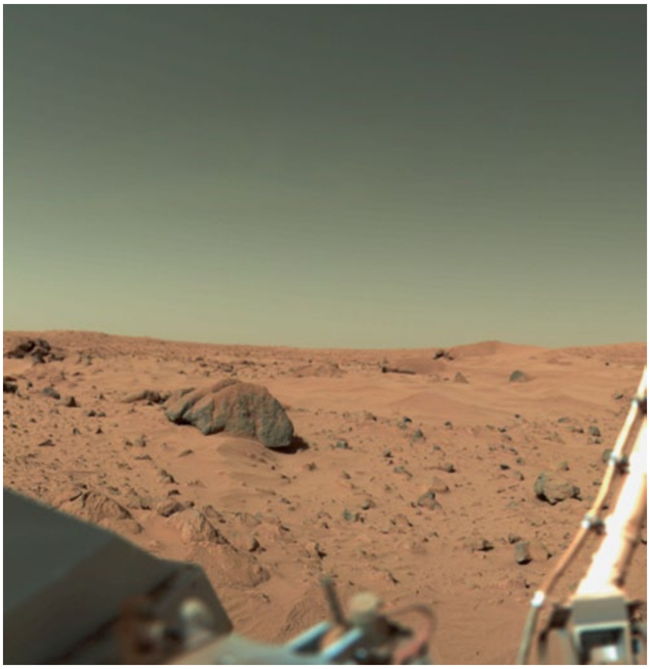


Fig. 6.27 The Viking 1 landing site on Mars. Behind and to the right are sand dunes, and on the horizon are hills that are the rims of the closer craters. The largest rock, "Big Joe," is 2 m (7 ft) in diameter. (Viking Lander 1: NASA: image processing by Roel van der Hoorn.)
AA

Fig. 6.28 Sand dunes in Dingo Gap. From the firm ground beyond Dingo Gap, the Curiosity rover was able to look back to her track where it had successfully risked crossing deep, soft sand. (Curiosity Rover: NASA, JPL-Caltech, MSSS; Digital processing: Damia Bouic.)
AA

THE SAND DUNES OF MARS

Deep canyons and precipitous mountain slopes might be at the bottom of the list of potential landing sites compiled by the director of a lander space mission, but flat areas of sand could be almost as bad, with the lander likely to sink into the sand and keel over. Or sand could blow into mechanisms and get them stuck. It is impossible to avoid sand on the surface of Mars (Fig. 6.27), and rovers have to be able to cope with some. They have large wheels, spiked for extra grip. There are some regions of extensive sand dunes, which rovers generally try to avoid, although sometimes a sand dune is less of a risk than traversing a rocky and dangerous terrain that lies between a rover and its objective (Fig. 6.28).

Early in 2014, Curiosity faced a dangerous and rocky terrain that lay between it and its objective, Mt. Sharp in the center of Gale Crater on Mars. The controllers took a calculated risk to detour the rover through a favorably positioned pass called Dingo Gap. Curiosity was directed to roll across a sand dune 1-m high to get through. Her short trip was successful. The rover did not bog down.

The danger that Curiosity avoided is well illustrated by the case of the Opportunity rover carried to Mars in 2004. The lander set down on a plain that was mostly rocky, but the rover was able to explore and thus stray into difficulty. In April 2005, the rover became stuck in the fine sand of a small drift (Fig. 6.29), with several of her six wheels buried. Knowing from the experience of driving a car off-road how easy it is in a case like this to make a bad situation worse, the mission controllers experimented for over a month to find the best way to unstick the vehicle. This was no easy task, since sand is held by the weak Martian gravity less strongly to the ground on Mars than on Earth, and, unless the sand has consolidated with a crust, the dusty sand is more like flour than is typical on Earth. However, Opportunity was maneuvered out of the dune inch by

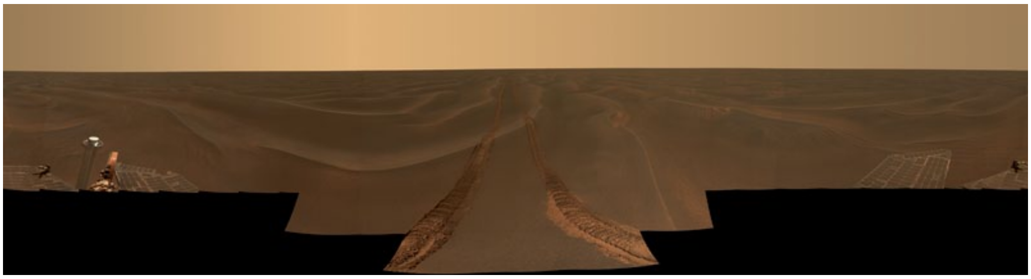


Fig. 6.29 Rub al Khali on Mars. The name is Arabic for "Empty Quarter," and refers originally to a barren region in Saudi Arabia. On Mars it is an area of drifting sand in Meridiani Planum, a plateau almost exactly on Mars' equator. The Opportunity rover was bogged down in sand here for 6 weeks, and had plenty of time to acquire the nearly 100 individual images, each of five colors, that have been stitched into this 360° panorama. At the center are the rover's tracks, showing the path that she took to get here, the ruts getting deeper, up to 15 cm deep (6 in.), as they near the rover's present position. (Opportunity: NASA/JPL/Cornell.) **AA**

inch. Controllers gave the place where Opportunity got stuck and caused them such a long time of anguish the name "Purgatory Dune."

Sand accumulates in the bottom of craters, blown there by sandstorms that can sometimes rage all across the planet. The sand forms patterns of dunes (Fig. 6.30), created by the turbulence of the wind blowing across the crater opening, as in the Endurance Crater. Grains of sand and small particles of different sizes and compositions (Fig. 6.30) are mobilized differently, so they end up in different zones on the dunes, as revealed by their subtle gradations of color. As in impressionist or expressionist landscapes (Fig. A.5), the color differences can be emphasized (Fig. 6.33), and make a surreal but beautiful scientific landscape.

The strong color differences in the Endurance Crater are due to "blueberries" (Figs. 6.31, 6.32). Opportunity first saw them in the Eagle Crater where it landed. These little spheres a few millimeters in diam-

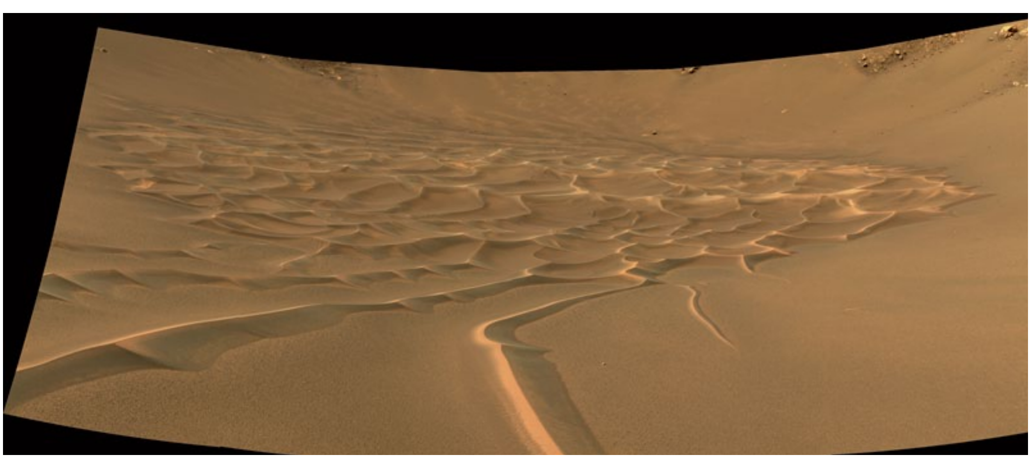


Fig. 6.30 Sand dunes in Mars' Endurance Crater. Creeping down the walls of the Endurance Crater, Opportunity closed in on the sand dunes at the crater bottom. Sinuous tendrils of sand 1 m high extend from the main dune field in the foreground of the landscape. (Opportunity: NASA/JPL/Cornell and the Pancam team, J.R. Skok, Jim Bell.) **AA**

Fig. 6.31 Blueberries. "Blueberries" are abundant hematite spherules about 5 mm in diameter (1/5 in.) that litter the Martian surface in the area of the Opportunity rover like rabbit droppings. This is a true color image. (Opportunity: NASA/JPL/Cornell.) **AA**

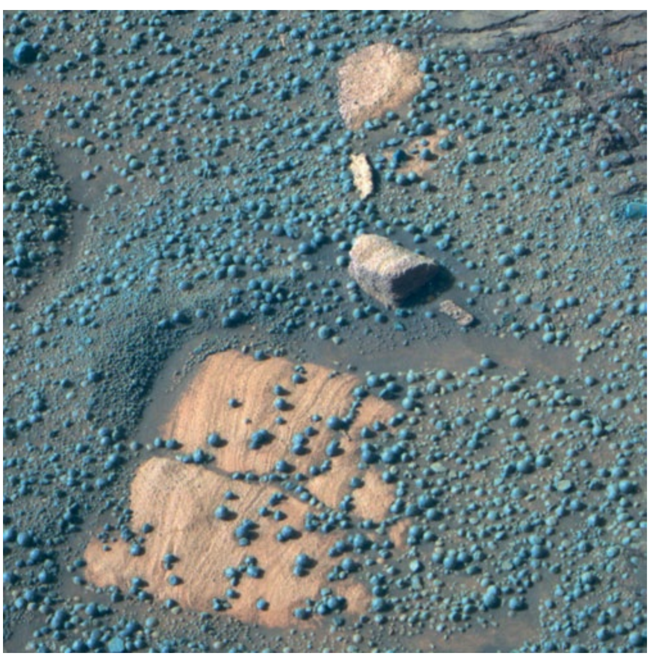


Fig. 6.32 Blueberries enhanced. In this picture the colors are exaggerated, revealing how the blueberries got their name. (Opportunity: NASA/JPL/Cornell.) **A**

eter are made of coarse hematite mineral that was less red than the surrounding rock. The red color of Mars is due to a fine-grained red kind of hematite. The less red kind of hematite is formed by crystallization of the mineral in water. "Less red"—that means "more blue," which was the color that the little mineral spheres showed on false color pictures. "Blueberries" was an apt name that stuck. The blueberries and the layered rock were both formed by the evaporation of salty water in a lake. The impact of a meteorite had broken through the rock layers and exposed the minerals within, like blueberries in a muffin. As the rock weathered, the blueberries popped out, one by one, millions of them altogether.

Frost on sand dunes (Fig. 6.34) stabilizes the sand on the surface of Mars, but in the heat of the Sun, at noon and in the summer, the surface grains of the sand dunes become looser. If the grains are disturbed, dust of a different color is revealed below. This can happen as the wind blows over the ridges of the sand dunes, creating whirlwinds that track around the undulating terrain, drawing patterns (Fig. 6.35) like an action painter, an unskilled graffiti artist with a spray can or a bronze-age man exposing chalk below the turf of a hillside to create a chalk figure. (Fig. 6.36)

DUST-DEVILS ROAM THE LANDSCAPE

Mars is a planet of winds and dust storms. When *Mariner 9* arrived at Mars in 1971, mission controllers were aghast at the lack of detail in the images that it returned to Earth—was there something wrong with their beloved spacecraft? No, a dust storm was raging across the entire planet, concealing the planet's surface.

The wind on Mars at ground level gusts at speeds that at the maximum might reach 200 km/h (120 mph). This is equivalent to

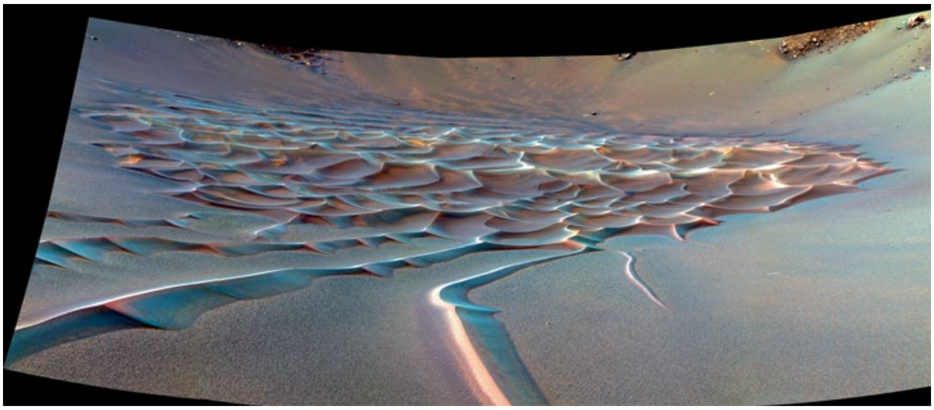


Fig. 6.33 Sand dunes in Mars' Endurance Crater. In an image in which the colors have been exaggerated, the flat crater floor between the dunes is bluer than their flanks. This is due to hematite spherules ("blueberries") that have collected there. (Opportunity: NASA/JPL/Cornell and the Pancam team, J.R. Skok, Jim Bell.) **A**

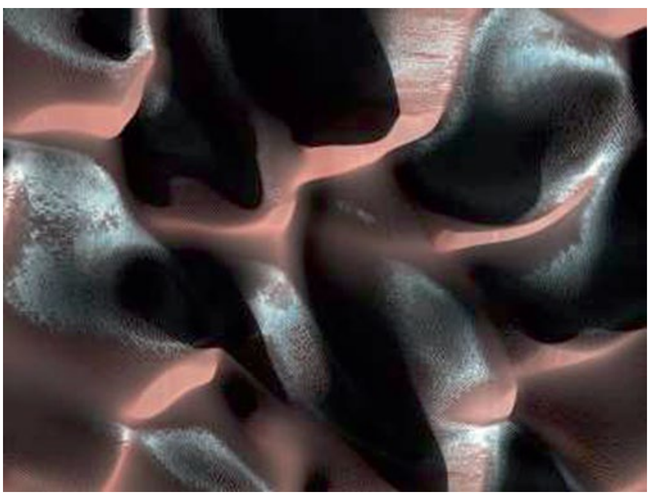


Fig. 6.34 Sand dunes in a crater in the southern highlands of Mars. Here the Sun was illuminating the area from just 5° above the horizon, sunlight striking the dune crests and raking across the smaller sand ridges that run along their steep sides. The bluish-white areas are frost that is settling here as the southern hemisphere approaches winter. Colors are intensified. (Mars Reconnaissance Orbiter HiRISE camera: NASA/JPL/University of Arizona.) **A**

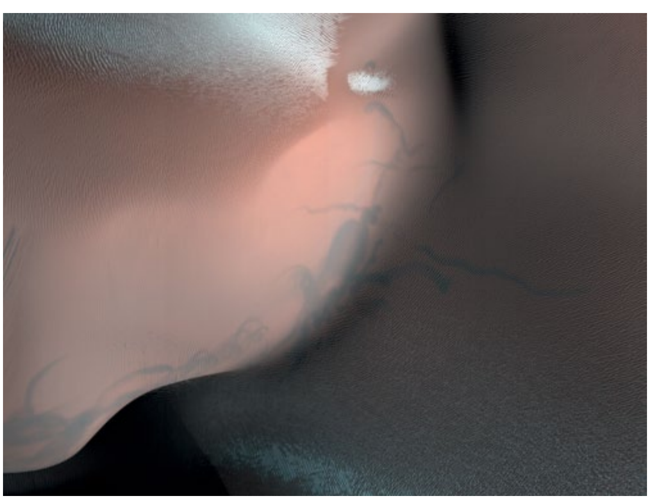


Fig. 6.35 Sand dunes, ripples, ice and dust-devils. At the top and bottom of this image are small ripples of sand on Mars, their south-facing slopes highlighted with frost. (The scene is in the southern hemisphere of Mars so south slopes face away from the Sun.) A large sand dune cuts diagonally across the image. Mysterious dark shapes lie along the uppermost ridge of the sand dune, where the frost has disappeared and loosened its grip on the sand particles. One of the shapes is that of a huge salamander. These graffiti were made by dust-devils, meandering along and down the ridge. (Mars Reconnaissance Orbiter HiRISE camera: NASA/JPL/University of Arizona.) **A**

Fig. 6.36 The Uffington White Horse. Located in Oxfordshire the White Horse is a stylized figure, outlined in trenches cut into the grass of the hillside to expose chalk below, and augmented by filling the trenches with chalk chips. It was created by people of the Belgae tribe, dating to before the Roman colonization of Britain. (U. S. Geological Survey: Wikimedi Commons: en.wikipedia.org/wiki/Uffington_White_Horse#mediaviewer/File:Uffington-White-Horse-sat.jpg.)

the wind speeds in a Category 3 hurricane, but wind speeds are typically much less. Because the atmosphere is so thin the wind force is much less than might be imagined from the high speeds, but Martian winds pick up the loose dust of the landscape in choking clouds. Making images of the dark scenery during a large-scale dust storm is difficult and unrewarding (Fig. 6.37).

The dust that has been blown up into the Martian atmosphere settles over the entire planet when the wind drops. Mars' polar icecaps are made of alternate layers of ice and dust, showing the annual cycle of the Martian weather. The dust settles on the rovers and landers that are sent to Mars. Gradually the effectiveness of their solar panels, which convert sunlight into electricity, decreases day by day as the dust builds up. Then, sporadically and unpredictably, there is a "dust clearing event" that blows the dust away. This is either a particularly strong gust of wind, or the nearby passage of a "dust-devil."

"Dust-devils" are erratic, small whirlwinds. In Australia they are called "willy-willies."

A dust-devil is formed by the action of the Sun. When the Sun warms the desert ground, it generates a column of rising air. The column gets a spin if it rises up through winds blowing in different directions at different altitudes. The column of rising, rotating air can draw up dust or sand (Figs. 6.38, 6.39). A dust-devil moves erratically over the ground, and lasts typically (on Mars) for about 20 min before it dissipates and dies away.

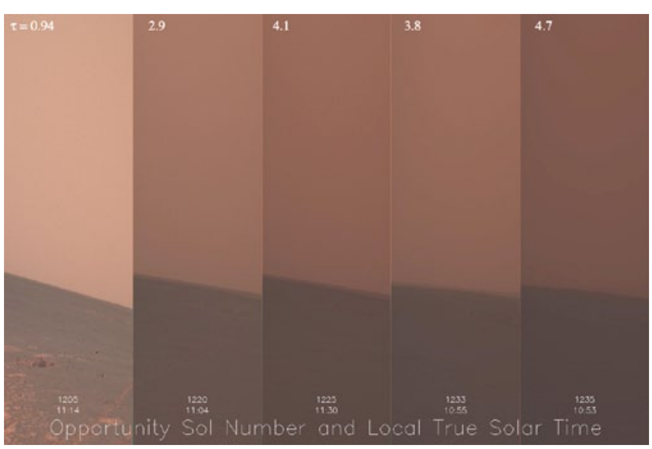


Fig. 6.37 Dust storm on Mars. Perched on the edge of the Victoria Crater, Opportunity sat out a dust storm for 30 Martian days ("sols") in June and August 2007. The image is a time-lapse sequence of images of the horizon, each image compressed horizontally. The numbers across the top of the image are a measurement of atmospheric opacity, the optical depth, symbolized by the Greek letter tau. The lower the number, the clearer the sky. A tau of 4.7 indicates that only 1.5 % of the sunlight is getting through the dust, which explains why there is little to see in the right-hand panel! This severe dust storm lasted so long that Opportunity could not generate much electricity from her solar panels and came close to depleting her batteries entirely; if that had happened it might not have been possible to reactivate the rover. (Opportunity rover: NASA/JPL-Caltech/Cornell.) **AA**

Some African people believe that dust-devils are living spirits. When this author was walking in the Karoo Desert at the South African Astronomical Observatory, a dust-devil overtook me. It raced past me at a distance of 10 m (10 yards), speeding like a sprinting animal. I felt little or no wind myself—the column of whirling, dusty air was contained—but I heard the sibilant hiss of the air and whirling sand, like the sound of a snake or a panting animal, and I saw the dust-devil leap, goat-like, from rock to hillock. It zigzagged in its course like an antelope, and it would have left an erratic track like those tracks in Fig. 6.35, except that the ground was rocky and bare. After its passage there were no signs that it had been there; it disappeared like a ghost. It is easy to understand why dust-devils could be thought to be frightening spirits. Of course they are not, but the reality is scary enough. The whirling wind is very powerful and can throw anything loose off to one side. There have been about 100 aircraft accidents attributed to dust-devils, of which four were fatalities, and an astronomer, David Thackeray, who had been working at the South African Astronomical Observatory in the Karoo, was killed in 1978 when a dust-devil overturned his vehicle as he left the site (Fig. 6.40).

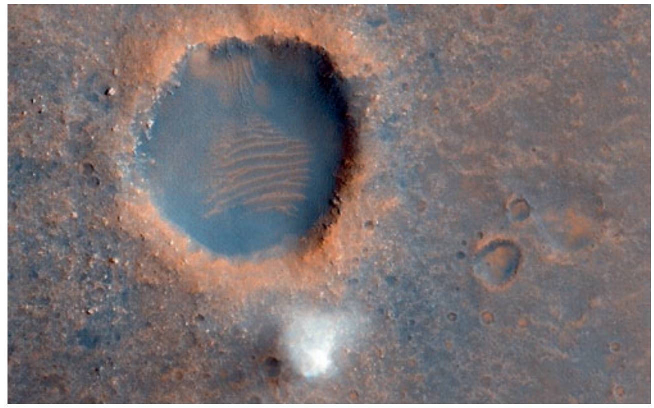


Fig. 6.38 Dust-devil near Gusev Crater. Seen from overhead a dust-devil is the white cloud of dust near the bottom center of this picture, and passing close by to the crater Gusev on Mars. The picture also shows NASA's Mars exploration rover, Spirit, whose solar panels are, by chance, reflecting the Sun up to the recording spacecraft. Spirit is a square of the brightest pixels in the picture, upper left, near the crater rim, casting a shadow to the left. (Mars Reconnaissance Orbiter HiRISE camera: NASA/JPL/University of Arizona.) **A**

Fig. 6.39 A spinning dust-devil. The dust-devil in Gusev Crater is imaged by the navigation camera of the Spirit rover in 2005. It is about 1 km (just under a mile) away and raced over 1.6 km (2 miles) in 10 min, at roughly half the speed of a 1-mile sprinter. (Spirit: NASA/JPL/Texas A&M.) **AA**

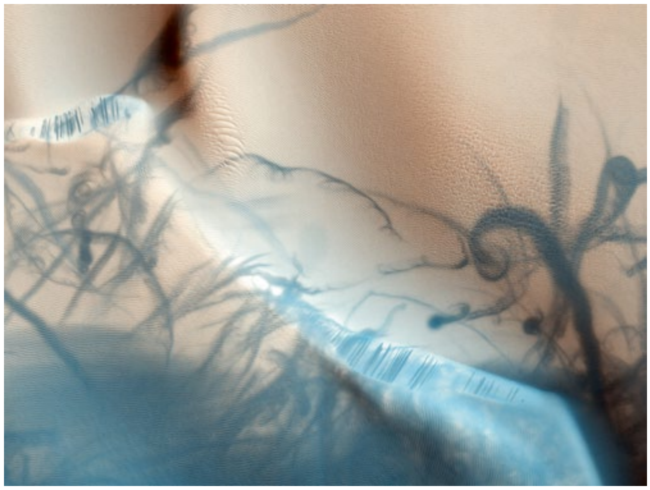


Fig. 6.40 Nature's action painting. As dust-devils criss-cross the Martian desert they scour up loose dust, cleaning the surface, leaving tracks. They provoke little, straight, parallel landslides of surface dust down in some of the steeper dune slopes. A dusty surface tends to be bright and to reflect sunlight, so dust-devils reveal the darker surface below. Driven by the erratic winds that flow turbulently around the uneven terrain the dust-devils scribble lines across the sand dunes, patterning the surface with arabesques, which gradually fade as the surface becomes dust-covered again. (Mars Reconnaissance Orbiter HiRISE camera: NASA/JPL/University of Arizona.) **A**

LANDSCAPES SCULPTED BY WIND

The second robotic explorer that was still active on Mars in 2014 is Curiosity. She is officially part of NASA's Mars Science Laboratory (MSL) mission and landed in Gale Crater on Mars on August 6, 2012. A veritable mobile scientific laboratory, Curiosity is the size of an SUV car, a larger and more developed version of Opportunity. She was landed on Mars in what appeared to be a hare-brained scheme, but which was in fact the least risky of all the options studied.

Curiosity arrived at the top of the atmosphere of Mars in a capsule traveling at 20,000 km/h (12,000 mph) and over the next few minutes was decelerated to touch down at no more than 4 km/h (3 mph). Slowed at first by thrusters and the friction of Martian air with a heat shield, the capsule deployed its parachute at a speed of 1400 km/h (870 mph) and at an altitude of 11 km (6 miles). Half a minute later the covers of the capsule were blown off by pyrotechnic explosions so that the descent radar could see the ground to control the rover's speed over the final minutes. At an altitude of 1.5 km (1 mile) the parachute was cut away and the rover dangled underneath a "sky crane," which used thrusters to slow its descent further. At 20 m (60 ft) above the ground, the sky crane came to a stop and hovered, lowering the rover on three ropes to the surface. Once the rover was on the ground, the ropes were cut and the crane was let loose to crash at some distance from the landing site.

Curiosity's landing site was in Gale Crater. This crater was made on Mars a long time ago and was apparently then filled up by loose, eroded material. This material was then eroded again by the wind, exposing a cliff face of layered deposits (Fig. 6.41). These deposits appear to have had a number of different formation histories. Some layers were deposited by the wind, some may have been deposited by water in an earlier period of Mars geological history, or by water melted by the impact from subsurface ice, and some may be igneous. One particular layer uncovered in the crater and near to Curiosity's exact landing site was a layer of water-rounded pebbles that had been deposited on the floor of a streambed, or the flow of water in a lake. This site for Curiosity's exploration was chosen in the expectation that it would show these kinds of geological features, and Curiosity's suite of scientific equipment was constructed to investigate the mineralogy and chemical composition of these rocks. The expectation is that this will reveal how the climate of Mars has evolved over its history. Mars' atmosphere is much less dense than Earth's. The air pressure on Mars is just 0.75 % of Earth's surface pressure, the same pressure at ground level on Mars as at an altitude of about 35 km (22 miles) above

Fig. 6.41 Chapters from history. The layered geological history of Mars is laid bare in this image from the Curiosity rover. The complex landscape shows the base of Mt. Sharp, the central peak of Gale Crater, the rover's eventual science destination. The peak rises 5500 m (18,000 ft) above the crater floor. The color of the scene shows Mars as it would be under the lighting conditions we have on Earth, in order to render the minerals in the rocks more recognizable to the geologists in the science team. (Curiosity Rover: NASA/JPL-Caltech/Malin Space Science Systems.) **AAA**

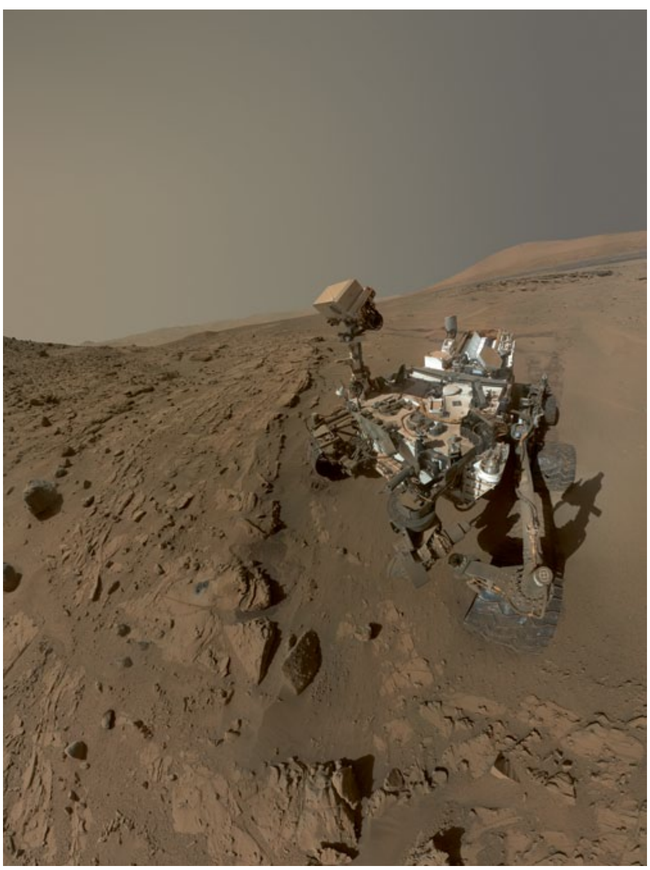


Fig. 6.42 Self-portrait of a landscape, by Curiosity. Curiosity obtained this self-portrait as she stood near a sandstone rock ledge known as "Windjana," the site in Gale Crater where it drilled into Martian rock to get samples to analyze (the sample collection hole center on the lower left of the rover is 1.6 cm in diameter). Sunlight diffuses weakly through the dust in the Martian sky. The panorama is a mosaic of images made by a camera on Curiosity's extensible robotic arm, whose image has been bypassed in the choice of images for mosaicking so that it appears that the photo was made by an independent photographer. (Curiosity: NASA, JPL-Caltech, MSSS.) **AAA**

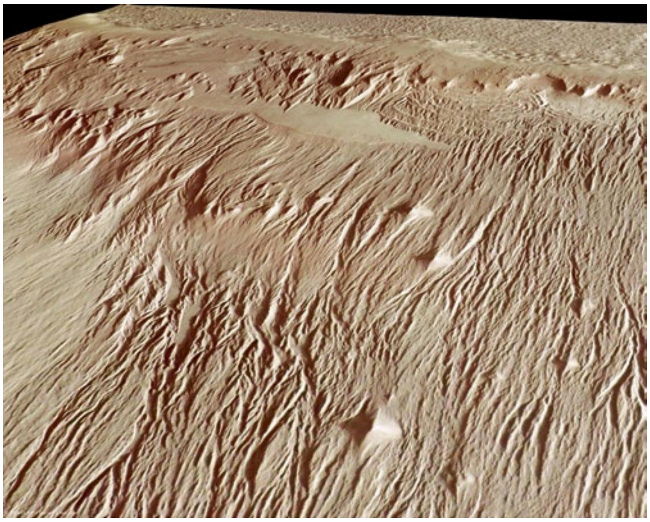


Fig. 6.43 Features known as Yardangs. A mountain range west of the Tharsis Province, Eumenides Dorsum is part of the Medusae-Fossae region and is made up predominantly of volcanic ash, with some areas of harder lava. The softer ash area is covered with linear ridges that have channels between. They are several kilometers long and lie in the same direction as the predominant wind. They are the wind-eroded "yardangs." The smooth areas in the image are harder rock, perhaps solidified volcanic magma. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **A**

ground on Earth. Nevertheless, the winds on Mars can be very strong and play a major role in shaping the Red Planet's landscape (Fig. 6.42).

Martian winds also erode soft sedimentary rocks on Mars into yardangs. The word is originally Turkish. Yardangs are ridge-like hills in soft, sedimentary rock, like volcanic ash, that have been eroded by the wind (Figs. 6.43, 6.44). The wind picks up loose surface material such as sand grains and sand-blasts the sedimentary rock, enlarging cracks or gaps and blowing the excavated material away.

LANDSCAPES SCULPTED BY WATER

In 1997, NASA landed Mars Pathfinder in *Ares Vallis* (Mars Valley), near the border with *Chryse Planita* (where the lander from *Viking 1* came down), and deployed a small rover called Sojourner to study, close up, some of the rocks nearby. The landing site (Fig. 6.45) had been chosen from photos made by the Viking orbiters. It was picked because it was on an ancient floodplain. It was named the Carl Sagan Memorial Station in honor of the planetologist and popularizer of astronomy. The lander was slowed in its descent by parachutes and retrorockets and was dropped from a height of a few hundred feet, bouncing on airbags onto the Martian surface. The airbags were deflated and separated from the lander. The lander opened up, and the Sojourner rover descended down a ramp to analyze nearby rocks. The specific rocks for study were chosen from pictures sent back to Earth by cameras on board the lander.

Fig. 6.44 Yardangs from above. A close-up of yardangs on the floor of an old, large crater reveals that the crater has been partially filled by windblown material in sedimentary layers, which can be seen cut through stepwise on the steep slopes of the ridges. There are patches of dark sand in the low areas between the ridges and on the ridge slopes. Colors are exaggerated. (Mars Reconnaissance Orbiter HiRISE camera: NASA/JPL/University of Arizona.) **A**

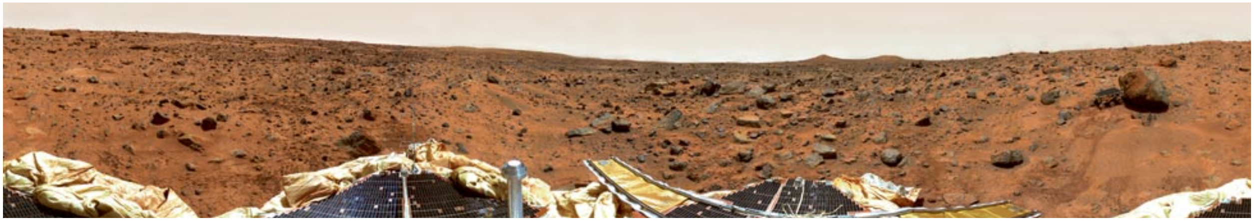


Fig. 6.45 The "Presidential Panorama." The landing site for Mars Pathfinder is overlooked by the Twin Peaks, on the horizon, right of center. A little rover, called Sojourner, has left its wheel tracks in the sand after she rolled down the ramp from the lander, and is carrying out measurements on the large rock, Yogi, to the right. Unlike the rocks at the Viking 2 lander site, Yogi has lost the sharp edges to its fractured faces. Above a number of partly buried white rocks and protruding above the horizon to the left is a slab-like rock with noticeably rounded corners. Rocks strewn in the shallow depression to the right of center show different colors and are made of different minerals. This landscape is a dry floodplain, and different kinds of rocks have been tumbled in water to this location. The colors are a good approximation to what a human would see here. (Mars Pathfinder: NASA.) **AA**

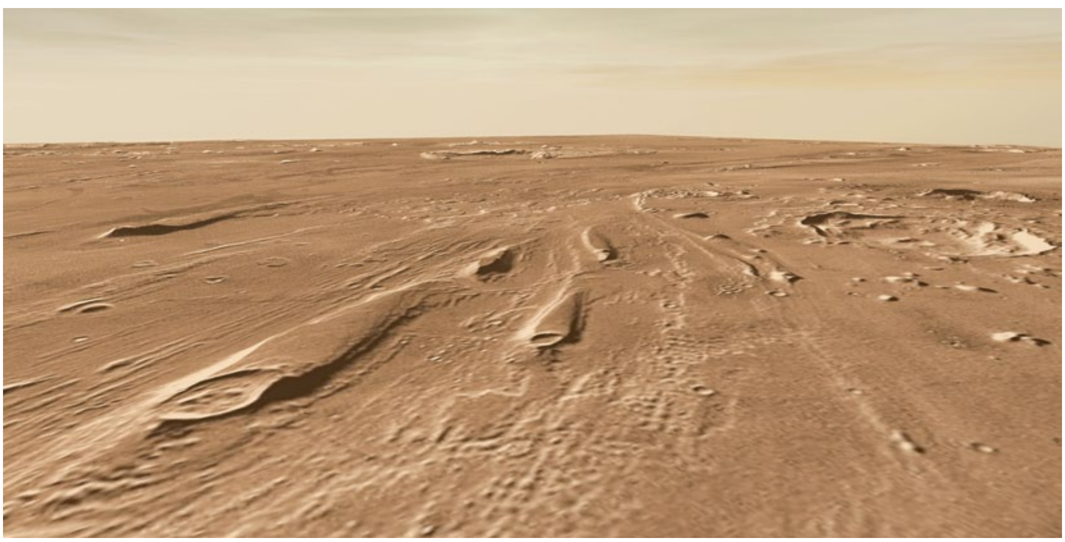


Fig. 6.46 Teardrop mesas. In Ares Vallis the mesas are 200 m (650 ft) high and extend like yachting pennants behind impact craters, where the raised rocky rims diverted the floods that swept this area. The crater ramparts protected the downstream ground from erosion and created downstream turbulence where sediment was deposited in the tails of the pennants. Long, low ridges in the flat bed of the valley (left of the picture), typically a few tens of meters high, were produced by the scouring floodwaters that eroded the channel. The wrinkly terrain in the foreground resembles giant sand dunes, created by turbulent flow of the deep, fast-flowing floodwater. This perspective monochrome image has no height exaggeration. (Mars Odyssey orbiter, MOLA and THEMIS: NASA/JPL/Arizona State University, R. Luk). **A**

Ares Vallis is a valley on Mars that has been carved by flowing water, and some of the rocks on this plain have been brought there from elsewhere by floods (Figs. 6.46, 6.47), tumbled with the flow. For this reason, the rocks have lost their sharp edges (Fig. 6.48). Some of them are in fact rather rounded. The rocks also show much more variety of color than the rocks in the *Viking 2* lander site, because they are different types of minerals from distant rock deposits of various sorts gathered together in the rush of water, as Sojourner confirmed.

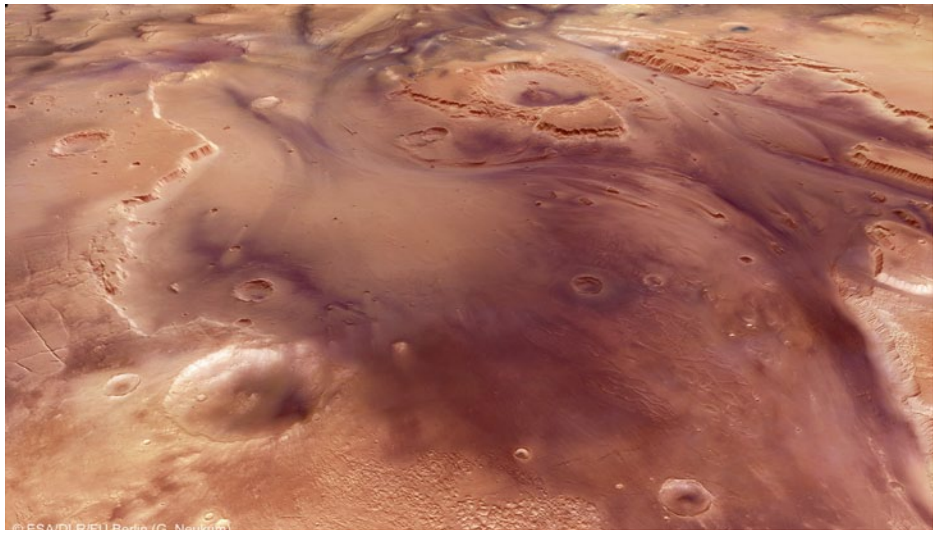


Fig. 6.47 Floods on Mars. Kasei Valles is one of the largest outflow systems on Mars and was formed by several gigantic flood events. This picture shows a perspective view of an area about 1000 km in extent, and shows volcanic and glacial deposits that have been sculpted by flows of abundant water, surging floods that have created channels, terraces and teardrop-shaped islands. The name, Kasei, of this valley is the Japanese name for the planet Mars. The High-Resolution Stereo Camera on ESA's Mars Express collected the data for this image. (ESA/DLR/FU Berlin, G. Neukum.) **C**

Two hills known as the "Twin Peaks," a wry reference to the TV series, lie about 1 km (0.5 mile) away from the Pathfinder landing site, on the horizon (Fig. 6.48). They are small hills about 35 m (100 ft) high and have soft contours. Their sides would have been eroded in the floods that washed across this region of Mars several billion years ago.

What caused this flooding? One explanation is that water drained from the south pole of Mars into a lake in the Argyre Basin, a now dry large impact crater. The flow could move through a valley called *Uzboi Vallis* into a channel that links several smaller craters and downstream into *Chryse Planitia* and a presumed northern ocean. The flow might have been sporadic; there might have been major blockages by ice dams. The collapse of one of these might have caused the catastrophic surge of water

Fig. 6.48 Flood debris. The Twin Peaks, on the horizon about 1 km (0.5 mile) from Mars Pathfinder, were washed by the same flood that tumbled the corners off that spherical boulder in the foreground right corner. The scene includes ridges strewn with boulders and hummocks of rocky flood debris, left behind as the momentum of the flowing water lessened when the flood subsided. (Pathfinder: NASA.)
AAA

that scoured the *Viking 1* lander and Mars Pathfinder landing sites (Fig. 6.49).

Since the atmospheric pressure on Mars is so low, liquid water cannot now persist on Mars. Water is either gaseous or solid ice. Evidently at one time, in the first billion years of Mars' existence, the atmosphere was denser, and Mars was a planet with lakes, seas and rivers. A catastrophic climate change altered all that. What happened was that the iron core of Mars solidified, greatly reducing the magnetic field of the planet, almost to zero. (Mars' iron core is smaller than that of Earth and cooled more rapidly.) As the magnetic field weakened, solar particles were then able to break through and scoured off the Martian atmosphere, reducing its density and pressure down to current values. Mars dried out, leaving evidence in its landscape of its once benign climate in the past.

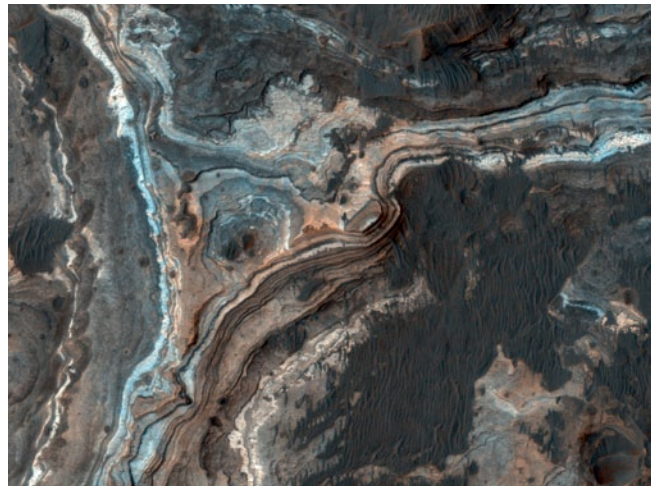


Fig. 6.49 Canyon system. Ladon Vallis, approximately 600 km (370 miles) long, is part of the drainage system that connects Argyre Basin to the Ares Vallis. It forms a canyon system that cuts through outcrops of layered light-colored deposits that contrast with the blacker material that covers the canyon floor. The light-colored layers may be sediments that have built up over time as water flowed from the Argyre Basin into the Ladon Vallis area and stagnated. Subsequently, major floods that surged out of Argyre Basin eroded the canyon and exposed the sedimentary layers, much as the Colorado River has cut the Grand Canyon. (Mars Reconnaissance Orbiter HiRISE camera: NASA/JPL/University of Arizona.) **AAA**

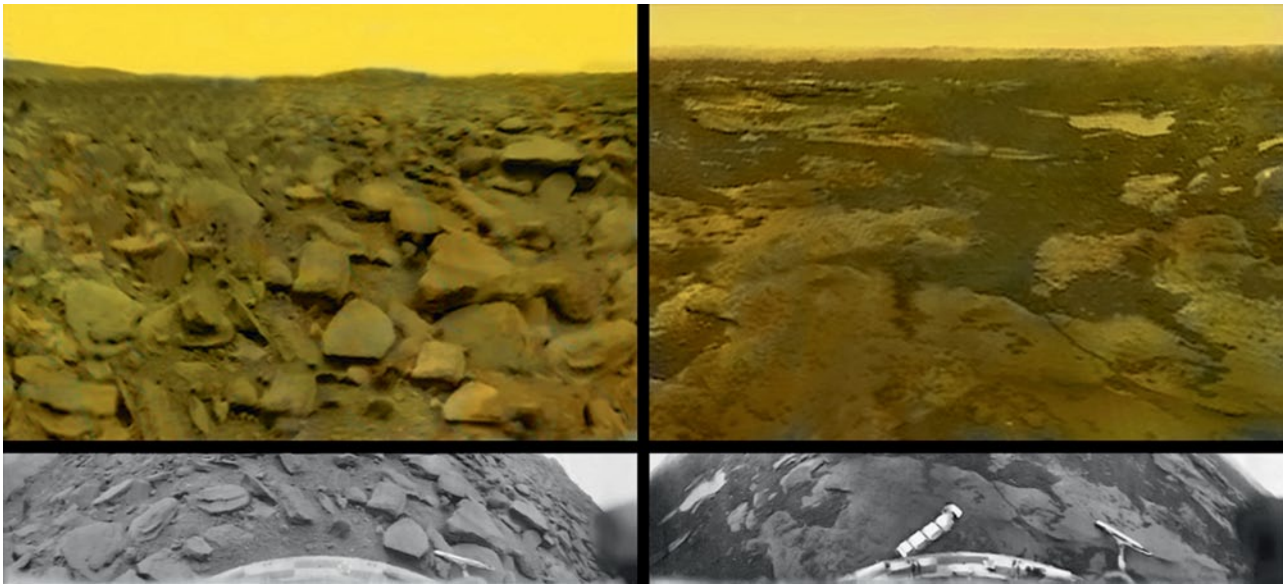


Fig. 7.1 Robotic feet on Venus. The landing sites of Venera 9 (left) and Venera 10 (right). At the base of the set of pictures are images made by the cameras of the landers as they looked down at the feet of the modules and covers that have been sprung off their instruments and fallen onto the rock below. The rock consists of black layers of volcanic lava that have split into scaly plates or fractured into rocks. Depressions are filled with a black soil. Venera 9 landed near the slope of a hillside littered with large rocks. Around Venera 10 is a flatter plain, with a cloudy ridge in the distance. The pictures are composites of separate images made at different times, which is why the shadows in different parts of the picture of the left are inconsistent. The black and white images have been artificially colored but with a hue based on previous scientific data. (Venera 9 and 10: Data from Russian Academy of Sciences, images© Ted Stryk 2007.) **AA**

Chapter 7

The Volcanic Scenery of Venus and Io

Venus is the non-identical twin of Earth, the same size but very different in appearance. To the naked eye Venus is very bright. In a telescope Venus shows as a white globe. It is covered in white cloud. Any markings of the disc of Venus that are visible in an Earth-bound telescope are low-contrast gradations of the whiteness, and perhaps slight irregularities in the boundary between the Sun-lit and dark sides of the planet, which represent different heights of the cloud.

Not everyone had seen Venus as a featureless globe. In 1896, Percival Lowell reported to the Boston Scientific Society that he had seen markings on the surface of Venus beneath its thin atmosphere. "The markings," he said, "proved to be surprisingly distinct…. A large number of them, but by no means all, radiate like spokes from a certain center. In spite of all this curious system, there is nothing in them of the artificiality observable in the lines of Mars. They have the look of being purely natural, not artificial…. The markings, which are of a straw-colored grey, bear the look of being ground or rock, and it is presumable from this that we see simply barren rock or sand, weathered by eons of exposure to the Sun." The Irish-British historian of science, Agnes Clerke (1842–1907), writing in 1902, accepted the reality of these makings and reported them in terms of the "mountainous elevations and permanent markings" in the landscape of Venus. Lowell was so convinced of their reality that he perceived the same features coming into view repeatedly as the planet rotated, and deduced that the Venusian "day" was 225 days long. No other astronomer at the time or since has seen anything like them, and they are spurious. Lowell's eyes deceived him. Clouds on Venus totally obscure the surface below.

Since the surface of Venus was invisible until the advent of new technology, the imagined landscapes of Venus covered a wide range, from a rocky, mountainous landscape like the Moon to a flat ocean of water, of oil or of water covered by a layer of oil, as inferred by astronomers Fred Whipple (1906–2004) and Donald Menzel (1901–1976), Fred Hoyle (1915–2001) and Carl Sagan (1934–1996), respectively, based on theories about the composition of the clouds. There was no evidence either way from optical astronomy, except various chemical theories. It was not until the advent of powerful radars that it was possible to penetrate the cloud layer and see radio waves reflected from the surface that the nature of the surface began to emerge from the gloom. In 1961–1965 the first radar echoes showed that the surface was rocky and, by and large, smooth—a surface of flat plates of undulating rock (or, some people thought, of dust). Radar can distinguish rough and smooth areas and, as the resolution of the radar images improved, it became possible to distinguish some mountainous areas, with peaks up to 3 km high.

Another new technology was applied to the problem. Images recorded by telescopes on Earth by detectors sensitive to infrared radiation

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showed hot spots—landscapes that were higher than normal and were responding to atmospheric conditions that had been changed by the extra altitude, or areas of more active volcanism than usual.

But the best images of the Venusian landscapes were obtained by the technology created in era of the Space Age. Spacecraft revealed the modern landscapes of Venus. Landers took cameras to the surface and, settling by design onto the less mountainous areas of the planet, pictured its distant rolling, rocky hills. Orbiting spacecraft carried radar equipment up close for a more detailed view of Venusian volcanoes and lava flows than from Earth, which is always at least 40 million km away.

The first spacecraft to land on Venus and return images of the surface was the Soviet *Venera 9* in 1975. Several further spacecraft in the same series recorded landscapes in a handful of locations. The Magellan spacecraft surveyed the entire surface of Venus by radar, orbiting the planet from August 1990 until October 1994, when it was deorbited into the Venusian atmosphere. These Space Age discoveries revealed black, rocky plains and lava-strewn volcanoes, the Venusian bad-lands that lay under the pure, white cloud.

THE BLACK, ROCKY PLAINS OF VENUS

Mars resembles Earth much more than Venus does. If Venus is Earth's twin, Mars is our small brother. Both planets have atmospheres, and their landscapes show the effect of age and weather. Mars has seasons like Earth. It has two icy polar caps that grow and fade in alternation, north and south, as the winter advances and recedes in the respective hemispheres. It's generally dry, desert-like conditions produce landscapes that are familiar, if not at first hand then by armchair travel.

Venus has one season—super-summer. Its surface is entirely dry, thanks to a runaway greenhouse effect produced by its dense carbon-dioxide atmosphere that brought its surface to a temperature of 450 °C (840° F). There are as many volcanoes on Venus as there are on Earth, and their effects dominate the entire landscape. As on Mars, major global changes have happened. About 500 million years ago the entire planet was resurfaced by a global outbreak of volcanic activity, when the whole planet resembled Hades.

Martian scenery is littered with broken, lumpy, red boulders of all sizes flung from the craters made by meteors that have impacted nearby onto old layers of rock. The boulders are silted with dust and sand. The landscape of Venus is very different. Its surface is covered, typically, with scaly beds of rocks from the lava flows that have covered the entire planet. The hollows and crevices of the bedrock are filled with a black soil, the product of surface rock that has been weathered by the severe atmospheric conditions of Venus—dense, hot winds and acid "rain" dripping through the sulfur-rich atmosphere. The rocks are dense and dark. They

Fig. 7.2 The black volcanic plains of Venus. The Venera 13 (left) and Venera 14 landing sites. The landscape has black layers of bedrock that flake off like scales, presumably built up from successive lava flows. They have weathered into smaller gritty stones that have collected in depressions. There is an abrupt drop-off in the middle distance of the Venera 13 landing site, with a flat-topped plateau beyond (left), and other hills in the background (right). The Venera 14 landing site is flatter, but there are low hills in the distance. Distant hills on Venus are made grayer by the atmosphere, as in Fig. 5.13. (Venera 13 and 14: Data from Russian Academy of Sciences, images Copyright © 2003, 2004 Don P. Mitchell. All rights reserved.) **AA**

are definitely basalts, but it is not clear what specific kinds—perhaps a basalt mineral known as gabbro. You've seen samples of this rock. It is incorrectly called "black granite" when it is used for kitchen counters and for headstones in a cemetery.

Because the dense, opaque atmosphere of Venus completely obscures what lies below, so our detailed knowledge of its surface comes from radar imaging that penetrates the atmosphere and from the Russian Venera series of spacecraft sent to land on the planet in the 1970s and 1980s. *Venera 13* and *14* were the final landers in the series, and in 1982 they sent back the first and so far only color pictures of the surface. The four Venera spacecraft that landed to take pictures landed on the plains of Venus, which cover more than three-quarters of the planet's surface. They were formed by lava flooding out of volcanoes, fissures and volcanic vents. There are channels of frozen lava that meander for hundreds of kilometers. Presumably the lava was originally very liquid, and able to flow in rivers almost like water (of which there is none on the surface of the planet). There are not many meteor craters, so the surface is relatively young. Something major happened to Venus about 500 million years ago, and the entire planet was resurfaced by a global outbreak of volcanic activity.

The Venera images show a bleak landscape, with broken plates of bedrock (Fig. 7.1). The *Venera 13* site was on a plateau with a sudden drop off in the middle distance and hills beyond (Fig. 7.2). The landscapes are foggy under a lowering orange-yellow sky. The color is the same color as the color of Earth's sky as the Sun is setting, and for the same reason. Sky color is due to the way that air molecules, whether on Earth or Venus, preferentially scatter blue light. Earth's atmosphere as seen slantwise along a long path towards the horizon mimics the effect of Venus' much denser atmosphere as seen upwards to the zenith. In addition there are effects in Venus' atmosphere due to compounds that it contains. The sky casts a sulfurous yellow light on the ground, as if the landscape was lit up with dim sodium lamps.

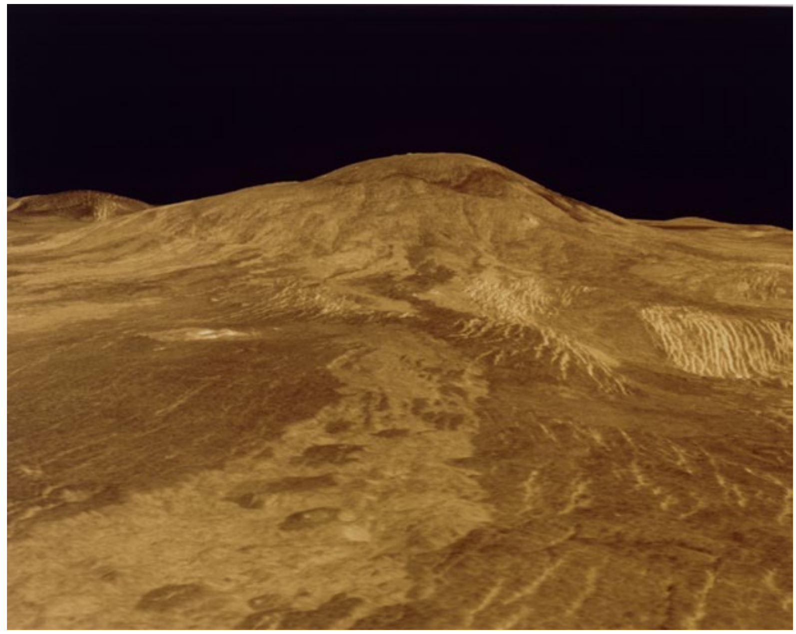

Fig. 7.3 A shield volcano on Venus. Bright and dark rivers of lava flow down from the peak of Sif Mons. The bright flows are relatively rough, and are the more recent. They lie over older, smoother and hence darker lava flows. The volcano is 2000 m (6600 ft) high. The data is constructed from radar altimetry data from the Magellan spacecraft, tinted orange to mimic the color of the sky as measured by the Venera landers. The sky is black since Venus' atmosphere is transparent to radar. In reality the sky should be a uniformly overcast with high clouds, as in the Venera images (Figs. 7.1–7.2). Likewise, the scene would be hazier than it appears here. The dense atmosphere is relatively transparent at the surface, below the base of the cloud layer, but it reduces the visibility of distant features, again as seen in the Venera images. (Magellan: NASA/JPL.) **C**

VOLCANOES ON VENUS

There are extinct volcanoes on Venus. None of them had been seen, not even suspected, until the 1970s, because the surface of Venus is hidden beneath a dense carbon dioxide atmosphere. From Earth, astronomers could see only white cloud tops, reflecting sunlight. Radio astronomers demonstrated in the 1960's and 1970's that radar could penetrate the clouds and were able to make low-resolution radar maps of the whole planet. The nature of the ground affects the reflected radar pulse, differentiating smooth sand from rocky lava, for example, so it is possible to create a radar image by pinging the planet with radar pulses and listening to what comes back. The breakthrough came in 1990–1994 when the NASA spacecraft Magellan orbited around Venus and imaged 98 % of its surface with a resolution of about 100 m (300 ft). It also carried an altimeter to measure the height of the features that the radar saw.

Radar landscapes show numerous volcanoes on Venus, in fact more than 100 of them. Like Olympus Mons on Mars they are shield volcanoes, up to hundreds of kilometers in diameter and several kilometers high (Fig. 7.3). On radar images they show bright by comparison to the plains—and they are rougher. Presumably the plains are silted with eroded dust that has been blown from the higher slopes, leaving them bare and rocky. Bright rivers of rough rock run down the volcanoes (Fig. 7.4). These are lava flows.

The volcanoes of Venus and Mars are similar to the volcanoes of Earth, lava heated from the core of the planet below fed through the planet's crust at weak spots. The core of the planet is hot and molten because of the heat that is trapped inside the planet from when it first formed and because of heat generated over time from the decay of radioactive elements in the core. Gases released during this time cause the molten rock to explode through the planet's surface.

Radioactivity is not the only way that the interior of a world can heat up and become molten. The lava that spews from the volcanoes of Io, one of the large moons of Jupiter, is heated in a completely different way. Io

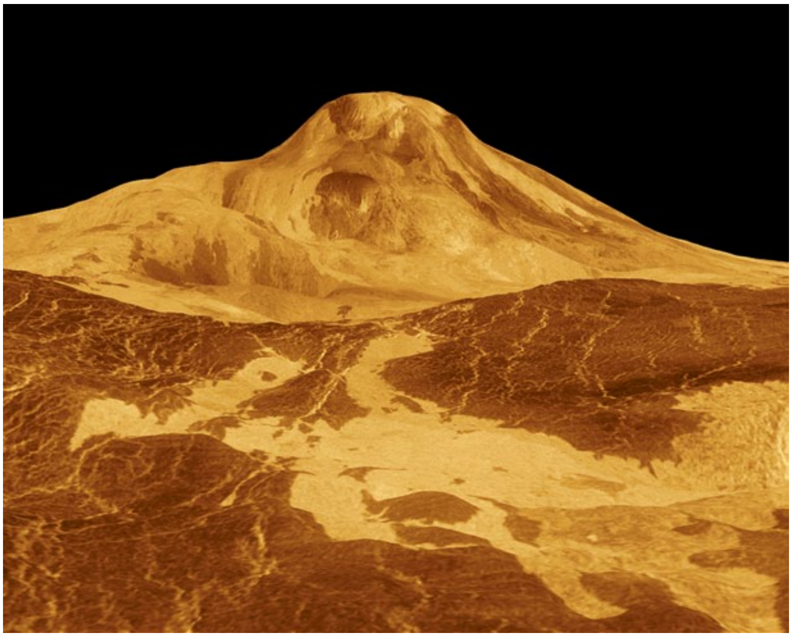

Fig. 7.4 Lava flows. Maat Mons is an 8000-m(26,000-ft) -high volcano on Venus. Lava flows extend for hundreds of kilometers from the volcano across the fractured plains in the foreground. (Magellan: NASA/JPL.) **C**

orbits close to Jupiter, and it is impacted by changes in the planet's gravity during its orbit. Jupiter effectively kneads the inner core of Io and warms it so much that it becomes molten. The entire world is a landscape of active volcanoes.

IO ERUPTS

Terrestrial volcanoes are considered "active" if they have erupted during the past 10,000 years. On Earth, there are about 1500 active volcanoes on land, and a further unknown number, about as many again, under the sea. About 600 volcanoes have erupted during recorded history. From 50 to 70 volcanoes erupt each year, and there are about 20 erupting at any given moment.

Volcanic landscapes are dramatic, with conical peaks, highly colored red, yellow and orange ash, black lava, strangely shaped rock formations, and distinctively shaped geological features. Erupting volcanic landscapes are dynamic, with glowing red fire or lava fountains, and columns of ash and steam rising up tens of kilometers into the sky. And behind the beauty is the implicit danger of mass destruction—poisonous gases, burning red-hot rock, suffocating clouds of dust and tumbling avalanches of loose rock and ash.

Like Earth, Mars and Venus are also volcanic worlds. However, neither has a volcano that is currently erupting (or at least, given the detection of methane in the atmosphere of Mars, not erupting very much). Their volcanic landscapes are drawn as large on the face of their planet as ours are, but they are static.

There is only one other world in the Solar System, beyond Earth, that has very active, very large, erupting volcanoes. It is Jupiter's moon, Io, with as many as 400 volcanoes, half of them erupting (Fig. 7.5). The largest of these is *Loki Patera,* which releases as much energy as all the volcanoes on Earth put together. It has an enormous caldera, 200 km (120 miles) in diameter, the size of Maryland or the Netherlands, filled with liquid magma.

Not all mountains on Io are volcanoes. There are steep-sided mountains formed by other tectonic processes. One of them, *Euboea Montes,* is 13,000 m (43,000 ft) high. But the actively erupting volcanoes dominate the landscape, columns of ejecta rising not just kilometers above the surface of the world but hundreds of kilometers above.

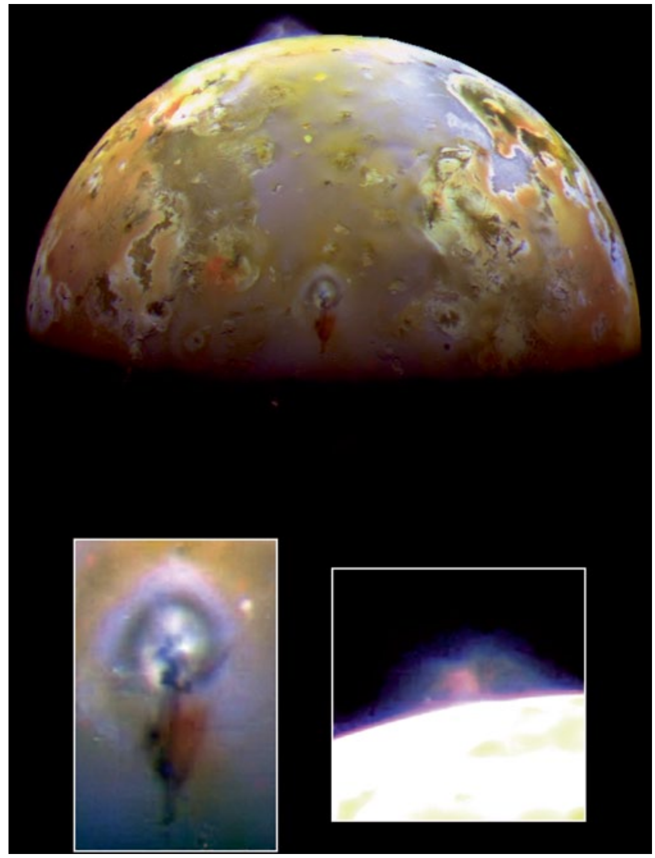

Fig. 7.5 Volcanoes and mountains on Io. Io's landscape is brightly colored with material ejected from its volcanoes. The nature of the chemicals is still not known exactly. A blue plume rises about 140 km (90 miles) above Io's surface from a volcano called Pillan Patera. In the center of Io is the volcano called Prometheus, above which rises a plume 75 km (45 miles) above the moon's surface, its shadow trailing towards the day/night boundary. The volcano has been erupting and the plume has been visible since the Voyager flybys of 1979. Pink, yellow and orange colors that spread over the rest of the ground are reminiscent of terrestrial landscapes such as the Painted Desert. (Galileo: NASA/JPL.) **AA**

Io was discovered at the end of 1609 by Galileo Galilei, when he began to use the telescope for celestial observations. As mentioned in Chap. 3, he observed the Moon and saw how like Earth it was. He also observed the planets. Early in the New Year of 1610 he wrote a letter to an unknown recipient with a further momentous discovery: "And besides my observations of the Moon, I have observed the following in other stars. First that many fixed stars are seen with the telescope, which are not otherwise discerned; and only this evening, I have seen Jupiter accompanied by three fixed stars, totally invisible by their smallness…"

When he came to look at Jupiter again a night or so later, the three stars were all on the other side of Jupiter. It seemed at first that Jupiter had simply moved on from its first position, leaving the stars behind. Galileo missed the next night's observations because of cloud, but on the following two nights he was surprised to see that there were two stars only, on one side of Jupiter. The next night all three stars were back, two on one side of Jupiter, one on the other. "It appears that around Jupiter there are three moving stars invisible to everyone up to this time," he wrote. Then he discovered that the three stars were actually four. One had been quite separated from Jupiter outside the narrow field of view of his telescope, but had moved closer.

Galileo realized that the four "stars" were moons, in orbit around Jupiter. He called them the Medicean stars, after Cosimo II de' Medici, head of a powerful and wealthy Florentine family. Galileo was hoping for and received patronage for this tribute. But, generally, astronomers rejected Galileo's name for the satellites, not accepting that celestial bodies should be named after patrons. Four names based in mythology were given currency by the German astronomer Simon Marius (1573–1625) and generally adopted—Io, Europa, Callisto and Ganymede, all of them Jupiter's partners.

Io is the closest to Jupiter of its four largest moons. Until the advent of large telescopes in the last years of the nineteenth century, Io remained a featureless, yellowish point, a world or moon 3600 km (2200 mi.) in diameter (over a quarter the diameter of Earth). Nevertheless, astronomers seized on the slightest of hints to speculate about its landscapes.

Edward Barnard (1857–1923), using the Lick Observatory telescopes, saw changes in Io's brightness that suggested it had a surface whose color and reflectivity varied as it presented different faces towards us. Evidently, the surface of Io changed in nature from area to area. This implied that Io *had* a landscape, some sort of terrain that differed from place to place. In the twentieth century, an astronomer at Arizona University, R. B. Minton (his first name is his initials) was able to show that Io had reddish-brown poles and a yellow-white equator. Its surface colors were very different from the other three ice-covered Galilean satellites. Matching the colors to the possible chemicals on its surface suggested that its surface was covered with sulfur salts. This was given credence when the Pioneer space probes passed Jupiter in 1973–1974. The mass of Io was determined from the amount by which it deflected the spacecraft. Astronomers found that Io was denser than the other satellites, with less ice and more rock. *Pioneer 11* took a fuzzy picture as it flew over Io's pole; it showed Io's yellow color and some uninformative dark patches. But why sulfur? The first theories were conservative. The rock was covered with minerals seeping in melted ice from the interior, deposited on the surface where the water vaporized, and then perhaps modified chemically by cosmic rays.

As they flew towards Jupiter in 1979, the *Voyager 1* space probe took close-up views of and analyzed the composition of Io's surface. *Voyager 1* transmitted magnificent pictures back to Earth. Io's surface was brightly colored with reds, oranges and yellows, the colors of sulfur compounds. There were no meteor craters, showing that the surface was young, and that some geological processes had erased craters that had formed earlier. However, Io had pits that were not at all like meteor craters but more like calderas, mountains taller than any on Earth and what seemed to be lava flows. It was a volcanic landscape. It was quickly realized that widespread volcanism on Io, if it occurred over the age of the Solar System, would quickly deplete this small world of the volatile chemicals needed to drive such volcanism. One exception was the volatile element sulfur. This was why sulfur is ubiquitous on Io today.

Even while *Voyager 1* was still passing through Jupiter's satellite system, heading outwards, it discovered that the volcanoes were active. The navigation engineer for the spacecraft was Linda Morabito. Her immediate task was to identify stars in images made by the spacecraft's navigation cameras, determine the position of the spacecraft and correct the spacecraft trajectory in real time, so it could pick its way through the shifting moons of the Jupiter system and not crash. She had also to re-analyze the images even more accurately to reconstruct the spacecraft's trajectory as precisely as possible, as a basis for stitching together images of the moons' surfaces to map their landscapes in detail.

On the morning of March 9, 1979, Morabito began processing several images taken by the *Voyager 1* spacecraft as it was looking back over its shoulder for one last view of the Jovian system. One image, taken from a distance of 4.5 million km, had been put up on TV monitors for everyone to see the surfaces of the planet and its satellites. Working on the image

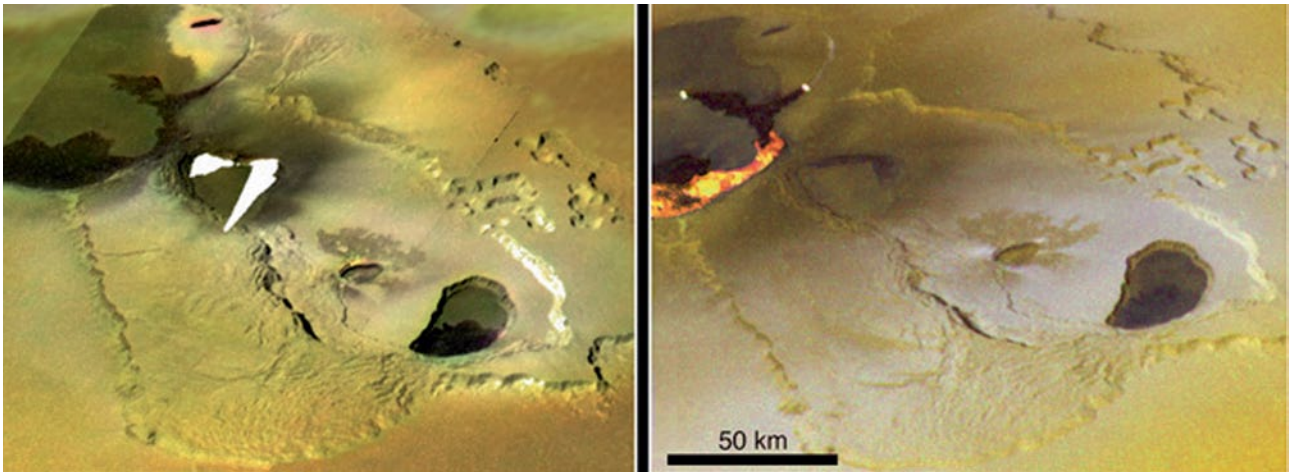

Fig. 7.6 Lava flows on Io. Tvashtar Catena is a chain of giant volcanic calderas. Their volcanic fire shows in images by the Galileo mission. In one image, from 2000, the volcanic liquid lava shows red hot in the caldera. In the other, from 1999, hot fountains of lava were so bright that they overpowered the camera's detector and are registered only in white. Colors in this image have been enhanced, and the heat of the lava has been recorded from infrared light that would not be visible to human eyes. (Galileo: NASA.) **A and B**

privately at her desk, Morabito "stretched" it. She increased its contrast to look for a particular, dim star, ignoring the fact that this saturated the surfaces of the planet and moons to pure white. She noticed what no one had been able to see on the picture as ordinarily displayed. There was an anomaly to the left of Io, just off the rim of that world. It was extremely large with respect to the overall size of Io, and crescent-shaped. It proved to be located over a large heart-shaped feature on Io. It was a plume from a volcano, and the heart-shaped feature was the volcano itself, with its slopes, ejecta and lava flows. This was the first sight of any active volcanoes outside Earth.

Nine volcanic plumes were discovered later by re-processing images obtained in the same flyby. Two were visible on Morabito's discovery image. One of them was on Io's limb (edge), above the volcano later named Pele, in which ash clouds were rising more than 260 km above the satellite's surface. The second, above the volcano Loki, was on the terminator (shadow between day and night), where the volcanic cloud was catching the rays of the rising Sun.

The Voyager spacecraft were flybys; the spacecraft flew past Jupiter without going back. Their instruments were programmed to range widely over as much as possible of Jupiter's system, but of necessity their time on any one subject was brief. The Voyagers were exploring, to lay the groundwork for future explorations, in which a space probe would stay in the Jupiter system for some time, studying its subjects in greater detail. That spacecraft was the Galileo spacecraft.

Galileo orbited through Jupiter's system for 8 years, from 1995 to 2003, visiting each satellites several times. It was prevented from passing too close to Io for fear that its hostile plasma environment would cause damage to its CCD, but it had the opportunity in this time to witness many eruptions on Io, viewing a fiery landscape from a distance that the controllers made sure was safe (Fig. 7.6); it saw ten plumes in 1998, and

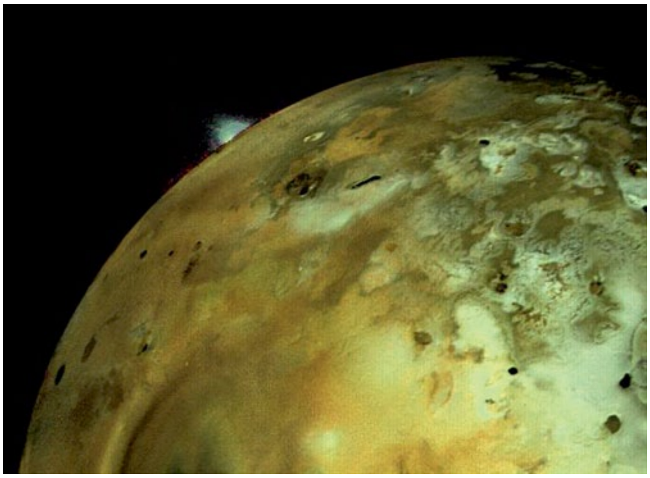

Fig. 7.7 An enormous volcanic eruption by Loki. The eruption is silhouetted on the horizon at Io, as recorded by Voyager 1. Its volcanic material has been thrown up to an altitude of about 150 km. (Voyager 1: NASA.) **A**

there are in total at least 15 active volcanoes among the 100 or so mountains on Io. One, Loki, has been continuously active for 20 years (Fig. 7.7). The low gravity of Io means that the plumes reach as high as 500 km above the surface.

According to calculations by scientists Stan Peale, Patrick Cassen, and R. T. Reynolds, the interior rocks of Io are squashed and expanded by interaction with Jupiter and the other moons of Jupiter. This heats them and creates the volcanic eruptions, which coat the surface with sulfurous deposits, covering meteor craters, developing pits and mountains, with lava flows hundreds of kilometers long and hundreds of times the volumes of recent flows from volcanoes on Earth that bulldoze aside earlier deposits into deep channels.

The discovery of volcanoes on Io transformed our view of planetary systems. The “habitable zone” of a planetary system is the zone in which water can exist in liquid form, a zone that is warm enough to melt ice, but not so hot that water turns to steam. On the assumption that liquid water is essential to the existence of life, this zone is where life can exist. Up to Morabito’s discovery astronomers had calculated the size of the “habitable zone” in the Solar System and in extrasolar planetary systems entirely on the basis of how much the Sun, or other central star, warms individual planets or moons orbiting at various distances. The central star supplies warmth to a greater or lesser extent, depending on the distance. Morabito’s discovery identified as important a second possible source of heat—volcanic activity—an activity that was possible in many circumstances in which a moon orbited a planet. Such a moon could be warmed to a temperature that could sustain liquid water, even if the planet and moon were a long way from their sun and would normally be frozen solid.

The volcanic eruptions give Io a thin atmosphere that is exposed to the strong particle radiation from Jupiter and shows colorful aurorae. The atmosphere and the plasma above Io leak along Jupiter’s magnetic field lines and impact the top of Jupiter’s atmosphere to produce an auroral footprint of Io.

RARE CRATERS ON VENUS

Venus has about 900 meteor craters, roughly the same number as Earth. In both cases the number of craters is small, and the fundamental reasons are similar. Earth has an atmosphere, it rains, and there is tectonic mo-

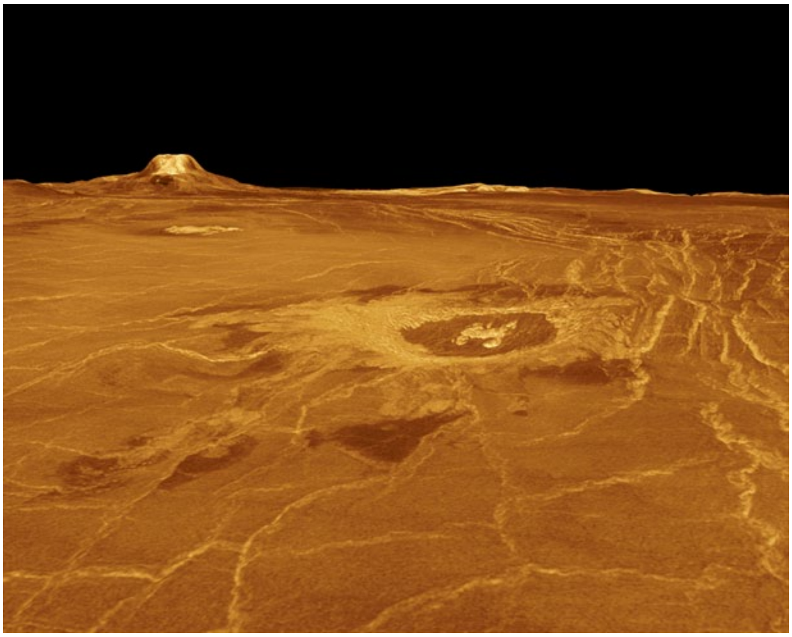

Fig. 7.8 Meteor crater on a volcano. The Gula Mons volcano on Venus is a volcano 3000 m (10,000 ft) high on the plain called Eistla Regio. It stands on the horizon in this image from the Magellan spacecraft. It has coated the surrounding area with lava, after which a meteor impacted on to the lava plain. The crater that it made is called Cunitz and is 50 km (30 miles) in diameter. (Magellan: NASA.) **C**

tion. This activity has erased many craters. Venus, like Earth, also has an atmosphere, and it has recently been volcanically very active, so its surface is also new. Craters are few and far between at the surface (Fig. 7.8). Presumably, under those lava plains are buried many older craters.

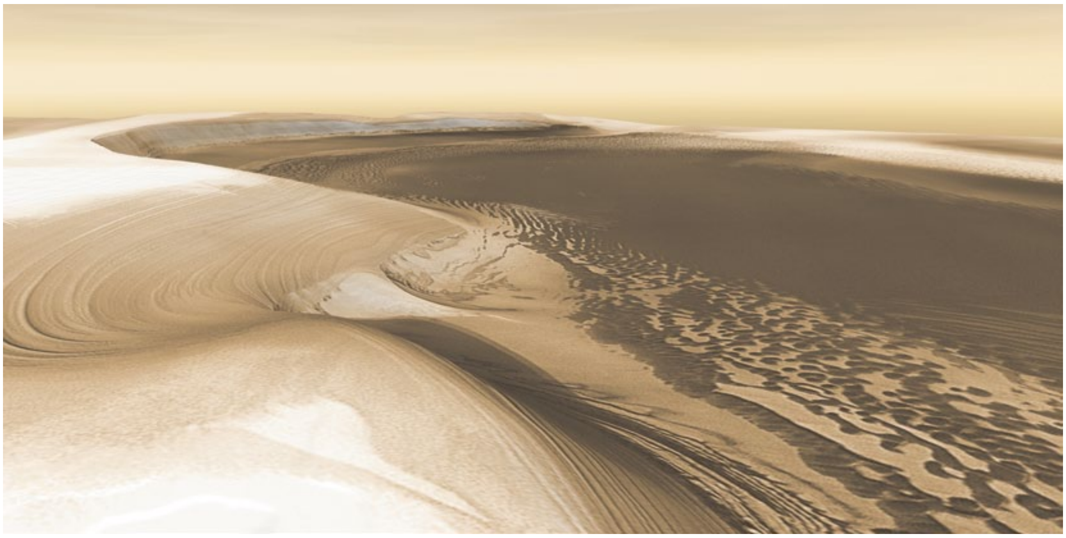

Fig. 8.1 Polar ice cap. The Chasma Boreale is a canyon that reaches 570 km (350 miles) into the layered ice of the northern polar cap of Mars. Its walls rise 1400 m (4500 ft) above the canyon floor. Where the ice cap has retreated, sheets of sand are emerging; the sand was blown there between the ice layers during ice-free periods of the climate. Winds blowing off the ice have now pushed the loose sand into dunes. The vertical scale is exaggerated here by 2.5 times. (Mars Odyssey: NASA/JPL/Arizona State University, R. Luk.) **BBB**

Chapter 8
Frost, Ice and Snow

POLAR CAPS

Buzz Aldrin's words as he gazed at the lunar landscape for the first time were "Magnificent desolation!" Surely the same words could be used to describe the icy wastes of Antarctica and the sea ice of the North Pole. Since so little grows in these cold climes the polar landscapes have an extraterrestrial quality—and they have their analogs on Mars and Jupiter's satellite Europa.

In 1666 the Italian-born French astronomer Giovanni Domenico Cassini discovered a white cap over the south pole of Mars, and speculated that it was a snow cap like the polar caps of Earth. In 1704, the French-Italian astronomer Jacques Philippe Maraldi found that the size of the polar caps varied throughout the Martian seasons, with the northern polar cap growing down to a latitude of about 45 as winter approached in that hemisphere, and reducing size in the spring; likewise for the southern polar cap. In a paper written in 1784, William Herschel visualized the landscape at the Martian poles. It is an ice field, he thought, like the Arctic regions. Making the analogy between Mars and Earth, Herschel hypothesized that because "the globe we inhabit has its polar regions frozen and covered with mountains of ice and snow, that only partially melt when alternately exposed to the sun, I may well be permitted to surmise the same causes may probably have the same effect on the globe of Mars."

Herschel does not seem to have referred elsewhere to the nature of the polar regions of Earth, and one can only surmise what he might have known of them and from where he got his knowledge. The Antarctic lands and ice fields remained unknown in Herschel's time, with the first sightings of southern ice fields by European explorers being made in the southern summer of 1819/1820, but, in general in Britain in 1784, quite a lot was known about the nature of the latitudes of the far north, although the North Pole itself was too difficult to reach. For a century, since the second half of the sixteenth century, the natural resources of Canada and its waters, including furs, whales and minerals such as copper, attracted adventurers and fortune hunters who were keen to exploit them and brought back to Europe their experiences as well as goods they could sell. The idea that it might be possible to sail to China and the Far East by passing to the north of Canada via the hypothetical Northwest Passage, or to the north of Russia, provoked the attention both of merchants and learned gentlemen. The barrister Thomas James (c. 1590-c.1635) made "A Strange and Dangerous Voyage to Hudson Bay" in the years 1631–1632 and on his return wrote the first best-selling narrative of a polar expedition in an account that showed verve and careful observations of natural phenomena. First published in 1633 and reprinted many times, it is said to have been a source for Samuel Taylor Coleridge's poem "The Rime of the Ancient Mariner," written in 1797–1798, about the same time that Herschel was

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writing about Mars. Herschel may well have been familiar with the passages from James' book that the natural scientist Robert Boyle quoted in "New experiments and observations touching cold" (published in London in 1665) concerning the heating and melting of ice, as well as the heating/cooling of Earth and its origin.

Herschel would also have known of the expedition in 1736 of French astronomers to Finland, sponsored by the Parisian Academy of Sciences and led by the mathematician Pierre Maupertuis (1698–1759), to measure the shape of Earth at high latitudes, during which they ventured into the mountains and overwintered on the frozen sea near the Arctic Circle. Maupertuis wrote a scientific account of this expedition in 1738. A member of the expedition, the Abbé Réginalde Outhier (1694–1774), wrote the "Journal de voyage," which he published in French in 1738, with an English translation appearing in 1777. It has colorful accounts of the animals and people of Lapland, its snow and icy terrain, and the way the snow and ice covering changes seasonally as the Sun warms the land in spring.

Closer in time to Herschel's work on Mars was a private expedition to Iceland in 1772 about which he must have heard at first hand, because it was made by Herschel's friend and mentor, the naturalist Joseph Banks (1743–1820). Banks traveled with Lt. John Gore (1729/1730–1790) to Iceland, where they studied the island's natural history and saw some of its volcanoes and icy peaks.

In the same year, the British Admiralty sent Captain Constantine Phipps (1744–1792) in two ships to make scientific observations and to search for the open polar sea hypothesized to exist in the far north, based on a theory by the Swiss scientist Samuel Engel (1702–1784) that polar ice was from estuarine fresh water and that brine would never freeze, so that there would not be pack-ice in the saltier water far from land. Phipps sailed north from the river Thames to Spitsbergen, where he encountered pack ice that he was unable to penetrate, even though he pushed so far into the ice that his ships had to be dragged out with ropes pulled by the crew. Phipps reached to latitude 80° 48' N (then a record for the furthest northern point reached by a ship). The voyage is best known for an account of how the 14-year-old midshipman Horatio Nelson encountered and scared off a polar bear after his musket failed to fire and his companions had fled. On his return, Phipps published in 1775, *A Voyage Towards the North Pole Undertaken by Her Majesty's Command 1773,* and this book would have been current as Herschel was writing.

Gore returned to Arctic waters in the expedition in HMS *Resolution* in 1776–1780, led at first by Captain James Cook (1728–1779), to explore the possibility that there was an entrance to the Northwest Passage from the Pacific Ocean. In 1778, Cook sailed along the Bering Strait between Russia and America to the northwestern corner of Alaska, but at a place he called Icy Cape he found the pack ice impenetrable. It formed a bar-

Fig. 8.2 Exposed layers on the scarp at the head of Chasma Boreale. The right hand surface is 700 m above the terrain to the left, with both planes covered by winter ice. Between these two surfaces lies a scarp cutting through the alternate layers of ice and sand. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona.) **A**

rier across the strait 12 ft (nearly 4 m) high. Captain Cook retreated to overwinter in Hawaii in 1779, where he was killed by native Hawaiians. After the subsequent death of Cook's second in command, Captain Charles Clerke (1741–1779), the leadership of the expedition's two ships, HMS *Resolution* and HMS *Discovery*, passed to the third in command, Lt. Gore. Under Clerke and Gore, the two ships carried out a second, unsuccessful attempt to break through the ice north of Canada. Gore returned to England in 1780 with his impressions of the Arctic, describing the ice-covered seas, snow-covered mountains and erupting volcanoes of Alaska in northwestern America and the Chukchi Peninsula in easternmost Siberia. The story of what came to be called "Cook's Last Voyage" was a sensation, with several accounts published by members of the expedition.

So the nature of the Arctic landscape was well known in 1784, and was even a somewhat fashionable topic of conversation in enlightened circles such as the ones that Herschel moved in. The Arctic wastes and mountains set the mental image of the Martian ice caps. However, because Mars is colder than Earth, its polar caps are composed of both water-ice and frozen carbon dioxide ("dry ice"), so the seasonal change in its polar caps are not from a scientific point of view quite the same as the change in Earth's. The carbon dioxide cycles into and out of Mars' atmosphere, and from one pole to the other. During winter, the temperature of the polar regions is so cold that carbon dioxide freezes there. In the spring and summer the carbon dioxide evaporates,[1] and returns to the atmosphere.

In the northern hemisphere, the carbon dioxide ice cap completely vanishes in the summer. Underneath is a water ice cap, which remains there all year round. Dark areas show through the ice, and it is perhaps only meters thick in those places (Figs. 8.1–8.2). The dry ice is tens of centimeters thick. In the summer the north polar cap shrinks to a diameter of about 350 km (200 miles).

The circumference of the generally circular polar caps is irregular, suggesting that the caps cover hilly land, with the icy deposit varying in thickness so that it melts and drains into the surrounding landscape at different rates. Percival Lowell claimed that, even with the ground-based telescopes of the last years of the nineteenth century, astronomers could

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[1] On Mars the temperature and atmospheric pressure are such that both dry ice and water-ice change from solid to gas without passing through a liquid stage. So ice on Mars does not 'evaporate', it 'sublimates.' On Earth temperature and atmospheric pressure are such that frozen water melts to liquid water and then evaporates to vapor. But dry ice (frozen carbon dioxide) sublimates directly to vapor without becoming a liquid, which is one reason why dry ice is used to cool packets of food being delivered by mail order.

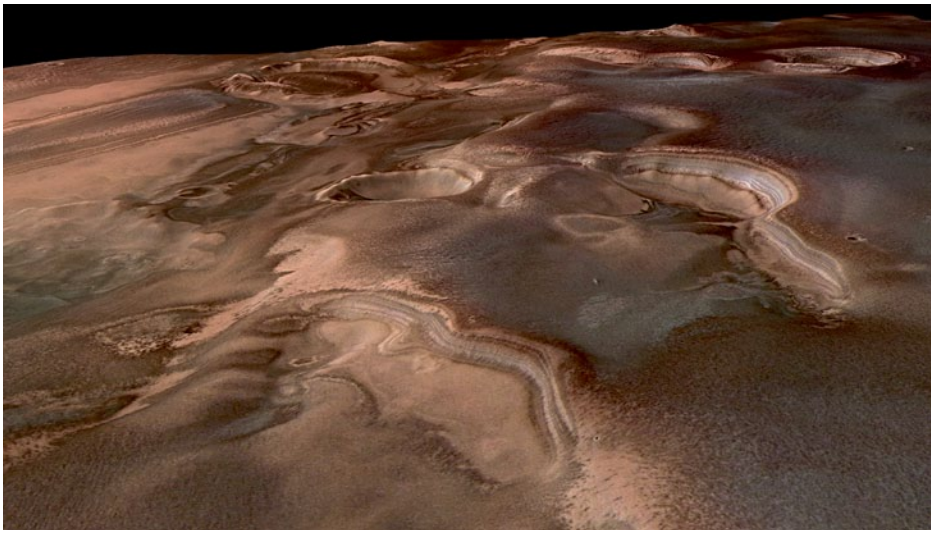

Fig. 8.3 The southern polar ice cap. This ice cap is also made of layers of snow and ice that have fallen during successive winters, and that are dusted with sand and dust blown there by dust storms. The south pole of Mars is higher than the north pole. Scarps at the edge of the ice sheet often form arcs that are caused partly by underlying meteor craters, as here in this landscape. In front of the ice sheet (left) there are isolated ice deposits among areas of sand dunes. Two huge meteor craters in the southern hemisphere are enough to influence the climate at the south pole so that the southern polar cap is offset from the geographical south pole of Mars by 150 km (100 miles). (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **A**

"gaze upon the actual surface features of the Martian globe" and had described a polar sea: "It lies in a valley between two mountain ranges. Of this we are almost as sure as if we had climbed one of the enclosing summits and looked down upon it." The sea as an area of standing water was imaginary, but the valleys and mountain ranges are real enough.

The southern polar cap lies at 6000 m greater altitude than the northern polar cap, so it is colder, and dry ice covers the south pole all year round (Fig. 8.3). There is water-ice about 8 m (30 ft) below the dry ice surface. The southern polar cap is about 1000 km (600 miles) in diameter in the southern summer.

Dry ice persists at the south pole all year round (Fig. 8.4), but there is a carbon dioxide cycle from gas to solid (Fig. 8.5). This "annual" cycle

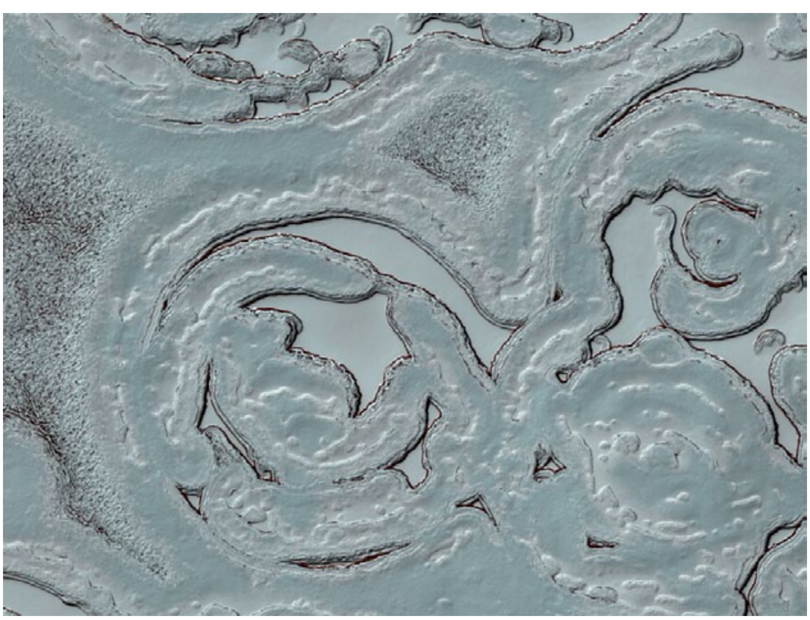

Fig. 8.4 Swiss cheese terrain. Dry ice persists at the deepest part of the south pole even during the summer; this area is called the south pole residual cap. Relatively smooth mesas (up to 10 m, or 30 ft high) of solid carbon dioxide ice at the south pole residual cap is broken up by circular, oval and blob-shaped depressions, making a pattern called "Swiss cheese terrain." The dry ice has vaporized from the depressions, leaving a flat floor of water-ice behind. The complicated shapes arise when evaporating and growing depressions intersect. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona.) **A**

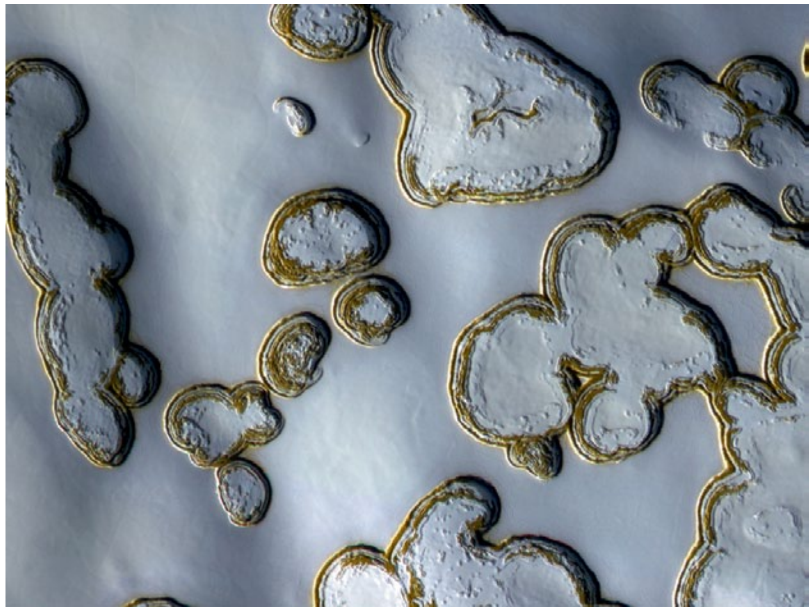

Fig. 8.5 The south pole residual cap of Mars. In this image, taken in the southern spring, sunlight throws the "Swiss cheese terrain" into relief, highlighting the layers of icy deposits. Swiss cheese terrain forms at the end of every Martian summer, when the warm weather causes the carbon-dioxide ice sheet to vaporize. Dust lines the interior walls of the pits so that they appear lined with gold. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona.) **A**

moves carbon dioxide from north to south and back again, which has a significant effect on the amount of carbon dioxide in the Martian atmosphere, changing the mass of the atmosphere by tens of percent.

The areas around the polar caps cycle back and forth with the seasons between cold and dry in the summer to very cold and snowy in the winter. As in the temperate zones of Earth, the topography governs the snow cover, with snow and frost more likely occurring on high hills, such as those in the centers of craters, and on the shadowed sides of mountains, such as the polar facing side of crater walls (Figs. 8.6, 8.7). Fog is common. The

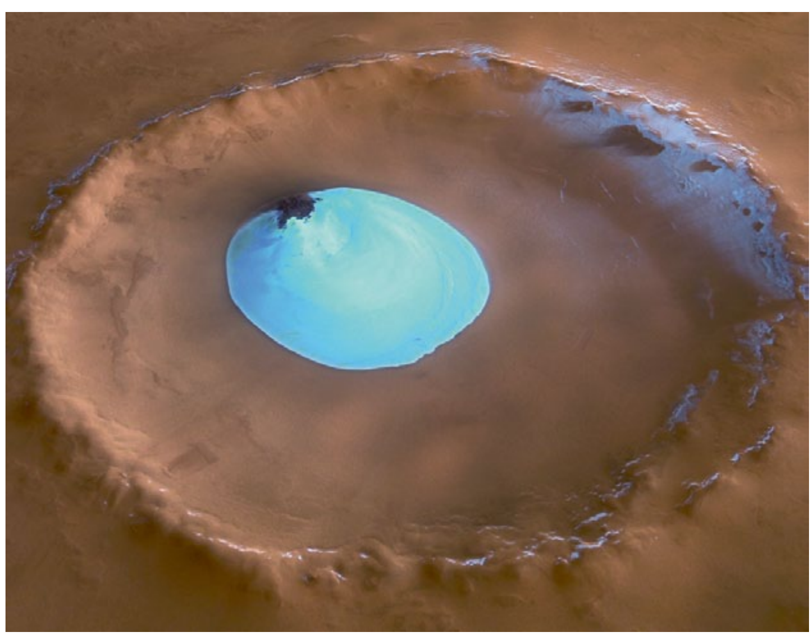

Fig. 8.6 Snow in a crater near the north pole of Mars. The unnamed crater is 35 km (20 miles) in diameter and is 2000 m (6500 ft) deep. The latitude, temperature, air pressure and shady conditions at the floor of the crater are such that the ice persists all year round, even late summer (when the image was obtained). The dry ice that overlies the water-ice in the winter has all vaporized. The inner walls of the crater on the south side (right) are frosted with ice because these walls never receive direct sunlight. In this image they are obviously in shade. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **A**

cycle of temperature and frost deposits causes the ground to heave and re-solidify; this results in curious patterns appearing in the ground (Fig. 8.8).

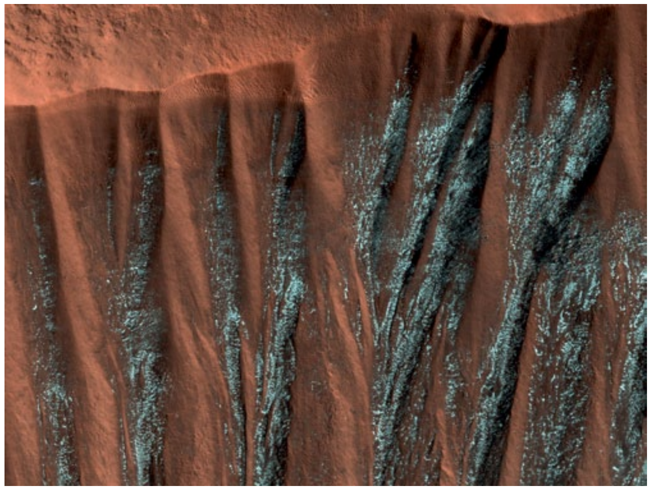

Fig. 8.7 Frost on Mars. Some craters have walls that are ridged with vertical gullies, like this one near the north pole of Mars. Some scientists believe that the gullies have been carved by running water; others believe that repeated freezing and unfreezing of the ground loosens the soil, which then falls in repeated small avalanches. It was late summer when this image was obtained, but there is still frost in the most shadowed gullies. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona.) **A**

Fig. 8.8 Flat and foggy plains. The northern polar region of Mars near the Phoenix landing site is covered with small pebbles. The hard, frozen ground of the shallow valley where Phoenix landed shows polygonal patterns a few meters in size, similar to those seen in permafrost on Earth, for example in Canada and Finland. There are no sand dunes, but low hills appear in the far distance on the horizon, blocking the view of the rampart walls of a 10 km (6 miles) crater, Heimdall, the nearest identified feature to the landing site, some 25 km (15 miles) away. By digging with a robotic arm, Phoenix showed that indeed there was ice underneath the surface. This image was made from two colors, a blue and an infrared one, with a third green image interpolated artificially from the other two to give a representative color landscape. The site is nearly monochromatic. (Phoenix: NASA/JPL-Caltech/University of Arizona.) **BBB**

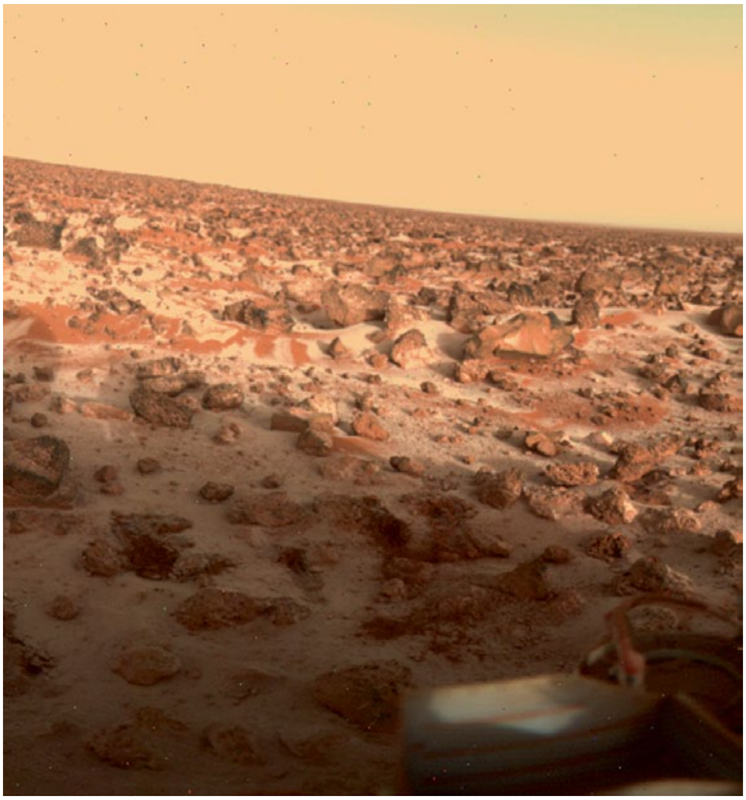

Fig. 8.9 Frost on Mars. For about 200 days in the Martian winter, frost formed on the rocks at the Viking 2 landing site on Utopia Planitia. The frost settled to the ground in a thin layer when dust particles in the atmosphere were weighed down by water-ice and dry ice. When they warmed from the Sun, the carbon dioxide was released, leaving behind water and dust. (Viking 2: NASA/JPL.) **AA**

COLD WINTERS

The Viking landers monitored the Martian weather with weather stations. The highest temperature around noon in the summer was about – 15 °C. The landing site for the *Viking 2* lander was the colder of the two. The lowest pre-dawn temperature in the winter there was – 120 °C, about the frost point of carbon dioxide. A thin layer of frost covered the ground around the *Viking 2* lander for about 200 days each winter (Fig. 8.9).

SPRING RELEASES THE ICY GRIP OF WINTER

One springtime, this author had been working through a long, freezing cold night at a telescope at the Roque de los Muchachos Observatory on La Palma in the Canary Islands. As the dawn broke and my work finished, I was tired but still tense with the pace of my astronomical observation program. I knew I would not be able to go to sleep right away, and I decided to go to the nearby highest point on the island, 2400 m above sea level, and watch the sunrise; I wanted to wind down before driving to the Residencia and my bed. I sat quietly on a rock under the golden sky and looked down on the purple, triangular shadow of the mountain laid out to the west on the cloud tops below. In the silence of the dawn on this remote mountain top, I gradually became aware of episodic small sounds from all around me, whispers on the ground, tiny disturbances. Looking around, I spotted the cause: from time to time a trickle of small stones would slip down a slope, making a noise that was only just audible. What was happening was that, during the night, ice had frozen onto the ground, breaking the surface but cementing the little stones until the warmth of the Sun melted the ice. When this happened, the stones were loosened and slid down the slopes. What I was witnessing was happening, gram by gram, everywhere over the mountain, night after night, springtime after springtime, over millions of years. Eventually, over more time than I would be able to see it, the mountain would be worn down to a stump by the cumulative effect of this tiny but persistent process. I was witnessing erosion in action.

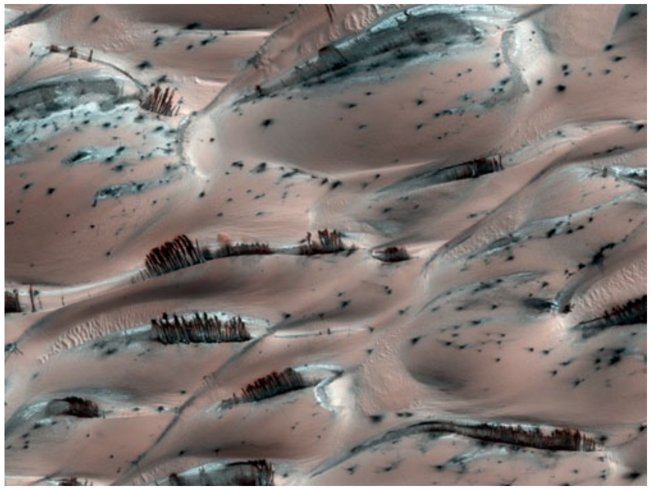

Fig. 8.10 Landslips. The steep side of sand dunes at the north pole of Mars in the springtime slide into the dune valleys, disturbing the dusty surface and revealing in parallel streaks the darker material below. The dark landslides surge down the slopes across white streaks of frost in the valleys. The pink surface dust settles in its valley, puffing in rosy clouds on to the opposite side of the valley. In this image, one puff (left of center) is caught in the very action of the landslip. In some places the pink dust has blown away to reveal dark stains underneath. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona.) **A**

Something similar happens on Mars. Near to the poles the sand dunes are frozen in the winter, and their surfaces are hard. As spring comes, the ice—most probably dry ice, not water-ice—loosens its grip and the sand can slip, making small landslides (Fig. 8.10). On more vertical walls of rock in the winter, ice breaks into crevices and pries apart the rock, holding the rock together while the ice remains frozen but loosening tons of it in avalanches (Fig. 8.11).

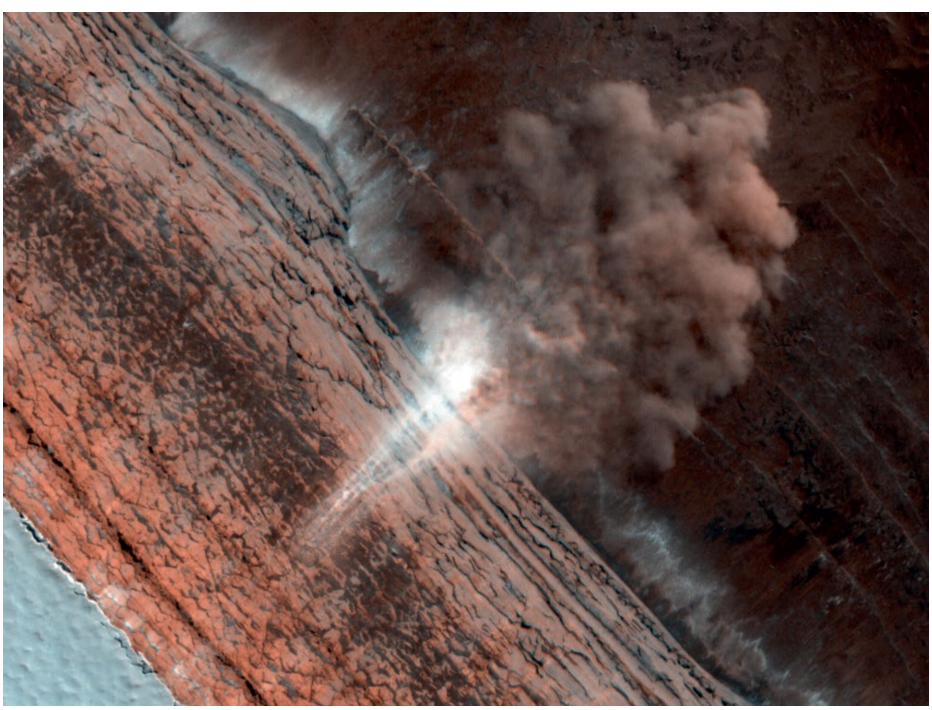

Fig. 8.11 Landslide. There are steep scarp faces at the edge of the northern polar ice cap, up to 700 m (2300 ft) high. Here a section of the steep scarp cuts diagonally across the image, dividing the upper icy surface of the polar cap (lower left) from the lower plain below, covered with sand dunes (upper right). The build-up of the polar cap in dusty, sandy layers of ice is revealed in the scarp face. Icy fragments have been loosened in the cliff by the approach of spring, and, simply set free or perhaps disturbed by the wind (or even a Marsquake), with white sprays of the fragments falling from the upper layers of the scarp. The fragments set off an avalanche, knocking material from the cliff face below. Where it has cascaded down, bouncing on the lower layers and onto the plain, there billows a cloud of red dust 200 m (650 ft) in diameter. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona.) **A**

ICE FLOWS AND ICE FLOES

There is no surface water on Mars. The atmospheric pressure is such that water vaporizes immediately. Indeed, over much of the planet there is no ice, because ice does the same. But there was a considerable amount of water on Mars in the past, and some of the water remains in the form of ice lying on the surface at the poles and under the surface of much of the rest of Mars. At intermediate latitudes, the amount of subsurface ice can be considerable and, mixed with the soil, can be mobile and flow downhill. On Earth, high in mountain valleys at intermediate latitudes, flowing ice is familiar as a "glacier." On Mars, glaciers exist at middle latitudes, and may be many meters, perhaps hundreds of meters, thick. The ice flows faster in the middle of the glacier and is retarded by the valley sides. The glacier flows faster and slower as the seasons progress, stretching and piling soil and rocks on the glacier into ridges. In this way, the surface of the glacier shows ridges of soil that curve across the valley (Fig. 8.12). Alongside the glacier, the ice grinds away at the valley walls; rock and soil falls onto the surface of the stream of flowing ice and is carried downhill. If and when the glacier melts away, the soil becomes muddy and is dumped onto the ground (Fig. 8.13).

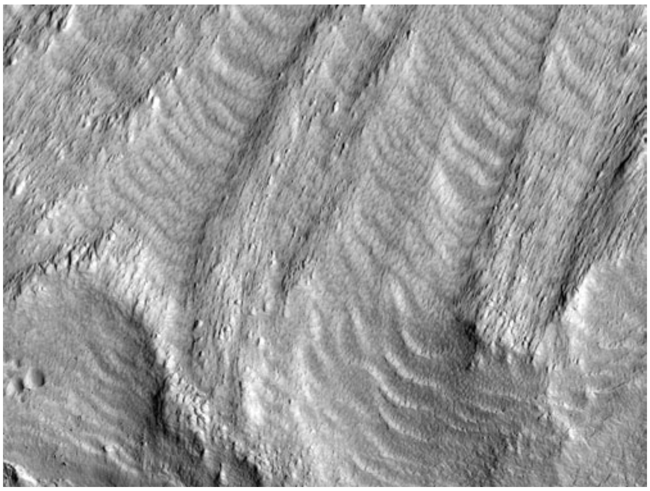

Fig. 8.12 Glaciers. Snow and ice, mixed with soil and rocks, is slowly flowing downhill in this hilly area on Mars. (Mars Reconnaissance Orbiter: NASA/JPL/University of Arizona.) **AA**

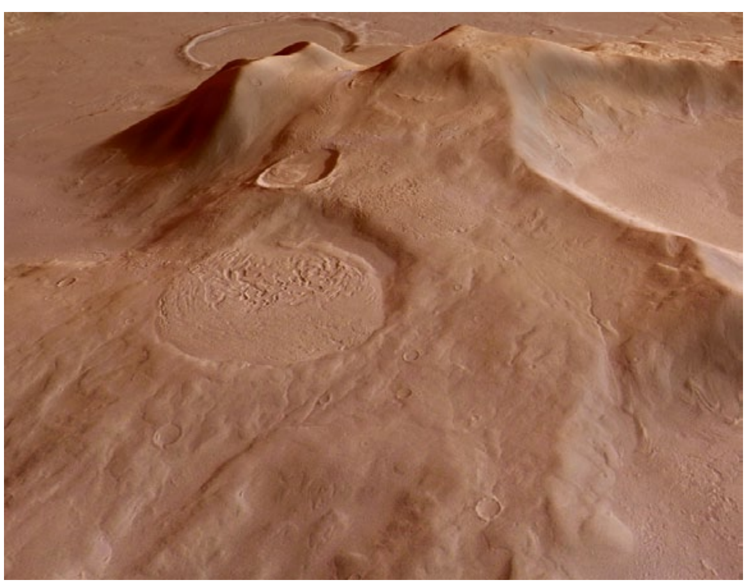

Fig. 8.13 A mud glacier on Mars. Glaciers once flowed from the mountains, Promethei Terra, at the edge of the Hellas Plain. One of them, laden with a large amount of rock and soil flowed into a meteor crater 9 km (5.5 miles) in diameter, filling it to the brim. The glacier overflowed the crater and flowed further into a 17-km (11 miles) crater 500 m (1600 ft) below. As the glacier melted, it deposited mud in the two craters, filling them with a flat bare floor, in an hourglass shape. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **A**

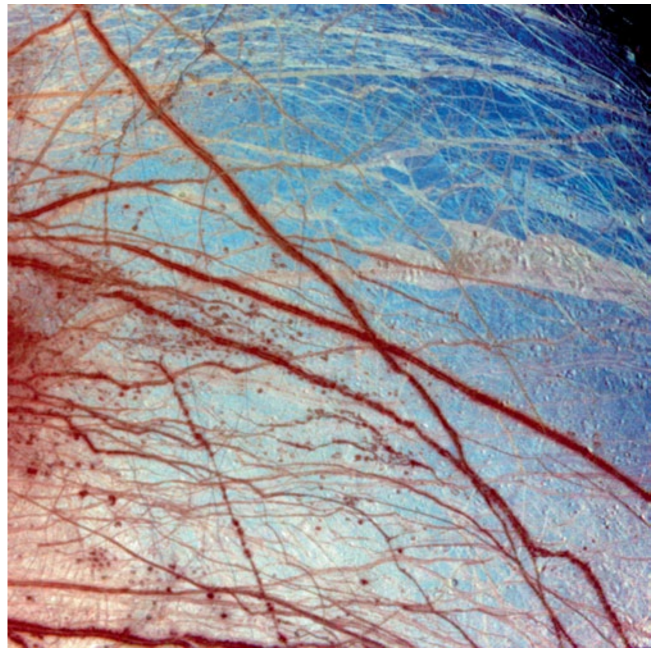

Fig. 8.14 The icy surface of Europa. Colors in this image of the surface of Europa have been exaggerated. The icy plains are blue, with different tones indicating differences in the texture of the ice. The brown and red bands indicate cracking between ice floes, where upwelling from the ocean below has deposited different chemicals on the surface. The area covered is 1260 km (780 miles) across. (Galileo: NASA.) **BBB**

There is ice on Mars in thin layers at its polar caps and under its surface. The ice on Jupiter's satellite Europa covers its entire surface and is kilometers deep.

Europa has the distinction of being one of the most spherical objects in the universe. It is the second of Jupiter's four main satellites outwards from Jupiter. Like Io, Europa was discovered by Galileo at the end of 1609, with his new telescope. Like Io and Jupiter's two outermost satellites, Callisto and Ganymede, it is about the size of Earth's Moon and does not have a significant atmosphere. Europa is also basically a rocky, icy body, but it is cooler than Io and warmer than Callisto and Ganymede. The reason for this is that all four moons are subject to compression by the tidal forces that Jupiter exerts, with the tidal energy dissipated as heat that warms them up. As might be expected, the tides are stronger on the inner moons.

All the moons except Io disturb Jupiter's magnetic field as they pass through it. This means that Europa, Callisto and Ganymede each contain liquid water. Water laced with mineral salts that occur as natural impurities is an electrical conductor and changes any electrical and magnetic fields that lie nearby. Europa is the most extreme of the three. It has an ocean of water, by contrast to Callisto and Ganymede, which have pockets of water interspersed in their rock.

The heat generated by Jupiter's tides within Europa has melted the ice there, which has risen to the surface of the moon and covered it entirely with an ocean. The water has re-frozen at the top of the ocean, so Europa's surface is covered with icy plains, crisscrossed by grooves (Fig. 8.14). The grooves are cracks in the ice, and the icy plains are in fact a jigsaw of ice floes, the size of cities. Frozen "puddles" smooth over older cracks. Water has seeped up through the cracks from the ocean below and has stained the surface of the ice floes with colored salts, to make a pattern reminiscent of abstract expressionist painting, which the framing and coloring of Fig. 8.14 is clearly meant to recall.

There are very few meteor craters on Europa's surface. When a meteor does make a crater in the ice, the meteorite and the chemicals that it brings sink into the ocean, the shifting ice floes close up overhead and quickly erase the traces of the impact. It is estimated that the surface renews itself totally in a time of about 50 million years.

The ice layer of Europa is perhaps as much as a kilometer thick or more, and it is the pressure of the floating ice and radioactive and tidal heating of Europa's interior that liquefies the water. The ocean may be as deep as 100 km (60 miles). The average depth of the oceans of Earth is only 5 km (3 miles). Europa has more water than the total amount found on Earth, a salty ocean under an icy cover. It seems possible that life has evolved there.

GEYSERS ON ENCELADUS

Volcanoes are very energetic and explode with molten rock, but there are less energetic events that explode with water and water vapor. These are called geysers. The term originated in Iceland as the name of a place, *Geysir,* but the most extensive concentration of geysers is in Yellowstone National Park in Wyoming (Fig. 8.15).

The most distant concentration of geysers is on Enceladus, a moon of Saturn. Enceladus is a small, rocky and icy moon, but its surface is remarkably varied. It has several types of tectonic features, including faults, scarps, belts of grooves and ridges and, most impressively, explosive active geysers coming from unknown processes in its interior. Some areas resemble the terrestrial hot springs and geysers seen in Yellowstone and

Fig. 8.15 Grand Prismatic Spring. Steam rises from the spring in Midway Geyser Basin, Yellowstone National Park. (Photo by Jim Peaco, U. S. National Park Service.) **AAA**

Iceland. The wrinkled terrain of the southern hemisphere of Enceladus is cut by large dark cracks or fractures, called "tiger stripes," that are very young and surrounded by ice that has welled up from below. Seen through the cracks are warm swathes of heat lying along the fractures (Fig. 8.16). Peak temperatures along one of them exceed 100 °C (– 150°F) and may be higher than – 30 °C (– 20 °F). One scientist on the Cassini spacecraft team that made these measurements, John Spencer, said "The fractures are chilly by Earth standards, but they're a cozy oasis compared to the numbing – 220 °C [– 360 °F] of the rest of Enceladus' surface. The huge amount of heat pouring out of the tiger stripe fractures may be enough to melt the ice underground."

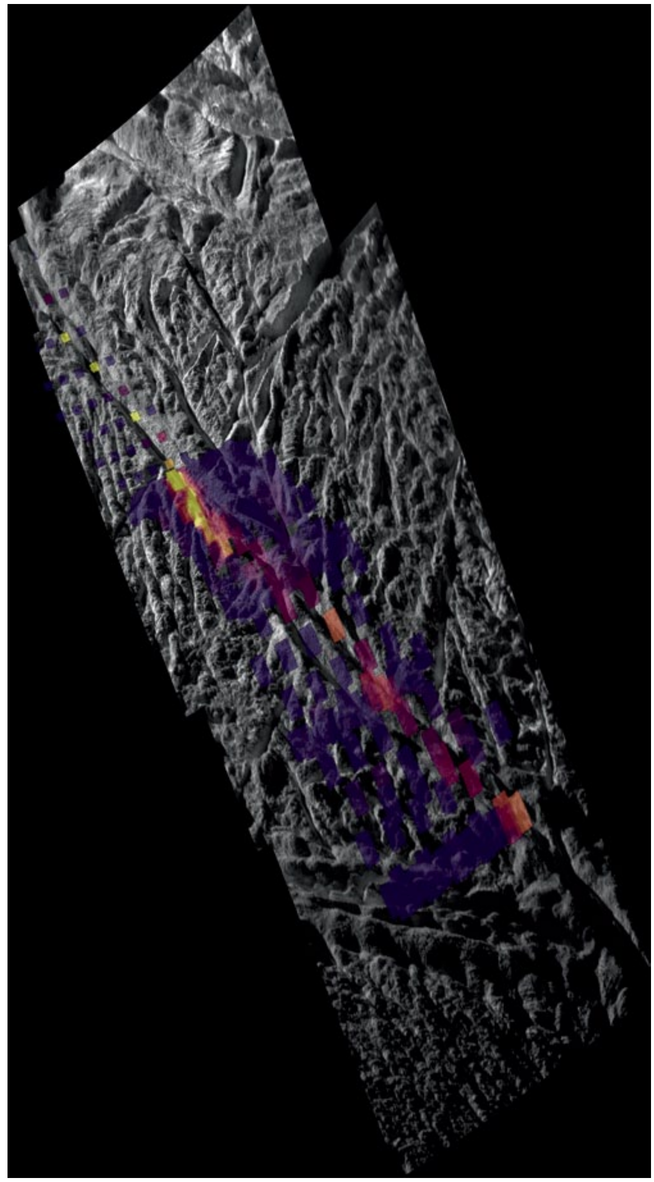

Fig. 8.16 Tiger stripe. The longest tiger stripe on Enceladus, known as Baghdad Sulcus, is 40 km (25 miles) long. Warm areas show red in this wrinkly landscape. The red part of the image was obtained with infrared light that brings the infrared color into the visible spectrum that we can see and exaggerates its contrast with the surroundings. (Cassini: NASA/JPL/GSFC/SWRI/SSI.) **BB**

In 2008, the Cassini spacecraft discovered that there are sprays of water and water-ice chips (hail and snow) in a gas of methane, carbon dioxide and other simple organic molecules, bursting from four tiger stripes. The sprays—hundreds of geysers—were first imaged on a pass of the satellite over the surface in 2006, when it was positioned specifically to view the sprays, backlit by the Sun (Fig. 8.17). The sprays of snow and hail last for millennia, possibly for millions of years. The snow falls back onto the surface of Enceladus in a repeatable pattern, and the sprays have blanketed areas of the surface in a thick layer of tiny ice particles. The resulting terrain is unusually smooth, with ghost-like undulations indicating buried old canyons and craters. The larger of these canyons are 500 m (1600 ft) deep and 1.5 km (1 mile) across, not unlike the canyons of the American Southwest. The overlying layer of fine, powdered snow is sometimes 100 m (300 ft) deep in this area, having accumulated at a rate that is extremely slow by terrestrial standards, less than a thousandth of a millimeter per year, but which has built up what would be a fine place for skiing.

The sprays of ice that have produced this potential all-year playground for winter sports are geysers fed by reservoirs of liquid water perhaps not far below the surface. The source of the heat from the south pole of Enceladus that is driving these geysers is not known. Flexing of the body of the moon by the tidal forces of Saturn, in the same way that Io

Fig. 8.17 Geysers on Enceladus. The southern polar region of Saturn's moon Enceladus shows jets of water vapor ice chips and other particles spewing from fissures on the surface, backlit by the Sun. (Cassini: NASA/JPL-Caltech/ Space Science Institute.) **AA**

and Europa are flexed by Jupiter, is not energetic enough. But however it happens, inside Enceladus is hot rock, whose warmth melts its internal ice and fill its underground caverns with pressurized water, producing a magnificent landscape of geysers.

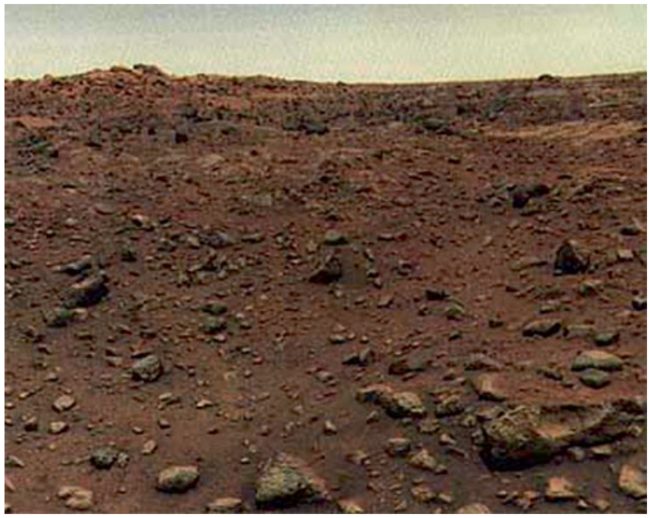

Fig. 9.1 Blue sky on Mars? The first color photo from the Viking 1 lander, taken on the Mars surface July 22, 1976, shows a blue sky. This version was released that same day. (Viking 1 Lander: Reproduced from On Mars: Exploration of the Red Planet. 1958–1978, by Edward Clinton Ezell and Linda Neuman Ezell, NASA SP-4212, 1984.)

Chapter 9
Cosmic Skyscapes

Conspiracy theories are about groups of people who are executing a coordinated secret plan to achieve some nefarious purpose, something important. On a scale of 1–100, where a conspiracy to achieve world domination defines the top end of evil, the conspiracy theory that NASA alters the color of its landscape pictures of Mars ranks, one would think, below number 1. However, the theory has a surprising currency in the universe of conspiracy theories that is the Internet.

The conspiracy theorists allege that NASA is falsely presenting the color in its pictures from Mars in order to conceal something from us about that planet. The pictures that NASA releases show that Mars is a dusty world of red deserts. Perhaps, they say, it is actually more benign, like Earth, and pictures could reveal that it has blue sky and areas that are green with life. Perhaps NASA has already found that there are intelligent Martians but is concealing the evidence of this from us.

This theory sprang from the very first color pictures from the surface of Mars, made in 1976 from the Viking landers, and survives in 2014 in lay analysis of the images from the Mars exploration rovers that, in different versions, may show inconsistencies of color. The color of the sky in all these pictures is said to be where NASA slipped up and is, apparently, the big giveaway.

The truth is less dramatic in one way—NASA is innocent—but shows the importance of the sky color in how we interpret pictures of the landscape. We talk of a dark gray sky as "lowering" or "threatening." A blue sky is "happy." What are we to make of a landscape in which the sky is orange-brown? At first a picture that shows this is not credible.

The blue sky in the first landscapes from Mars (Fig. 9.1) arose from a mistake made under pressure. In 1976, the Viking science team had taken steps to produce accurate color pictures, by calibrating their cameras and filters before the spacecraft left Earth so that they could add the separated color images into a single color picture, but they were caught out by some subtle effects for which they had not planned. In addition they did not realize the interest that there would be in the first pictures and the pressure that they would be under from the media, who demanded instant responses in the 24/7 news agenda.

Tim Mutch, leader of the Viking lander imaging team, describes what happened:

> In contrast to the attention we lavished on planning of the first two black and white pictures, we were dismally unprepared to reconstruct and analyze the first color picture. In a general way we understood that thorough preflight calibration of the camera's spectral sensitivity was mandatory. We also knew that we would need software programs that efficiently transformed the raw data. What we failed to appreciate were the many subtle problems which, uncorrected, could produce major changes in color. Furthermore, we had no intimation of the immediate and widespread public interest in the first color products. For example, intuitively corrected color images were shown on television within 30 min following receipt of

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data on Earth. Although we struggled to delay the deadline, we were obliged to release the first color prints within 8 h after receipt of data.

As previously mentioned, there are three sensors with blue, green, and red filters in the focal plane of the camera. These record the radiance of the scene in blue, green, and red light. However, the multilayer interference filters used in the cameras (simpler absorptive emulsion layers would have been degraded by preflight heat sterilization) have very irregular spectral response. The blue channel, for example, responds slightly but significantly to infrared light. The extraneous parts of the signal must be subtracted, so that the absolute radiances at three specific wavelengths in the blue, green, and red are represented. A color print is produced by exposing conventional color film to separately modulated beams of blue, green, and red laser light, scanning the film with the same geometry employed in the camera.

When the first color data from Mars were received on Earth, we immediately used the same normalization techniques to calibrate the image. The result was surprising and disquieting. The entire scene, ground and atmosphere alike, was bathed in a reddish glow. Unwilling to commit ourselves publicly to this provocative display, we adjusted the parameters in the calibration program until the sky came out a neutral gray. At the same time, rocks and soil showed good contrast; the colors seemed reasonable. This was the picture released eight hours after receipt of the data. But to our chagrin the sky took on a bluish hue during reconstruction and photo reproduction. The media representatives were delighted with Earth-like colors of the scene.

Meanwhile, continued analysis supported the reality of an orangish tint throughout the scene, the atmospheric color resulting from small suspended soil particles. Several days after the first release, we distributed a second version, this time with the sky reddish. Predictably, newspaper headlines of "Martian sky turns from blue to red" were followed by accounts of scientific fallibility. We smiled painfully when reporters asked us if the sky would turn green in a subsequent version.

So what do skyscapes look like, arching over planetary landscapes? Lunar landscapes are characterized by the blackness of the sky. There is no light from the sky. Astronauts look straight into the darkness of space. In spite of this, however, astronauts walking on the Moon do not see stars. Their eyes adapt to the bright sunlight on the scene around, and they cannot detect the stars, which are faint and below the sensitivity of the eye when it is coping with the bright land. The brightness of stars is also below the sensitivity of cameras if they are set to record the general scene. For the ease and the safety of the lunar exploration, there have never been astronauts on the Moon at night, but if there were, no doubt the stars would be visible to them, if the space helmet design permits.

It is, of course, the lack of atmosphere on the Moon that is the reason why the lunar sky is black. Since the lunar sky is black and the interest in the picture lies in the solid surface of the Moon, lunar landscapes typically show only a thin strip of sky (Fig. 5.12).

By contrast, the sky is a prominent feature of terrestrial landscapes, indeed the word "skyscape" developed in the first years of the eighteenth century to describe a landscape in which the treatment of the sky is a major part of the picture. Where does the light come from, to produce something so worth painting? The light of the sky is the light of the Sun diffused by Earth's atmosphere.

The atmosphere on Earth is made up of atmospheric gases, solid particles and liquid drops of water, the latter two constituents called aerosols. Light from the Sun diffuses through the atmosphere, some of it directly along the line of sight to our eyes and some to left and right, along a line to an adjacent place on the ground. The direct beam of light encounters the atmosphere, and any of its constituents can deflect some of the light. The direct beam of sunlight will certainly dim, which is why sunlight is less intense during cloudy weather or during a time of a dust storm when there are many solid particles in the air. Raindrops and dust suspended in the air in clouds block sunlight.

The beam of sunlight may also become colored because one color is more likely to be deflected than another. Raindrops and dust particles are likely to be large and deflect all colors equally. But when the atmosphere is clear, the irreducible minimum content of the air is composed of gas molecules, which are very small particles compared to the wavelength of the light. In this case the deflection of light that the particles cause is called Rayleigh scattering, and the mechanism strongly deflects blue light and affects red light less. As a result, the direct beam of sunlight reddens. When the Sun is directly overhead the path length through the air is at a minimum, and the image of the Sun becomes slightly yellowish. When the Sun is setting, the beam of light shines slantwise through lots of atmosphere and the Sun appears orange or red.

The light that is lost from the direct beam of sunlight is deflected off to one side, out of our line of sight to the Sun. It might enter the view of someone off to the side, who will be looking not directly at the Sun but across the light from the Sun to us. This person will view the light that has been deflected—the blue light. This is why off to the side of the Sun the sky is blue.

Air made blue by Rayleigh scattering is the reason that Earth seen from space is blue, a color that is especially obvious over those parts of its surface that are naturally dark, such as the deep oceans. However, the blue haze covers the whole of Earth's disk and is especially obvious where the light reaches the eye (or camera) after it has traveled through a denser part of the atmosphere, towards the limb of the planet.

Many of the images of Earth from space, like those photographed by astronauts, are corrected by removing the blue, so the landscape below looks "natural" or are made at wavelengths that minimize the effect of Rayleigh scattering. By contrast, artists will deliberately create a blue haze over distant features in a landscape in order to suggest the depth of air between the viewer and the distant feature and thus suggest how far it is.

Because of the lack of atmosphere on the Moon, there is no effect of distance on the Moon due to the mistiness and change of color of the surface features to blue in the distant land that stretches to the horizon—

Fig. 9.2 Sunset over the rim of Gusev Crater on Mars. To avoid strain on its batteries, the Spirit rover would normally have been put to sleep as the Sun set and the temperature fell, but on this day in 2005 she was commanded to stay awake briefly to record the twilit sky. Occasionally the science team did this to determine how high into the atmosphere the Martian dust extends, and to look for dust or ice clouds. The filter combination used on this occasion has produced a color image that is similar to what a human would see, but with the colors slightly exaggerated. In this image, the bluish glow in the sky above the Sun is how the sky would look to us if we were there, but the redness of the sky farther from the sunset, caused by dust, has been exaggerated. The image of the Sun is smaller than it would appear in a terrestrial sunset, because Mars is farther from the Sun than Earth is. The terrain in the foreground is the rock outcrop "Jibsheet," the floor of Gusev Crater is visible in the distance, and the Sun is setting behind the far wall of the crater some 80 km (50 mi.) distant. (Mars Exploration Rover Spirit: NASA/JPL/Texas A&M/Cornell.) **AA**

no "blue, remembered hills." By contrast, on Venus the atmosphere is much denser than on Earth, and the effect of Rayleigh scattering more intense. The Venusian air completely scatters not only the blue but also well into the yellow and red. The Venusian sky is a golden color.

So what about Mars? It is further from the Sun by a factor of 1.4, so sunlight is less intense by a factor of about 2. On Earth we experience a diminution of the Sun by this factor or more as it sets or if the weather becomes cloudy but in the context of an additional reddening or whitening of the sky. If the Sun's light diminishes at noon in a cloudless sky, as in a solar eclipse, the illumination of the sky reduces, so although it remains blue, its effect on the landscape changes. The landscape becomes steelier in color. This helps generate the feeling of unease, adding to the effects of the chill as the warmth of the Sun is cut off, not to mention the mystery of the eclipse event itself.

On Mars the sky is less bright, not only because the Sun is less bright but also because its atmosphere is thinner than Earth's. The sky of Mars is basically blue, but a less intense blue than the cerulean blue of Earth's sky (Fig. 9.2), and a blue that is often mixed with airborne red dust. As on Earth, the color changes through the Martian day, and there are strong twilight effects. But here's an additional feature of the atmosphere of Mars: it is composed not only of gas molecules (carbon dioxide and nitrogen) but also with plentiful quantities of dust, blown up and carried by the wind. The dust is the red soil of the Red Planet. The sunlight that it reflects is therefore red, but red in variable quantities and mixed with the intrinsic blue color. It seems that the typical color of the dusty Martian sky is reddish, yellowish brown (Fig. 9.3).

Cloudscapes on Mars are subtle. Clouds on Mars are thin. Clouds at low altitudes (up to 20 km, or 12 miles) are made of water-ice and, at high altitudes above 20 km, carbon dioxide ice. The clouds are wispy, akin to cirrus clouds in the terrestrial air. Billowing cumulus clouds, formed by the cooling of humid air as it rises on a warm afternoon, are impossible on Mars because of the lack of water and the cold temperature. Martian cloudscapes promise no rain. Clouds of ice crystals or water reflect all the sunlight that falls on them, so they appear white. On Mars the white clouds are tinted by the dust that lies below them (Fig. 9.4).

Fig. 9.3 Orange sky over the "Twin Peaks." The color of the Martian sky over this feature at the Pathfinder landing site was yellowish brown, similar to the color of the sky at the Viking landing sites. (Mars Pathfinder: NASA/JPL.) **AA**

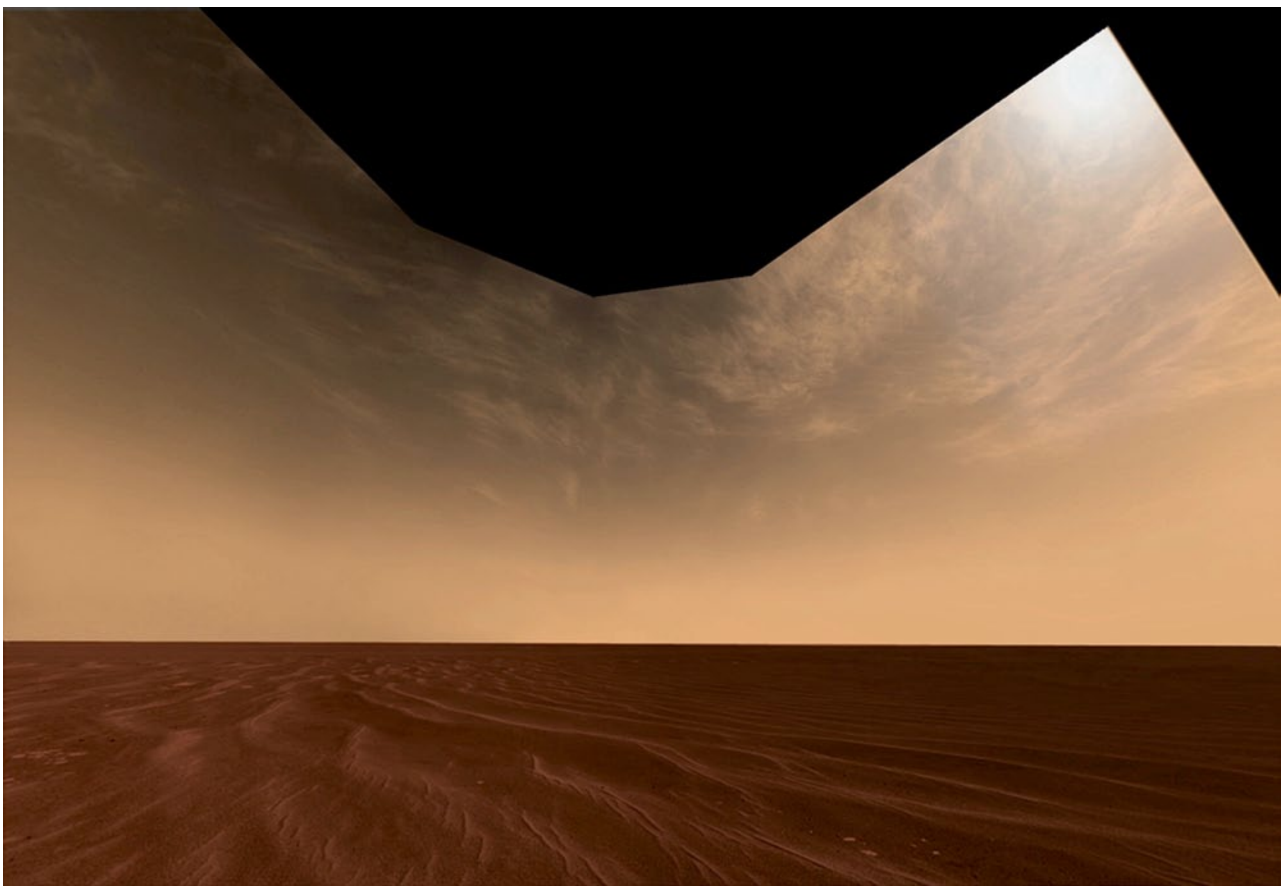

Fig. 9.4 Martian cloudscape.The Opportunity rover captured this cloudscape from the area of Victoria Crater in 2006. She viewed the distant flat horizon across a sandy plain of dunes, above which the orange Martian sky was filled with wispy clouds. (Opportunity: NASA/Cornell/ JPL; image processing by M. Howard, T. Öner, D. Bouic & M. Di Lorenzo for unmannedspaceflight.com.) **AA**

Fig. 10.1 Wanderer Above the Sea of Fog (1818) by Caspar David Friedrich. The explorer looking over a terrestrial landscape of mountaintops could be the artist himself, a self-portrait seen from the back, an artist investigating his world as an explorer investigates the land. The picture reminds us that landscape is what the artist finds, selects and represents; so, too, in this book the planetary landscapes are selected by the scientists, engineers and data processors who operate the space missions—the spacecraft, the instruments and the data analysis. (Kunsthalle, Hamburg: Wikimedia Commons, commons.wikimedia.org/wiki/File:Caspar_David_Friedrich_-_Wanderer_above_the_sea_of_fog.jpg.)

Chapter 10

Representing Alien Landscapes

Landscape (noun)
1. An expanse of scenery that can be seen in a single view.
2. A picture depicting an expanse of scenery.
3. The branch of art dealing with the representation of natural scenery.
4. The aspect of the land characteristic of a particular region…
5. An extensive mental view; an interior prospect.

Scenery (noun)
1. A view or views of natural features, especially in open country.
2. Backdrops, hangings, furnishings and other accessories on a stage that represent the location of a scene.

-From the *American Heritage Dictionary of the English Language* (Houghton Mifflin).

THE CONCEPT OF AN ALIEN LANDSCAPE

This book has been about the landscapes and scenery of other worlds in the Solar System that have been discovered by space exploration and that space travelers will see if and when they arrive there. According to the dictionary definitions, a landscape is a picture showing the expanse of scenery that can be seen in a single view. It is a definition that almost requires the presence of a human observer. A perfect example of this interpretation of the word is the landscape painting *Wanderer Above the Sea of Fog* (Fig. 10.1) by Caspar David Friedrich (1774–1840). The observer dominates the foreground, a terrestrial landscape stretching into the distance, dwarfing the human being but also showing us the explorer's achievement in getting to this viewpoint. The lone walker is interpreting the landscape in front of him in terms of his own experience. Von Guérard's painting of Mount Kosciusko (Fig. 1) is similar.

If we applied too strictly the interpretation that a landscape had to have a human observer and if we insisted that the landscapes had to be as viewed by human eyes, the book would contain only two kinds of extraterrestrial pictures. There would be landscapes of lunar scenery, since the Moon is the only extraterrestrial world that humankind has set foot on. There would also be pictures representing distant overhead views of the surface of the nearer planets of the Solar System seen from far away by astronomers peering through powerful terrestrial telescopes that, nevertheless, showed little detail. Such pictures put us in the position of detached observers, looking down on other planets just as the remote Greek gods of Olympus looked down on humans on Earth below.

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However, the last decades have made planetary landscapes more varied, more detailed and, above all, more engaging. Proxy humans, in the form of robotic spacecraft, have been sent in the last 50 years to explore the worlds of the Solar System. It is almost as great an achievement to create a spacecraft that is able successfully to view the other worlds of the Solar System as to send someone there to see the landscape for themselves. Until human exploration of the planets becomes possible again, even of the Moon, whose surface has not been seen close up by human eyes for 40 years, the spacecraft is the explorer; as a proxy human only, the spacecraft has behind it the experience of the space scientists controlling the spacecraft from Earth to interpret what the spacecraft sees. In Fig. 10.2, the Opportunity rover is parked on a cliff edge, looking at a distant prospect across the bottom of a crater on Mars, parts of her own structure in the foreground, simultaneously showing the planetary landscape and its observer.

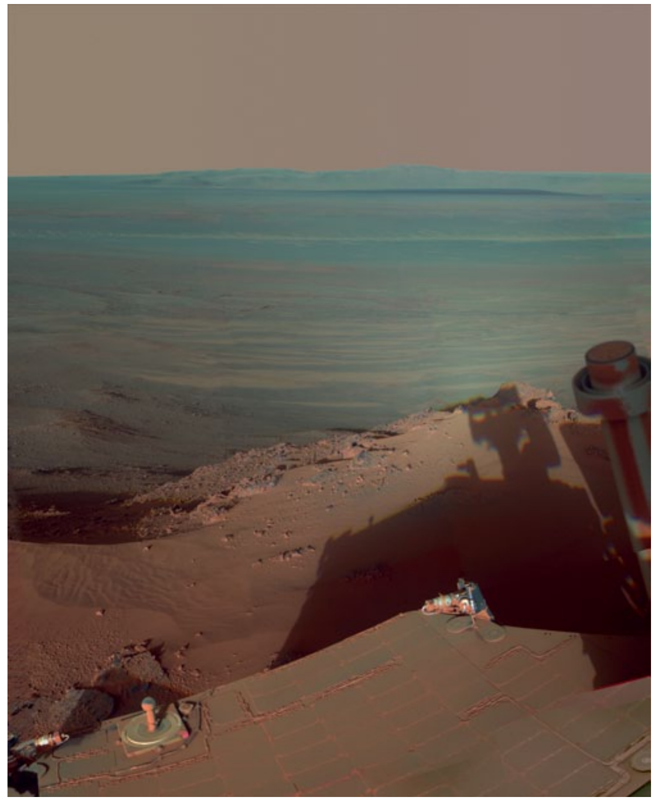

Fig. 10.2 Sunset at Endeavour Crater. This image shows the view from the Mars exploration rover Opportunity late in the Martian afternoon on January 27, 2012. The Opportunity rover, part of which can be seen in the foreground, had just been reactivated after hibernation over the Martian winter on the rim of the Endeavour Crater at a vantage point called Greeley Haven. The far rim of the crater is 22 km (14 miles) away. The sun was behind the cameras, and the shadow of the rover perched on the ridge stretched across the reddish deserts of the crater interior. (Opportunity: NASA/JPL-Caltech/Cornell/Arizona State Univ.) **AAA**

The dictionary definitions suggest that a landscape picture is "art," and make no explicit mention of "science" which is the main reason for obtaining pictures of planetary landscapes. Space scientists would certainly insist that the pictures contain objective records of what is there. Figure 10.2 is about as realistic a picture of the Endeavour Crater as the scientists operating the Opportunity rover can make it.

However, even a record of a landscape that has been obtained for objective scientific reasons has been selected by someone to show other people for discussion. This in itself is a subjective choice about what is interesting or informative. Additionally, the scene has been cropped and framed to make a picture about which to talk. This is a process that requires the exercise of an appreciation of the aesthetics of composition. For the speaker effectively to get the point across to peers, the picture has to appeal to the audience. At first the talk is among the scientists, about the geological and geographical features of the landscape. But of the dozens or hundreds of pictures that are made for discussion in a selected scientific group of people are some that diffuse out into a wider viewership. Some pictures are used for display by the scientists in talks with large audiences, some are reproduced in articles in popular science magazines and in newspapers, some are selected by people in the outreach department of the institute in which the scientific data has been generated for dissemination as a press release, and finally some are chosen by journalists, authors and editors for publication. At each stage of the process the subjective content of the collection of pictures is increased by a natural selection process based on aesthetic appeal.

In a few cases, an amount of artistic skill goes consciously into making data into attractive or pleasing pictures. The same data that went into Fig. 10.2 has been developed by the space artist Don Davis into a very engaging planetary landscape, Fig. 2. The appeal of this picture was shown when, in 2012, it went mildly viral on the worldwide web. Artistic conventions have influenced what space scientists show us and discuss among themselves. The scene in the frontispiece takes this process a step beyond what is usual. Davis has not only changed the colors, he has also enhanced the halo of light around the anti-Sun point and enhanced the shadow of the spacecraft on the crater floor.

University of Chicago art historian Elizabeth Kessler has studied how the same process occurs among the scientists of the Space Telescope Science Institute when images from the Hubble Space Telescope are processed. These images have become well known to all for their cosmic beauty. Subtle distinctions in light intensity are evident to astronomers when analyzing the data, she writes, but "[t]o create a visual representation of these variations, image processing specialists amplify them by adjusting the light intensity scale of the data. Using software, they stretch light values in the middle of the range and allow those at the darkest or brightest ends to be lost in black or white. The resulting image reveals fine details. But these adjustments are not determined by a set of universal standards; they depend on the object being observed, the areas of greatest interest, and on the judgment of the image specialist… [C]olor decisions are not necessarily governed by strict rules, and the final choice often reflects a subtle mixture of scientific conventions and aesthetic judgments."

"There's a lot of translation that occurs between the data the Hubble collects and the final images that are shared with the public," Kessler has said. The Hubble images balance both art and science. In that sense, as well as in their appearance and emotional impact, Kessler has said, they resemble nineteenth-century Romantic landscape paintings, especially those of the American West. "The aesthetic choices made result in a sense of majesty and wonder about nature and how spectacular it can be, just as the paintings of the American West did. The Hubble images are part of the Romantic landscape tradition—they fit that popular, familiar model of what the natural world should look like." Some Hubble pictures look strikingly like pictures of the American West by painters of the Hudson River School. "Just like Bierstadt's or Moran's paintings, the hope here is that the final image will capture the feeling of awe and majesty and wonder about nature," Kessler said. If this is true of the Hubble pictures, how much more so is it true of planetary landscapes?

One space scientist has told us that he goes about his investigations explicitly imaging the Martian landscape with artistic values in mind. Cornell University planetologist Jim Bell is the lead scientist for the Pancam camera on the Spirit and Opportunity rovers that were sent to Mars in 2004 in order to explore the Red Planet, and which provided Fig. 10.2 and many of the other pictures in this book. He has written that he uses the camera not just to "acquire images" of the surface of Mars but to "take photographs," and traces this back to his interest in landscape photography as a boy:

> When I am designing a camera sequence for the Pancams—panoramic cameras—for example, I can think about the same sorts of issues that landscape photographers consider in their quest to capture the spirit and the stories of the land. How can we frame this particular shot? Can we include some foreground rover parts in the image to give the view a sense of depth? What is the balance of the sky and ground? Do we view the scene in natural light or with enhancing filters? And how do we interpret the view later, in the computer "darkroom" where we process the images?

The result is the stark beauty of the Martian landscapes as seen in images from the rovers. Bell modestly underplayed the pictures by calling them "postcards from Mars." The ones that we have reproduced in this book have more artistic value than the word "postcard" implies. In most of the pictures, such as Fig. 10.2, there is limited interference with the scientific process of making the pictures. But a few of them, including the frontispiece, have their origins in the scientific material originated by Bell and his team but have been developed, within some limits, with freedom and license for artistic purposes. In enhancing aesthetic appeal, this process may have reduced some of the scientific value in the image by reducing its grounding in reality, but it has increased the value of the representation in terms of human reaction to the Martian landscape.

The point of view from which the landscape is observed is a crucial factor in the reaction to the picture. The view is, in fact, the primary feature of a landscape. The word "landscape" that developed in English first referred to a kind of picture before it also came to mean the scenery that could be depicted in a picture. The word "scenery" has connotations from theatre that imply that a landscape is a natural scene seen from a low viewpoint, not much above the ground, looking more or less horizontally, into a depth of field that stretches out in front.

Most spacecraft look down on what they orbit over. In Chap. 1, we compared these views to views out of an airplane window. Everyone who has flown knows how detached you feel, looking down on the land below. But there have been a surprising number of spacecraft able to look horizontally to see the surface of the planet in perspective before them and bring us better engagement with some of the worlds outside our own. Appendix 2 in this book lists 40 spacecraft that have landed on the surface of another planet and sent data back from the surface, usually including pictures. The 40 landers have been sent principally to half a dozen of the nearest worlds. Several of them, but more besides, have been explored by orbiting spacecraft that have viewed their surface from a low angle. They skimmed the surface, or targeted scenes at grazing incidence on the edge

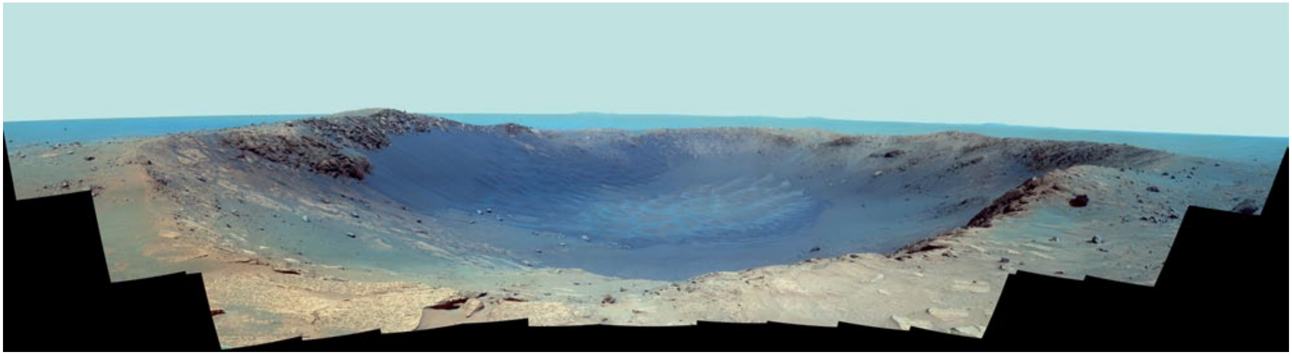

Fig. 10.3 Santa Maria Palos. This mosaic of a meteor crater on Mars was acquired by the Mars exploration rover Opportunity in 2010. She was positioned at a location called Palos on the rim of Santa Maria Crater, looking eastward across the football field-sized crater. The mosaic is shown with a "color stretch" to enhance the subtle color differences in the scene. (Mars Exploration Rover-B: Opportunity: NASA/JPL/Cornell.) **A**

of the planetary sphere. They viewed the reflection of sunlight on a lake, the ash from erupting volcanoes or the spray from geysers against the blackness of space. We have featured in this book landscapes obtained in all these ways.

A lander has to have some surface on which to land, and pictures from landers therefore show landscapes from planets with a hard surface. Such a planet is called a "terrestrial planet," because it is like ours. Given that a lander has to land, its controllers naturally seek the safest places on which to do so—flat areas, free of slopes and hillsides that might cause the lander to topple as it touches down, relatively free of boulders that might smash up the underside of the vehicle. Most of the landscapes seen from landers are therefore plains.

A lander can however carry a rover, a motorized vehicle with wheels, that can explore the area around the landing site. If driven carefully, it can approach more dramatic landscape features, carrying its camera some way from the landing site—usually not very far. The record for the longest space drive on the surface of another world was obtained on July 27, 2014, by Mars' Opportunity rover, when it surpassed the previous record set by the unmanned Russian *Lunokhod 2* rover, which, according to measurements by the Lunar Reconnaissance Orbiter of the tracks *Lunokhod 2* left in the lunar dust, toured 39 km (24 miles) on the Moon in 1973. (The astronaut-driven lunar roving vehicle of the *Apollo 17* mission traveled 35.7 km (22 miles) in December 1972, and Opportunity's space trek is continuing.)

Space treks are usually cautious—rovers do not usually venture onto very high or very steep hills, very deep chasms or very rocky outcrops, because of the greater possibility of an accident in these dangerous terrains. The trek of the rover to position herself to make such views for science (Fig. 10.3) mimics the exploration of mountainous terrain by landscape painters, to position their easel in front of a terrain that will inspire awe (Fig. 10.4).

If human safety is involved, as in the landings by the Apollo program on the Moon, the selection of a landing site is even more conservative. The planners seek out flat areas on plains. Nevertheless, the last Apollo astronauts, with the help of their moon buggy, have looked across some

Fig. 10.4 Llyn-y-Cau, Cader Idris by Richard Wilson (1713–1782). The picture (1774) is of the lake of Llyn-y-Cau, on the mountain of Cader Idris in north Wales. The crater is not volcanic, nor a meteorite crater; it is a glacial erosion crater called a "cirque," or in Welsh, a "cwm" (pronounced "coom"). Richard Wilson was one of the first artists to paint such rugged and uncultivated scenery, devoid of inhabitants (save for the few figures in the painting that give scale). Previously this landscape would have seemed raw and disorderly, the reverse of "sublime." However, Wilson has not recorded the raw scene in its exactitude. He has heightened the precipice at the rear of the composition (Craig-y-Cau) to create a better composition. (Tate Gallery, London: Wikimedia Commons, commons.wikimedia.org/wiki/File:Richard_Wilson_-_Llyn-y-Cau,_Cader_Idris_-_Google_Art_Project.jpg.)

impressive terrain (e.g., Fig. 5.12). Some even more dramatic planetary landscapes are included in this book from overflying orbiters, which can view inaccessible land from a low but safe enough height (Fig. 3.4).

Because plains are uniform, they could be regarded as uninteresting, by contrast to the types of terrestrial landscapes that seem to have an archetypical appeal in the aesthetics of art. Such a terrestrial landscape, created from motives of artistic value, would typically combine open spaces with woodland or mountains, like parkland, savannah or a valley. The open vistas combine in the picture with places of retreat and safety. An immediately pleasing landscape picture has contrast between horizontal and vertical features, with interest both in the foreground and the background.

Possibly these instinctive preferences go back to the natural environments in which early humans evolved. They would have sought out shelter and fortified positions on hills and in caves with easy access to woodland and plains so as to seek food, and with an open view of approaching danger. The parts of our brain that carry artistic aesthetics might be hardwired from an earlier stage of human civilization to appreciate the typical, popular landscape paintings that hang in most art galleries.

However, some adventurous artists have taught us to appreciate landscape outside these familiar and comforting norms. People now appreciate landscapes like the wilderness of the desert Southwest of the United States (Fig. 10.5), as painted by Georgia O'Keeffe (1887–1986) and other artists of the Santa Fe and Taos schools in New Mexico. O'Keeffe was attracted to the colors in the New Mexico landscapes, which translated directly onto her palette: "Badlands roll away from my door, hill after hill—red hills of apparently the same earth that you mix with oil to make paint… All the earth colors of the painter's palette are set out there in the

Fig. 10.5 Untitled (red and yellow cliffs), 1940 by Georgia O'Keeffe. These hills in New Mexico mimic the cliffs of Mars in color, shape, underlying geology and erosional history. Their abstract shapes and color palette are the form of beauty that attracted Georgia O'Keeffe to settle in the state. Where the New Mexico landscape contrasts with the landscape of Mars is in the small trees and shrubs that, at the same time, emphasize the general lack of living things in the picture and testify to the tenacity of life on Earth, even in the desert. (Georgia O'Keeffe Museum, Santa Fe, NM; Oil on canvas, 24 × 36 [61 × 91.4], Gift of the Burnett Foundation [1997.06.36], © Georgia O'Keeffe Museum/DACS/Scala, Florence 2014.)

many miles of badlands. The light Naples yellow through the ochres—orange and red and purple earth—even the soft earth greens."

We now find aesthetic value in untouched, dramatic landscape, and nowhere is that more typically located than in the other planets of the Solar System (Fig. 10.6).

Some people go so far as to claim that natural landscapes are always beautiful. "None of Nature's landscapes are ugly so long as they are wild," wrote the American naturalist, John Muir (1838–1914), the founder of the environmental lobby, the Sierra Club, an activist who campaigned for the preservation of the American wilderness and was instrumental in the creation of the national park system of the United States. He was agreeing with the English landscape artist John Constable (1776–1837): "I never saw an ugly thing in my life." Clouds, mountains, forests, seashores, grasslands, cliffs, canyons, cascades, and rivers are all beautiful, according to this aesthetic—some scenes, perhaps, more beautiful than others.

It is not surprising that it there is room for debate whether a plain of lunar dust or Martian rock is beautiful, since beauty is a human judgment. Under Muir's criterion they are. However, these two planetary landscapes are certainly interesting in themselves, as we hope we have shown. Beyond this, these landscapes can talk to us in their own aesthetic terms.

We can learn the new extraterrestrial aesthetic, just as Americans learned how to adapt the aesthetic that they had brought from Europe to appreciate the landscapes of their own continent. Are grassy plains beautiful? The first reaction to a landscape of a grassy plain might be that there is too much Sun, the land is too flat, there is too much grass but too few

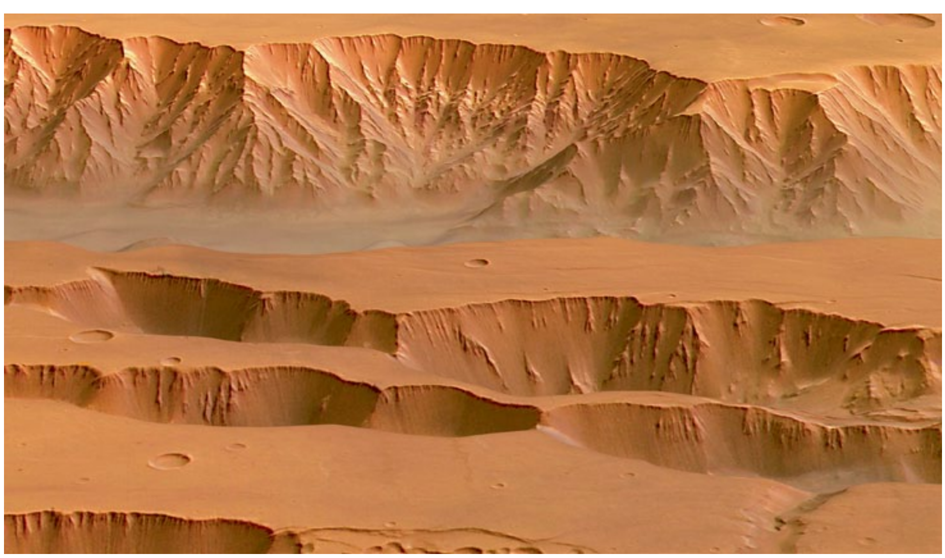

Fig. 10.6 Coprates Chasma. This valley lies in an eastern section of Valles Marineris on Mars. Here the absence of visible life is absolute. (Mars Express: ESA/DLR/FU Berlin; G. Neukum.) **A**

Fig. 10.7 The "Santa Anita" Panorama. This picture was obtained in 2004 by the Spirit rover. It shows the remote touch of humans on Mars through the robotic vehicle in the foreground. The rover was roughly 600 m (700 yards) from the base of the Columbia Hills on the horizon (left). It had left tracks in the Martian sand in its exploratory journey from its landing site. The convergence of the wheel tracks to the horizon gives a sense of the distance that it has traveled, unusual on the rocky landscape of Mars where there are few objects whose size we can judge and therefore whose distance we can appreciate. (Mars Exploration Rover, Spirit: NASA/JPL/Cornell.) **AA**

homesteads, and the composition is awkward because the scenery does not fit well onto a canvas or into a camera frame. But the void of the sky, the traces of farm equipment and of its traffic, such as converging wheel tracks that provide a sense of depth, evidence of the wind in moving grass and curtains, clouds lowering—all these pictorial elements form a new blend of the natural landscape that has its own aesthetic value. We can learn to discover the aesthetic appeal of the plains of planetary landscapes (Fig. 10.7), even if they contain fewer of these kinds of romantic elements.

In addition to terrestrial planets, there is another kind. These "gas giant planets" —Jupiter and Saturn are examples—are primarily gaseous. They are very common in the universe, because the cosmic material from which planets are assembled is primarily gas, including lots of the lightest element, hydrogen. In addition, most of the universe is cold, and it is only in warm zones very near to stars that the hydrogen and associated gaseous compounds are evaporated, leaving the small proportion of solid dust grains that fuse into the crusty residue that makes a terrestrial world like Earth. Gas giant planets are so massive that they keep their cold gas. Landscapes on the gas giant planets are impossible, so there are none in this book. However, gas giant planets have moons that are small in comparison. Their gravity is weak, and their gas drifts away into space, leaving behind a solid residue that forms a solid, terrestrial-like world. Their landscapes are represented here.

Included in this book are pictures made, not only by a camera of some sort, but after a considerable amount of data processing from more complex instruments and recorders. This includes radar scans by altimeters that determine the profile of the surface terrain. The data live in a computer file that is very hard to visualize. But when interpreted through a computer program that presents the data as an image on a screen for assimilation by scientists, that data is directly coupled into both human intelligence and human aesthetic appreciation. Human beings have enormous brains that have largely evolved in order to interpret pictures, and we have become very good at this process. The scientists who make these pictures are interested in showing and understanding geological features, not primarily making realistic pictures, so they may exaggerate the heights of features, or choose colors at will, in such a way as to demonstrate the science. These landscapes are not exactly what you would see if you went and stood in front of them, but there is no doubting the drama and the interest of these images, and they do represent in some way essential properties of the landscape.

THE DISCOVERY OF LANDSCAPE

The word "landscape" comes from the Dutch word *landschap*, from Middle Dutch *landscap*. This word itself is made up of two Dutch components: *land* (= land) + *scap* (= state, condition). The Dutch word at first meant simply "region", or "tract of land", such as a field with defined boundaries, or a natural region such as a river valley or range of hills. The word as a field entered the English language in its Dutch form in 1598, as an artistic term for paintings of natural scenery, but it was not until several decades later that the word is recorded as being used in the sense of real scenery. This implies that people first saw landscapes as they were in paintings and then saw landscapes in real life, viewing them as natural objects to admire for similar aesthetic reasons as art. Because of the variety of painterly effects that are possible, landscapes have figured in one way or another, to a greater or lesser extent, in Western art over the ages.

At first, landscape appears in western fine art only as an adjunct to human activity. In classical art, scenery is a sketchy backdrop to the adventures of a hero, as in the *Odyssey*, or of events from mythology, such as Jason and the Argonauts. In early western art, landscape is not something valued in its own right. Even in medieval times, there was little to enjoy in scenery itself. Fields and vineyards meant hard labor; hills and mountains meant bad weather, frustrating journeys and dangerous bandits; seashores meant violent storms and devastating shipwrecks; the oceans meant deadly sea monsters and hostile pirates.

It was in the fourteenth century that scenery was discovered as something to be appreciated—an escape from the city or a revelation of nature from which there are things to be learned, even if not something that is to be valued for its own sake. According to his own (somewhat exaggerated) account, the fourteenth century Italian humanist, Petrarch (1304–1374), was the first man to climb a mountain as an activity for its own sake. In 1350, he ascended Mount Ventoux in the Vaucluse region of southern France to admire the view from its summit—the Alps and the Mediterranean Sea in the distance, the river Rhone below. "I stood like one dazed," he wrote. "I beheld the clouds under our feet, and what I had read of Athos and Olympus seemed less incredible as I myself witnessed the same things from a mountain of less fame." Petrarch was not, in fact, the first man in his day to climb a mountain only "because it was there." German writers in the tenth and eleventh centuries described various ascents, and a Parisian, Jean Buridan (1295–1358), even climbed the same mountain as Petrarch just before him. But Petrarch was the first mountaineer whose written account of his experience was widely read. What the spin doctor says has a more long-lasting impact than unsung heroics!

Petrarch was ambivalent about whether he should contemplate the natural scenery or set it aside and concentrate on man's place in the world, before God. He quoted the *Confessions* of St. Augustine (A. D. 354–430):

"Men travel to wonder at the heights of the mountains, the mighty waves of the sea, the wide sweep of rivers, the tides of the ocean and the revolutions of the stars, but they do not pay enough attention to themselves."

In paintings of the fourteenth to sixteenth centuries, landscape became important subject matter but was used with the religious motivation recommended by St. Augustine. It was usually expressed behind a scene of human life (i.e., farming, fishing or hunting), or to depict events of religion or history. It was rarely seen on its own. Often the landscape was stylized, with grotesque mountains, fairytale castles, imaginary cities or fanciful trees. Often, too, the landscape was of a kind inappropriate to the subject matter of the scene. For example, central European farmland stretched behind events in the life of a hermit from the Middle East. In the fifteenth century, artists began to paint factual landscapes, and pictures became a way to show places to which it was not possible to travel, the way that this book has collected landscapes in part for the purposes of armchair space travel.

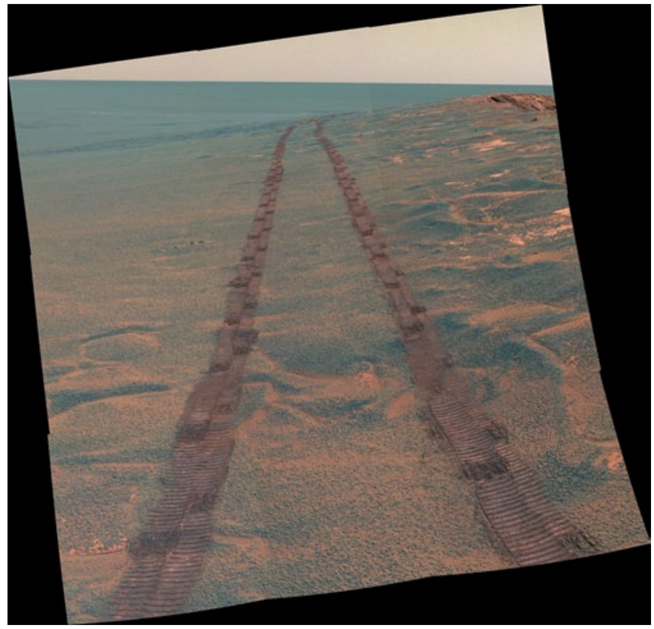

Fig. 10.8 Perspective on Mars. In a rare feature of planetary landscapes, Opportunity's parallel tracks over the sand dunes of the Meridiani Planum on Mars plainly show perspective and hence give a far clearer impression of distance than anything else in the scene. The illuminated sand dunes on the right hand edge, for example, show hardly any diminution of apparent size with distance, since it seems on close scrutiny, the more distant dunes are actually larger than the nearer ones. But the horizon of the plain beyond the hillside shows a similar blue to the effect of an atmosphere on Earth and indicates its distance, even though its blue color arises from effects of the surface geology and color processing. (Opportunity: NASA/JPL/Cornell.) **AA**

Factual landscape pictures convey the realism of the terrestrial landscape in ways that have not always been possible with the landscapes in this book. Artists delineate the landscape with single viewpoint perspective (invented in Florence by the architect Filippo Brunelleschi [1377–1446] in about 1425 and first described by Leon Battista Alberti [1404–1472] in 1435). They also incorporate effects of lighting to indicate the depth of the scene laid out in the picture, washing out the distant parts of the scene as if obscured by mist, and darkening the foreground. In 1604 the Dutch painter Carel van Mander (1548–1606) described the techniques in a chapter on how to paint landscapes in his book, *Het Schilder-Boek*:

> See how that hazy landscape in the distance begins to look like the sky, and almost merges into it. Solid mountains seem to be moving clouds. Notice how the ditches and furrows in the field taper and converge at the same vanishing point, looking just like a tiled floor. Do not get bored taking it all in, as it will give a convincing sense of space to your own background. I want you to pay attention to foreshortening and reducing as you see it in nature. Although it is not architecture for which you need to follow accurate rules, you still need to fix your focal or vanishing point on the horizon, that is to say, on the top line of the water. Everything below that line will appear as if seen from above, while everything else will appear as if seen from below.

Very few of these hints for making and interpreting landscape apply to planetary landscapes, since many planets have thin atmospheres (or none at all), and there is an almost complete lack of parallel lines, since these are primarily created by human activity. (Fig. 10.8 is a rare exception,

Fig. 10.9 St. Jerome in the Desert by Joachim Patinir (c. 1480–1524). St. Jerome shelters in a cave on the edge of a mountainous region. Behind is an amazingly varied landscape of farms, fortresses and pastureland, stretching to a little port and an estuary. (Louvre, Paris: Wikimedia Commons, commons.wikimedia.org/wiki/File:Joachim_Patinir_-_St_Jerome_in_the_Desert_-_WGA17100.jpg.)

showing both convergent perspective lines and a distant blue horizon—which, however, has its predominant origin in an exaggeration of the color of the surface rocks lying on the plain, as well as any contribution from atmospheric haze on Mars).

As well as describing perspective as a tool to depict scenery, Alberti invented a sort of camera obscura the better to sketch it. But, however realistic, the landscape was at the time still just a backdrop to human activity. Usually, the landscape was laid out in tiny detail behind large human figures who dominated the foreground. There were some exceptions, as in some paintings by the German painter Albrecht Altdorfer (1480–1538) or Leonardo da Vinci (1452–1519), where the landscape was much larger than the tiny figures. But, whether the figures were prominent or not, the landscape continued to play a role subordinate to the theme of the picture. One of the earliest dictionaries of the English language, *Glossographia*, was compiled by the lexicographer Thomas Blount (1618–1679) as "a dictionary interpreting the hard words of whatsoever language, now used in our refined English tongue" (first published in 1656). Blount says that "landtskip" was a painter's term for a "by-work", to express "all that which in a picture is not of the body or argument thereof". "Landtskip" was thus clearly of secondary importance and equivalent to the modern term "was thus c."

Not until late sixteenth and early seventeenth century in the Netherlands was landscape painted as a theme in its own right, perhaps with figures that fitted naturally into the scenery. But the landscapes remained at first generic, with features assembled into an idealized account of a place, better than nature. The pictures were, like some of the pictures in this book, manipulated to emphasize the point to be made. In the Antwerp school, founded by Joachim Patinir (1520–1524), the viewpoint was that of a bird flying high above the ground, the better to show the topography, and the vertical features of mountains and rocks were emphasized. The tones were muted browns, blues and greens. Patinir has been described as the "first European landscape painter". His landscapes were imaginary, a landscape of dramatic features assembled to make a picture that represented nowhere in particular as a background to the main interest (Fig. 10.9).

Very similar things could be said about Leonardo da Vinci's well-known portrait of the *Mona Lisa*. Most art historians believe the background landscape, seen from a high viewpoint, is an imaginary, composite landscape assembled from elements in the artist's imagination, although Italian art historian Carla Glori claims to have identified the landscape—through a detail of a three-arched bridge, appearing over the left shoulder of the woman—as that surrounding Bobbio, a village in rugged hill country south of Piacenza, in northern Italy. Leonardo began work on the painting in 1503 or 1504. The bridge was destroyed in a flood in 1472, and the figures "72" can be discerned near the image of the bridge.

The composition, vertical exaggeration, color palette and the viewpoint of the pictures by Patinir and his followers (Fig. 10.10) are echoed by some of the planetary landscapes created by Gerhard Neukum's planeotology group at the Freie Universität of Berlin with the High Resolution Stereo Camera on Mars Express (Fig. 10.11).

Fig. 10.10 Anonymous artist of the Netherlands school (a follower of Joachim Patinir and Pieter Brueghel the Elder), Landscape: A river among mountains, late sixteenth century. The artist has depicted himself at the base of the tree (left). (National Gallery, London.)

In the early part of the sixteenth century, Dutch landscape turned to become a recognizable, factual account of a place and perhaps an event. This may have been a direct result of the flourishing of science at this time, with its emphasis on the workings of nature, as epitomized by the work of Galileo. This was the age of observation, in art as well as in science, with artists such as Rembrandt expressing accurately perspective, lighting effects, shadows, reflections and the sky in their landscape pictures. In the case of Johannes Vermeer (1632–1675), he was aided by the invention of the camera lucida, a device to project a scene onto a drawing surface, which became a common painter' tool. Space artists such as Don Davis who use space imaging data are in Vermeer's tradition in using the latest technology to help their artistic endeavors. It was in Vermeer's time that the word " time that the w on to describe the realities of the arrangements and vistas inherent in nature itself, as well as a painting of nature. By the twentieth century, we were able to see scenery as an entity in itself, as in the landscape photographs of Ansel Adams (1902–1984) and the planetary landscapes of this book.

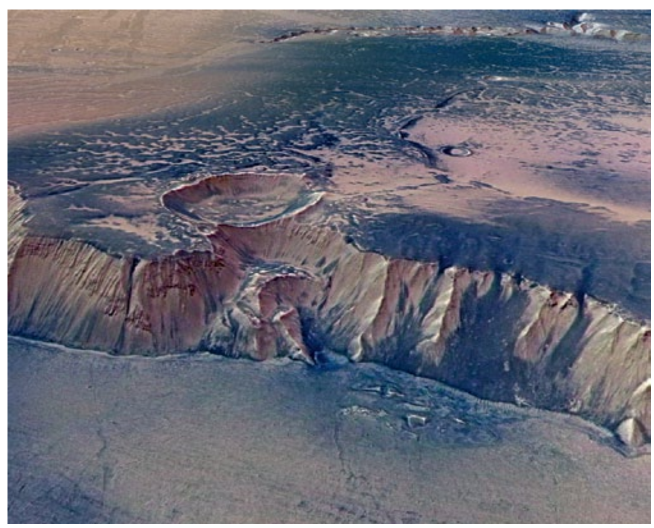

Fig. 10.11 Echus Chasma near Valles Marineris on Mars. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) **A**

PAINTING LANDSCAPE

In parallel to the development of Dutch landscape painting, Claude Lorrain (1600–1682), the French painter working in Rome, created historical scenes set in nature, but, as his career progressed, the figures occupied a progressively smaller area of the canvas. He worked during expeditions into nature, making notes, drawings and sketches to be worked up and incorporated into landscape paintings, often of imagined classical locations. The real scenery that he saw and noted as components of nature was often worked up into idealized aspects of the Roman countryside—a particular tree, and river that meanders in a particular way, and so on. In assembling these components Claude created landscapes that the art critic John Ruskin (1819–1900) noted did not really hang together. The pictures were unnatural.

Claude's direct contemporary, Nicolas Poussin (1594–1665), became as engrossed as Claude in natural scenery. The paintings of these two men drew attention to natural landscape in the aesthetes who were their contemporaries. But in transferring the scenery onto a wooden panel or canvas, they molded what was in front of their eyes into a picture, improving it.

In England, this attitude was captured by Thomas Gainsborough (1727–1788). Best known as a portrait painter of the English gentry, Gainsborough made his living from this work reluctantly and aspired to paint "landskips". He sometimes combined his portraits with landscapes showing the estates of the gentry folk who were his subjects (for example, *Mr and Mrs Andrews*, painted about 1750 and in the National Gallery of London). He often took his inspiration for his landscape-focused studies from the low-key countryside of his native county, Suffolk, which he painted in the Dutch landscape style, with rugged tree trunks, muddy roads and dilapidated cottages. These landscapes were distinctly terrestrial, indeed, distinctly English. However in later life he was attracted away from pastoral scenes of shepherds with their flocks to the grandeur of mountains in the Lake District and the West Country, which convey a drama that is more planetary in their impact, although always showing abundant life (trees, people and domestic animals).

The romantic pictures of dramatic scenery painted by Gainsborough expressed the concept of the "Sublime." The aesthetic quality of the Sublime is a reaction of awe or greatness, the feeling of human insignificance contrasting with the vastness of mountains, for example. Gainsborough's landscapes were not intended as a true record of the scenery, and he refused to paint real Views from Nature in this Country" because he had "never seen any Place that affords a subject equal to the poorest imitations of … Claude". The "Subject [of landscape] must be of his own Brain". Gainsborough made sketches of real scenes and, like Claude, reworked them into finished landscapes of imaginary places.

Gainsborough's views were in contrast to those of two English landscape painters who were his contemporaries: Richard Wilson (1713–1782) and Thomas Smith (c. 1720–1767). Both painted topographically inspired landscapes. They sought out as subject matter rugged scenes in the Welsh mountains (Fig. 10.4) or in the Lake District, often emphasizing the scale of the rocky scenery by adding small human figures. But they composed the pictures according to the principles of Claude and were not above adding details, moving scenic features or exaggerating scale to make a better picture. Their landscapes were reproduced in highly successful commercial engravings and were instrumental in developing the taste for travel and tourism, providing the best viewpoints of natural scenery.

The way the English natural landscape was viewed in terms of the art criticism of the late eighteenth century in Britain was exemplified by clergyman and schoolmaster William Gilpin (1724–1804) in *Remarks on Forest Scenery and other Woodland Views* (1791): "A succession of high-colored pictures is continually gliding before the eye. They are like the visions of the imagination; or the brilliant landscapes of a dream. Forms, and colors, in brightest array, fleet before us; and if the transient glance of a good composition happens to unite with them, we should give any price to fix, and appropriate the scene."

Gilpin was looking out of his carriage window, and he probably was using a Claude mirror to view the landscape. This was a small, black, convex mirror, held like a looking-glass, with which eighteenth and nineteenth century artists contemplated the landscape the better to appreciate its aesthetic properties; tourists followed the artists to view landscape from approved scenic points, much as present-day tourists may pull over into a designated spot on a mountain road to take a photo. In the national parks of the United States, the National Park Service still builds roadside viewing sites at the best spots to see scenery and erects panels that identify and explain the features in the landscape.

Because it is slightly convex, the Claude mirror distorts the perspective of the scene, bowing trees inwards at the sides so that they lead the eye to the central feature. The mirror reduces detail. By imposing a composition and simplifying the natural scene, the mirror makes the scene easier to paint. The mirror is tinted and alters the colors as if the reflection has been washed over with yellow varnish and in general makes the landscape look like a painting in the style of Claude Lorrain – hence the name of the device. For tourists it enhances the landscape's picturesque qualities; the landscape is "qualities;

The scientists who manufacture planetary landscapes may attempt to produce an objective rendition of the color of the scene, but they also often carry out the equivalent of looking in a Claude mirror by manipulating their data in *PhotoShop*®, choosing a color palette to express the inner "truth" of an unfamiliar landscape. They may well have "improved" the coloring, usually not by suppressing the range of colors, as with the Claude mirror, but by enhancing color, in order both to exaggerate differences in content (rock types, etc.) and for aesthetic effect.

Gilpin is regarded as the originator of the aesthetic ideal of the picturesque—by contrast to the formal and civilized symmetries of classical art, picturesque art valued as subject matter irregular ruins overgrown by vegetation, poor people dressed in rags, and craggy rocks. Picturesque means "like a picture," derived from the Italian *pittoresco*, meaning "like a painter", and Gilpin's definition was tautological: picturesque is "... a term expressive of that peculiar kind of beauty, which is agreeable in a picture." Picturesque aesthetic standards valued untouched nature without mani-

Fig. 10.12 Claude Lorrain (1600–1682) Landscape with the marriage of Isaac and Rebekah (1648). (National Gallery, London: Wikimedia Commons, commons.wikimedia.org/wiki/File:Claude_Lorrain_020.jpg.)

fest human presence, save as incidental detail, and perhaps to point up the pristine scenery. Planetary landscapes certainly have this property. No human presence is yet possible on any other world, except the Moon, where human impact was of limited duration, now in abeyance, and confined to few lunar locations!

The paradox of the Claude mirror, that in order to note the scenery you had to turn your back on it and look in a mirror in order to generate a scene with the "right" qualities, was not lost on critics of the picturesque movement. Likewise, in the present day one may see tourists marching through an historic or a beautiful place, their eyes fixed, not on the scene around them but on the screen of a digital camera held up in front of them. Astronauts were sent to the Moon to experience planetary landscapes, but their schedule was so crammed with demands to deploy equipment and record data that they had too little opportunity to experience the strange, exotic nature of the alien world around them to the degree that they may have wanted.

Most landscape paintings are in "landscape format," i.e., they fit on a rectangular canvas or other medium that has the longer axis horizontal, by contrast to "portrait format" in which the longer axis is vertical, such an orientation being better suited to fit a picture of a head. Within the landscape format, Gilpin noted that the composition should be unified, so an artist would select a subsection of the natural scene to fit the frame of the picture, not shrinking from the need sometimes to add an extra tree or rock formation as an "improvement". There would ideally be a dark "foreground", a brighter "middle-distance", and a "distance" without detail. There might even be middle—to foreground features to left and/or right.

Claude had similar ideas in the way he constructed his landscape paintings. He typically painted a dark, foreground feature on one side of the picture, with its shadow stretching across the central foreground, a middle plane with a large central feature, like a copse of trees, and two background planes, the most distant being the lightest and most luminous (Fig. 10.12).

Claude's pictures are more "natural" in their composition than Poussin's. Poussin imposed a more rigorously classical composition on his landscapes, dividing the spaces vertically and horizontally according to classically approved proportions, like the Golden Ratio, with verticals and horizontals exactly at right angles. On the canvas he "improved" nature to be more beautiful according to classical ideals.

The horizon divides the canvas into two, a top and a bottom. Elementary practical lessons on landscape painting suggest that the horizon should be one-third of the way down from the top, or two-thirds, but not midway. Placing the horizon centrally across the picture is sometimes said to be irds, but although Poussin typically did so. If the horizon is placed low, the landscape looks up to trees, mountains and the sky; if high there is more attention in the foreground. Gilpin and Claude favored the former position, the horizon low (Fig. 10.12), as more "sublime." A landscape with a low horizon gives the feeling that the viewer is looking up, as one does in a cathedral. It seems that it is human instinct that looking up generates feelings of respect and awe. One "looks up" to heroes, "putting them on a pedestal". Perhaps we learn this association cradled in our mother's arms. In the landscapes that have been constructed from radar data from the Magellan spacecraft of the planet Venus, the horizon is low and the height of the mountains has been exaggerated, so the viewer is impressed. The Venusian landscapes in these pictures are composed in the same way as the ideal, sublime landscapes represented in paintings.

Most of the planetary landscapes reproduced in this book concentrate on the surface of the planet in front of them and have a high horizon. These planetary landscapes originated as scientific records intended to investigate the geology of the surface of the planet. The composition of the landscapes was thus driven more by the primary purpose than by the aesthetics of landscape art, but, as Jim Bell describes in his book about the Opportunity and Spirit rovers (see Chap. 6), the scientists certainly have framed their subject, to produce a focused picture that directs attention to a feature of interest and to produce a pleasing landscape picture. Bell) s group at Cornell University, which produces the pictures from the Mars exploration rover mission, are collectively known as the Cornell Calibration Crew (CCC)—32 members are listed on the project website. Many have a powerful interest in the artistic qualities of the pictures. One of them, Emily Dean, writes that she was:

> …introduced to the mission at Cornell through an outreach program called LAPIS, which exposed her team to Mars exploration and mission planning. While earning a degree in Art and Architectural History at Ithaca College, she continued to support the MER mission until she had the opportunity to take a full time operations position at Cornell. Since then, she has served as a Documentarian, a "Keeper of the Plan," and a Pancam Payload Uplink Lead (Martian landscape photographer). She finds herself often applying an artistic eye to the technical aspects of her work, and a scientific eye to art. The journey of Spirit and Opportunity through space and the previously unexplored expanses of Mars have served as a major inspiration to her and she could not be happier to be a part of it.

SCENERY

The theatrical equivalent of a landscape is scenery. Early theatrical performances in Athenian Greece starting in the sixth century B. C. did not rely on any kind of representational scenery. The actors were positioned in an open air arena with a view beyond the confines of the theatre of hills and forests (like the classical Greek theatre at Epidauros). Off to one side was a small hut or tent (*skene*; in Greek, σκηνη) where the actor could do costume changes. This building gradually took on a more elaborate role and became part of the action, such as a lookout platform for a watchman, or a building with doors for dramatic entrances and exits, and it may have been painted with *trompe-l'oeil* architectural features such as pillars, as may also the inner walls of the theatre near the arena. Likewise, the Shakespearean theatre, for example the early seventeenth century Globe in London and its modern reconstruction, had, within roofless walls, a stylized, raised stage with pillars, arches, etc., to provide a simulation of a royal throne room, or somewhere where conspirators could talk and/or be overheard, and so on.

If at this time a performance of a play was to take place in a general purpose hall, the nave of a church, or another large building, scenery might be built temporarily around the perimeter as a series of structures or "mansions," representing a palace, a forest, a hermitage, a prison, etc., as demanded by the successive locations of the play's script. In Italy, the stage designer Bernado Bountalenti (1531–1608) built a theatre in the Uffizi Palace in Florence in 1586, with a stage framed at the top and projecting in front of a painted backdrop and a curtain to shut off the audience from the stage during intermissions. In France around 1635 there arose a demand for the neoclassical unity of place during a performance, i.e., the requirement that the action of the play takes place in a single location or certainly neighboring locations, and theatres were built with a proscenium arch—a decorative architectural frame over a thrust stage. The arch acts as a confining frame for the scenery and therefore the action of the play.

In these examples, the stage thus began to function like a picture. This concept was brought to Britain by the architect Inigo Jones (1573–1652), who built several theatres in this style. By the end of the seventeenth century, European theatres were roofed, with stages that had changeable scenery—vertical painted screens that were slid into position using grooves in the floor of the stage, or dropped down from above. The scenery consisted of side units ("wings"), a "backdrop" and the "heavens".

This composition of a is composition of frame, with near-ground planes to left and/or right, and a shallow middle area where the interest is focused, remains in the present day the most common design for the scene of a play in a western theatre. It must be the norm for the concept of "scenery" as experienced by most modern western-educated theatregoers. It is not a coincidence that this perception of scenery is imitated by the composition of many of the planetary landscapes in this book.

GOD'S—AND THE HUMAN—EYE

In the nineteenth century, landscape painting turned to a "romantic" style, in which the landscape represented not only itself but also human values and emotion—awe, beauty, solitude, discovery and spirituality.

This movement was typified by Caspar David Friedrich's landscape painting of the view from mountaintops, expressing what was in God's eye, contemplated by man. The distinction between man and nature was often expressed by painting a human spectator in the foreground.

In nineteenth-century America the Hudson River School of painters, founded by Thomas Cole (1801–1848) of New York, painted Romantic landscapes that expressed the abundance in nature and the vastness of the American countryside that was offered to the pioneers who struggled westwards. The paintings of the Hudson School expressed the relationship of Americans with the land, just as the NASA explorations of the planets and the images NASA displays from the planets express the aspirations of Americans with respect to its ventures into the Solar System.

Fig. 10.13 View from Mount Holyoke, Northampton, Massachusetts, after a Thunderstorm, by Thomas Cole (1801–1848), also known as The Oxbow, 1836. Cole has placed himself with his easel on the foreground cliff top (center, bottom edge). The picture is divided diagonally into two halves, a compositional structure that he (and his fellow member of the Hudson School, Frederic Church) often used, here contrasting the mountain wilderness with the pastoralization of the floodplain. (Metropolitan Museum of Art, New York: Wikimedia Commons, commons.wikimedia.org/wiki/File:Cole_Thomas_The_Oxbow_(The_Connecticut_River_near_Northampton_1836).jpg.)

Potential settlers who explore new lands in general may often be accompanied by schools of painting that convey their qualities. Australian painting has developed through an engagement with the land, starting with the indigenous people, the so-called aborigines, but taken on (independently at first) by European settlers who were inspired by the new scenery that opened out in front of them, not only the trees, birds and animals, but also the red, eroded rocks of the old continent. Austrian-born Eugene von Guérard (1811–1901) is one artist who from 1852 to 1893 found his inspiration in the awesome Australian landscape (Fig. 1).

Cole's Hudson School landscapes are typically composed from high vantage points (Fig. 10.13), with a dark ridge of high ground on one side of the composition, flat ground in the middle distance and a background of mountains, very similar to the view from a crater rim (Fig. 10.14). Where the subject matter of the Hudson River landscapes differs strongly from planetary landscapes is that there is usually water in the terrestrial landscape—a lake, a river, a waterfall—as well as vegetation, a misty distance and a dramatic sky of cloud or rain.

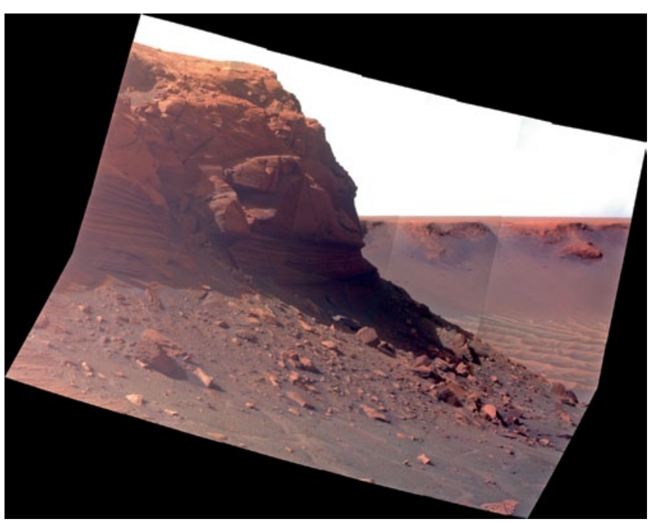

Fig. 10.14 Cape Verde.This cliff, one of several bedrock promontories along the rim of Victoria Crater that Opportunity studied, is about 6 m (20 ft.) tall. The diagonal of the picture divides the exposed cliff of the original Martian layers from the recently deposited windblown sand dunes in the bowl of the crater. (Opportunity Rover: NASA/JPL/Cornell.) **A**

In 1871, another prominent member of the Hudson River

Fig. 10.15 Below the towers of Tower Falls, Yellowstone Park by Thomas Moran (1837–1926), 1909. (San Diego Museum of Art: Wikimedia Commons, commons.wikimedia.org/wiki/File:Below_the_Towers_of_Tower_Falls,_Yellowstone_Park_by_Thomas_Moran,_San_Diego_Museum_of_Art.JPG.)

School, Thomas Moran (1837–1926), accompanied a government-sponsored surveying group led by the American geologist Ferdinand Hayden (1829–1887) to survey the Yellowstone region. Moran's pictures, like *The Grand Cañon of the Yellowstone, The Chasm of the Colorado* and *Towers of Tower Falls, Yellowstone*, were products from the survey, as well as geological and geographical maps. Commenting on Moran's restricted palette, Elizabeth Kessler says that his pictures have a "[h]igh contrast between light and dark, vivid colors and suggestions of vastness and infinity." (Fig. 10.15). The Pancam scientists follow this technique in their color panoramas of Mars (Fig. 10.16), perfectly following the aesthetic of the sublime.

At the end of the heyday of the Hudson River School's activities, which was at the end of the nineteenth century, a third member, the German-American painter Albert Bierstadt (1830–1902) accompanied surveyors into the Rocky Mountains and recorded the magnificence of the wilderness and the intrusion of the surveyors at the very start of the time that the landscape was domesticated by settlers. Bierstadt helped make the Rockies into a national symbol, just as NASA's Stars and Stripes flags and decals on manmade features in the foreground of some of the planetary landscapes make the American exploration program of the Moon and Mars a symbol of American capability (Fig. 5.2).

Bierstadt painted landscapes not just as panoramas but also as geological studies. Stung by criticism about the way that he depicted geological features, he produced paintings in which the rocks were lovingly depicted

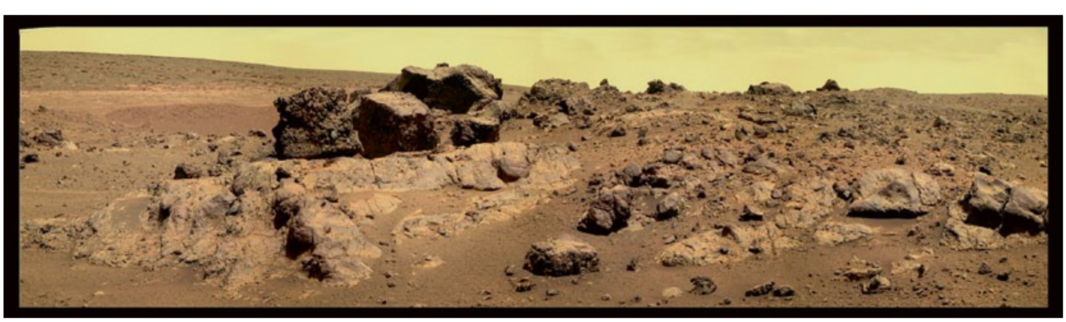

Fig. 10.16 Kirkland Lake, a boulder field at Endeavour Crater, obtained by the Opportunity rover. Picture processed by Stuart Atkinson. (Opportunity rover: NASA/JPL-Caltech/Cornell/S. Atkinson.) **AAA**

in accurate geological detail, like *Niagara Falls*, in which the hard layer of dolomite, jutting out at the top of the falls, contrasts with the softer, more heavily eroded shales below. Bierstadt's painting *Looking Down Yosemite Valley, 1865*, is a view (Fig. 10.17) of a chasm yet to have any planetary analogy. Only a small fraction of the scene is representative of vegetation. It is completely bare of animals, which Bierstadt often included in his landscapes. Here in his Yosemite picture he was emphasizing the rocky scenery, not so much its romantic aspects as its sublime qualities, shown by its low vantage point. Bierstadt found it difficult to access his vantage point with painterly paraphernalia and created his picture in his studio from sketches made on the spot in a sketchbook. How much more difficult would it be to land a robot camera in the *Valles Marineris* to obtain the equivalent landscape from Mars!

Fig. 10.17 Looking Down Yosemite Valley by Alfred Bierstadt (1830–1902), 1865. (Museum of Art, Birmingham AL: Wikimedia Commons, commons.wikimedia.org/wiki/File:Looking_Down_Yosemite-Valley.jpg.)

In England, William Dyce (1806–1864) combined aspects of the exploration of Earth, space and time into one picture. He contrasted the rates of passage of human, geological and astronomical time in his picture of the chalk cliffs of *Pegwell Bay, Kent—A Recollection of October 5th 1858*, with Comet Donati in the sky above and Dyce's family on vacation, collecting specimens in the rock pools below, apparently oblivious to the planetary landscape around and above their heads (Fig. 10.18). How Dyce would have loved to be able to see the hidden planetary landscapes revealed in this book! How we ourselves would like to see Martian landscapes with people in them, making artistic points beyond what has been possible up to now!

Fig. 10.18 William Dyce (1806–1864) Pegwell Bay, Kent—A recollection of October 5th 1858 (1858-1860). (Tate Gallery, London: Wikimedia Commons, commons.wikimedia.org/wiki/File:William_Dyce_-_Pegwell_Bay,_Kent_-_a_Recollection_of_October_5th_1858_-_Google_Art_Project.jpg.)

The Romantics stressed the belief that people should not be separated from the landscape but be immersed in it. People are within nature, not apart from it. Even in his pictures allegedly of the American wilderness, Bierstadt inserted native American Indian campsites, or pioneer settlements. In an extreme, this belief in the connection between the natural environment and people was exemplified by J. W. Turner (1775–1851) through the lengthy title of one of his works: *Snow Storm—steam-boat off a harbour's mouth making signals in shallow water. The Author was in this Storm on the Night the Ariel left Harwich, 1842*. The impressionist

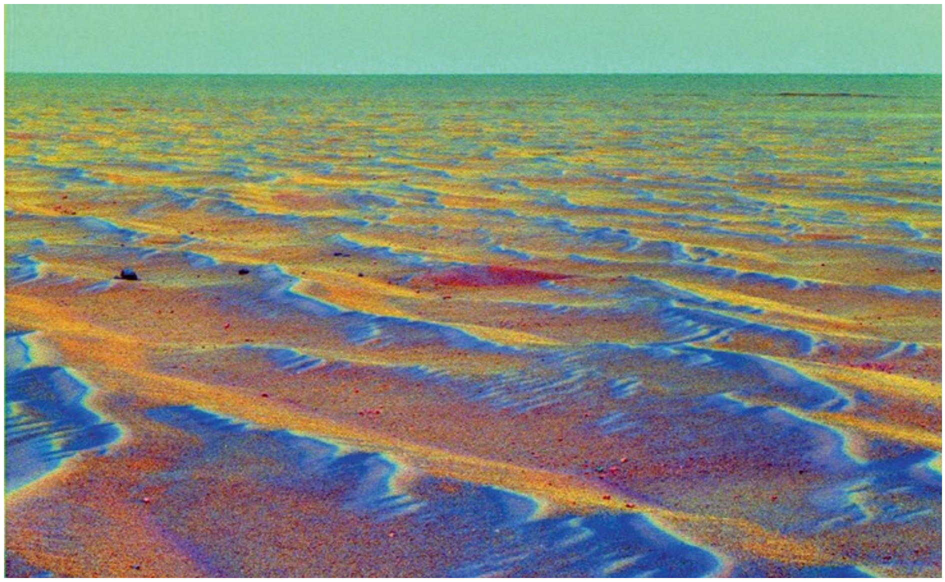

Fig. 10.19 Ripples. Like the sailors of the age of exploration of our world, Opportunity rover has crossed an "f our of waves, not on the surface of a sea but of ripples and dunes in the sands of Mars. The Opportunity rover drove across these dunes in February 2005 in its journey from the endurance to the Victoria Crater. The distances between ripple crests range between 1 and 2 m. The color range in the image has been heavily "stretched" to create this picture, which is almost abstract art. Having spotted some rocks in the middle ground of this vista that did not seem to belong there, Opportunity went on to investigate one of them close up, the first thought being that the rock was a meteorite. One rock, called "Russett" after a variety of potato, proved to be a fragment of the surface of Mars recently having been flung high into the air from a meteor impact a long way away and having fallen back onto the sandy surface. (Mars Opportunity Rover, Pancam image by NASA/JPL/Cornell and the Pancam team.) A

nature of his painting was heavily criticized by conventional critics of the time, but he was defended by the critic John Ruskin, who also attacked the idealization of landscape by such painters as Claude, calling them "a group of the artist's studies from nature, individually spoiled, selected with such opposition of character as may insure their neutralizing each other's effect, and united with such unnaturalness and violence of association to insure their producing a general sensation of the impossible."

Ruskin insisted on the necessity of "an earnest, faithful, loving study of nature as she is." In no other artists is this so epitomized as by the English painter John Constable, who "found his art under every hedge," and by the French impressionist Pierre Auguste Renoir (1841–1919), who labored into the landscape under the weight of his many canvases, which he would repeatedly take to his easel to work and rapidly discard for another as quickly as the light changed. The stream of pictures of Martian landscapes of a developing dust storm (Fig. 6.37) or as the sunsets in a Martian evening lie in Renoir's tradition.

Landscape painting remains one of the most popular forms of art. The story of art does not stop with realistic landscape painting but ventures on into abstraction. And so, too, do the planetary landscapes presented in this book (Figs. 10.19, 10.20). The power of space orbiters, landers and rovers to view the surface of a planet such as Mars is now so great that their telescopes and cameras have brought us inside the vista of impressive varied scenery to be face to face with individual forms of land. These geological features of the Martian landscape have been abstracted into pictures of impressive patterning or chaos, sometimes both together, with colors enhanced into pleasurable celestial hues, reminiscent of abstract art. The scientific features of these planetary landscapes have been emphasized, but there remain in the images unmistakable clues of the presence of human beings, if not in physical proximity to the scenery then in the making of the pictures. Manmade science and engineering have obtained the pictures, and the human eye of the picture maker has selected and presented the images. Most important of all, the viewer is ever present, contemplating the scientific meaning and sublime beauty of the landscapes.

Fig. 10.20 Beach at Heist (1891) by Georges Lemmen (1865–1916). Lemmen was a Belgian artist who painted in a pointillist style, with a vivid Art Nouveau mixture of anti-naturalistic colors. In this painting, the only sign of human life is a boat, abandoned on the sandy shore against a background dominated by the yellows and oranges of sunset. (Musée d'Orsay, Paris: Wikimedia Commons, commons.wikimedia.org/wiki/File:Lemmen2.jpg.)

Fig A.1 The Whirlpool Galaxy, M51, a grand design spiral galaxy. Both images are composites of monochrome pictures taken with individual filters and added into a color image. (NASA, ESA, and the Hubble Heritage Team, STScI/AURA)

Appendix

APPENDIX 1

Down to Earth

How realistic are the images of planetary landscapes in this book? If you stood on a planet in front of one of these landscapes and held up its image to compare, would the image look, in shape and color, very like the real thing? We are accustomed to regard photographs as realistic, even black and white ones. Are the images here as realistic as photographs? We are willing to accept as representative of the scenery in front of the artist a painting of a landscape hung now on the wall of an art gallery, and to understand that the painting is a human construction based on the colors available in the artist's imagination and palette, but are the planetary landscapes here more or less realistic than a watercolor or oil painting?

The processes that take place to produce a photograph with a commercially produced consumer camera are hidden in the click of the shutter. The processes that take place to generate a planetary landscape have to be explicit to aid their scientific analysis, and they take place step by step in computers as the space scientists manipulate the data. The images are "processed," but that does not necessarily make them any more unreal than the chemical development processes that used to take place in film in a darkroom or the automatic processes that occur in normal digital photography and the display of a picture on a computer.

Early in the history of space exploration, planetary landscapes were exposed in black and white (on film or in video cameras), but nowadays, most often, the camera in the spacecraft produces images in color.

The principle of color photography lies in fundamental discoveries about the nature of vision by George Palmer (ca. 1786), that the retina contains "particles" whose sensitivity to color differs. Thomas Young (1807) showed how there was a limited number of different retinal "particles" and suggested, from the practices used in color printing, that there might be three such particles. Hermann von Helmholtz (1852) proved how three light receptors in the retina were sufficient to define any color. In 1861 at the Royal Institution in London, the Scottish scientist James Clerk Maxwell (1831–1879) directed the creation of the first color photograph through what became known as the three-color separation process. His photographer Thomas Sutton exposed three slides of the same scene (a tartan rosette) through red, green and blue (RGB) filters. Maxwell projected the three slides with three "magic lanterns," each equipped with the filters. When he had brought them into superposition, he had made the first color photograph.

Maxwell's technique was engineered into a single package in the invention (1935) of color sensitive film—three sensitive photographic emulsions layered onto a supportive base. In modern consumer opto-electronics, digital cameras contain a single sensor with individual pixels covered by a mosaic of three color filters arranged in square groups of four (one R, one B and two G). Signals from the individual pixels are combined by software that is fixed in the camera to make a digital color image that can be printed or projected onto a computer monitor. The same principle is used in monitors, with numerous groups of pixels that emit red, green and blue light, which, in combination and unresolved when viewed from a distance, provide a single colored pixel. The painting technique called "pointillism" likewise used individual separated dots of color to provide an "impression" of a colored scene (the technique used in Fig. 10.20).

A space camera exposes individual pictures in several color filters, as Maxwell's photographer did. The purpose of color vision in space exploration is to provide diagnostic scientific information, not simply pictures, but if three images have been obtained these

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three channels can be made to match with the three-color vision of the human eye. If the aim is a realistic picture of a planetary scene, three images have to be obtained and combined so that they stimulate the human eye in the same way that the real scene does.

In an ordinary camera, the color channels are separated, but they are all present in the camera, interleaved in the detector, all exposed at the same time, and assembled through fixed software into a single, color picture right from the start. The human eye does much the same, with the software being the marvelous operations of the human brain. In both cases, the software is what it is. There is little or no choice about the image that results.

In a space camera, images of the planetary scene are made in several different color channels, recorded, transmitted and stored individually. They are combined, scene by scene, into color pictures by general picture-processing software, in the use of which there is considerable freedom of choice on the part of the science team about how the end result will look.

This technique is similar to the technique that was brought to a high state of perfection in astronomy in the 1970's using photographic emulsions by renowned pioneer astrophotographer David Malin, using what was then the Anglo-Australian Telescope, and the same as is used by the Hubble Space Telescope to generate its gallery of wonderful pictures of galaxies and nebulae (Fig. A.1).

The color channels in a space science image do not, at the start, represent the color image as we would see it with our eyes. The color image has to be produced by balancing the color channels as they are combined. Astronomical photographs contain self-calibrating objects, namely stars that are on average white. The stars are too pink? Reduce the red intensity. Too green? Increase the red. It is more difficult to do this in constructing color pictures of the surface of a distant planet, where there is nothing familiar in the scenery whose color we know. To help, rovers and landers can have color reference charts that are mounted on the spacecraft in sight of the camera. The charts are objects whose color is known. That is not always an option for every spacecraft, and the color channels might have to be balanced from calibrations that have been made before the spacecraft was launched. The scientists hope that nothing changes during the flight and landing.

One aim of the balancing process might be to make a picture that is true to life, as realistic as possible. Another aim might be to make pictures that are what the scene would look like if it was here on Earth. This might help, for example, with the identification of minerals on Mars that exist here on Earth but which look different under Martian conditions of illumination.

The scientists do not have to be bound by the aims of making "realistic" pictures. Like artists, they are not always constrained by that restriction. The picture might be aimed towards bringing out some features of interest in the scene, like the spectral emissions of a nebula (Fig. A.1) or the mineral content of the rocks (Figs. A.2 and A.3). In such a case the colors might be exaggerated. This produces pictures that are like those you would see on a television if someone has been fiddling with color controls and turned up the contrast, or like an impressionist painting where the colors have been exaggerated for artistic effect, and in order to stimulate appreciation of subtle colors (Figs. 10.20, A.1–A.4). Or they may simply be pictures that are pleasing or expressionist (Fig. A.5).

The picture might also be an intermediate stage between a scene that we cannot perceive completely and our brains. A picture might be made from an incomplete set of color channels, with one channel simulated, and the color contrast of the picture is diminished. A picture might be exposed in color channels like infrared, ultraviolet or radio radiation that human beings cannot see at all. These color channels can be combined into a color picture as if they were what we can see. In either case, the landscape picture that results gives us a view of a landscape that some terrestrial animals or some extraterrestrial beings might be able to see, if their eyes were sensitive to those kinds of radiation. These pictures may

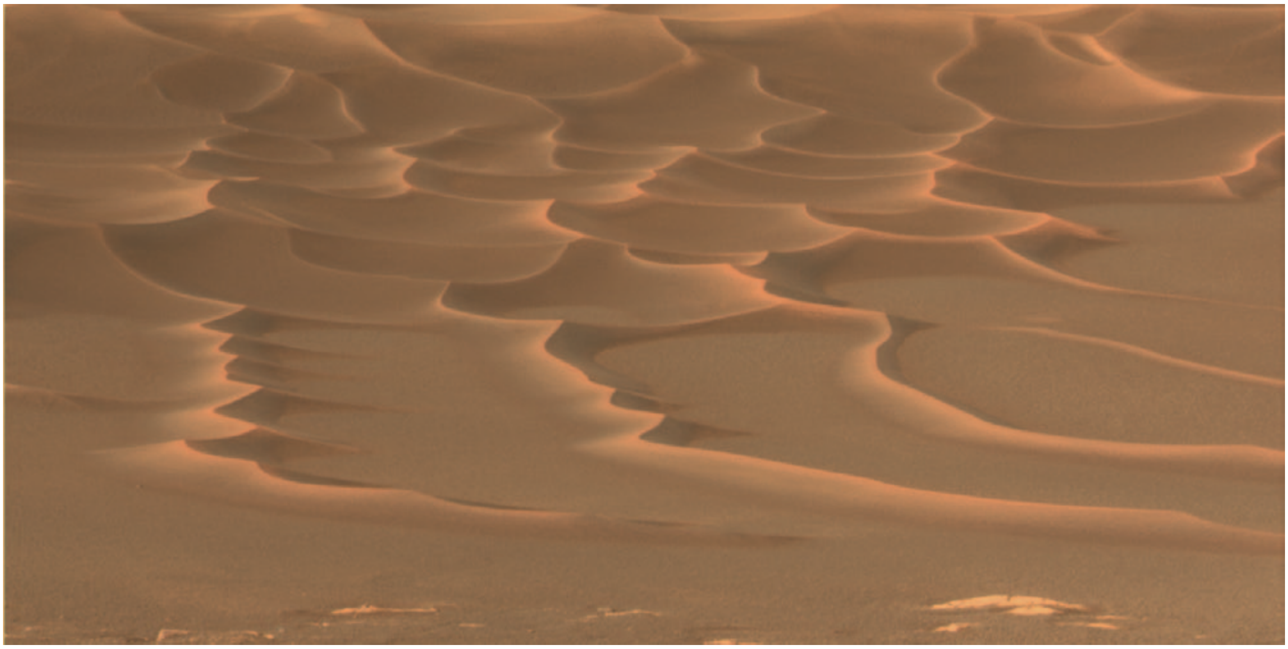


Fig A.2 A field of sand dunes in the crater Endurance. The thin tendrils of sand that creep into the foreground are less than a metre high. This landscape and Fig. A.3 have been made from the same set of scientific data. Fig. A.2 has been balanced to provide a landscape that is realistically coloured, and shows the reddish-coloured dust that dominates the scene. (Mars Exploration rover Opportunity: NASA/JPL/Cornell.) **AA**.

not be completely realistic for us, but they would be realistic for those hypothetical beings (Fig. A.6).

Sometimes pictures made in these vision-expanding ways are described as "false color" pictures. However, the color is not false; it is a presentation of colors that are really there but in such a way that we cannot ordinarily see them—the colors are different from what we normally see. Bees have eyes that respond to ultraviolet light that is invisible to us. Flowers evolved to attract bees and developed patterns that reflect ultraviolet light. Bees see in these flowers attractive patterns and colors that we cannot see. We could use an ultraviolet responsive camera and reveal these colors—not as they are to bees, but real, not false.

False color is a way of making pictures that use color to represent quantities unconnected with light or other radiation. Two examples would be the representation of height on a contour map—purple is high, brown is intermediate height, green is low—or temperature—blue is cold, yellow is warm, red is hot. The color palette in a false color image might well have been chosen to link with some correlation in our mind about what colors imply (the green color on a contour map is reminiscent of low-lying fertile flood plains, and the purple evokes high moorland) but in no way is that image what someone could really see. None of the images in this book are "false color," unless we specifically flag a picture as such (Fig. A.7) in any of the few cases.

Finally, some planetary landscapes have been made using computer files of data that have measured the terrain. These files constitute data that could be used to prepare a contour map. The data could be processed to produce a view of the scenery from an arbitrary point, and it could be colored, pixel by pixel, by overlaying a color photograph on to the data. This process could produce a landscape that is as real as a photograph, but the scenery might be pictured as if from a viewpoint that cannot in fact be reached, and the vertical relief might be stretched. Again, such pictures form a spectrum of reality, from quite literal to exaggerated. But they are not fanciful.

The landscapes reproduced in this book have been prepared in all these ways—see Appendix 2 in this book for further details. To help the reader assess the reality of each landscape, we have given a "reality grade" to each picture in this book, along the lines of Standard and Poor's credit ratings for financial institutions or bond issues. **AAA** is as

Fig A.3 Blueberries among the sand dunes in the crater Endurance. The thin tendrils of sand that creep into the foreground are less than a metre high. In this landsape, made from the same data as Fig. A.2, the colours have been exaggerated to show how the dune crests have accumulated more dust than their flanks. The blue colouration on the flat surfaces is due to a litter of spherules that contain hematite (the scientists termed them "blueberries" after a casual remark by Steve Squyres, the principal investigator for the Mars Exploration Rover Mission, who, when they were discovered, commented that the spheres "looked like blueberries in a muffin"). The blueberries have accumulated on the flat surface between the dunes, the floor of the crater. (Mars Exploration rover Opportunity: NASA/JPL/Cornell.) **A.**

realistic as a photograph on color film or by digital photography, even though these familiar processes have their limitations. All the subclasses of Reality Grade **A** are as realistic as a picture produced by an artist of what he sees of a scene, but as the grade is reduced to **B** or even **C** the landscape is departing from reality in ways that would be progressively jarring if the picture was held up on view and compared against the landscape. At grade **C** the landscapes are representative but not very realistic. The criteria are described in the Introduction.

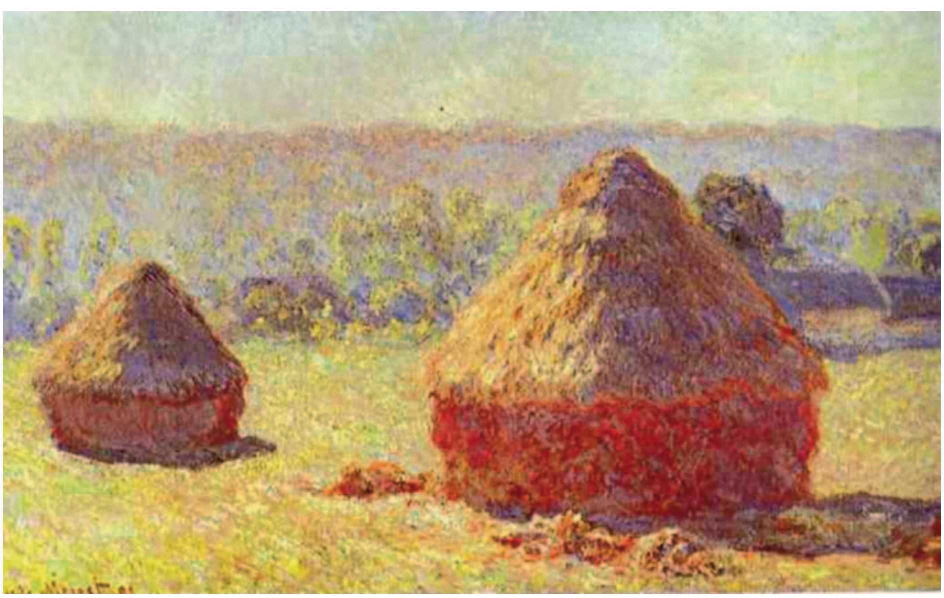


Fig A.4 An impressionist landscape Haystack: End of the Summer; Morning, 1891, by Claude Monet (1840–1926). Monet has expanded the color palette to exaggerate the colors inherent in this landscape, so that the viewer can see a beauty there that is enhanced over the usual perception. (Louvre, Paris: Wikimedia Commons, commons.wikimedia.org/wiki/File:Claude_Monet._Haystack._End_of_the_Summer._Morning._1891._Oil_on_canvas._Louvre,_Paris,_France.jpg)

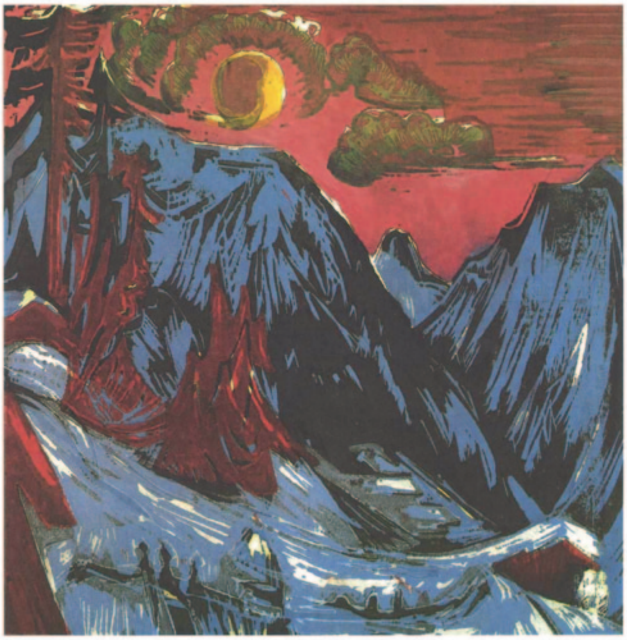


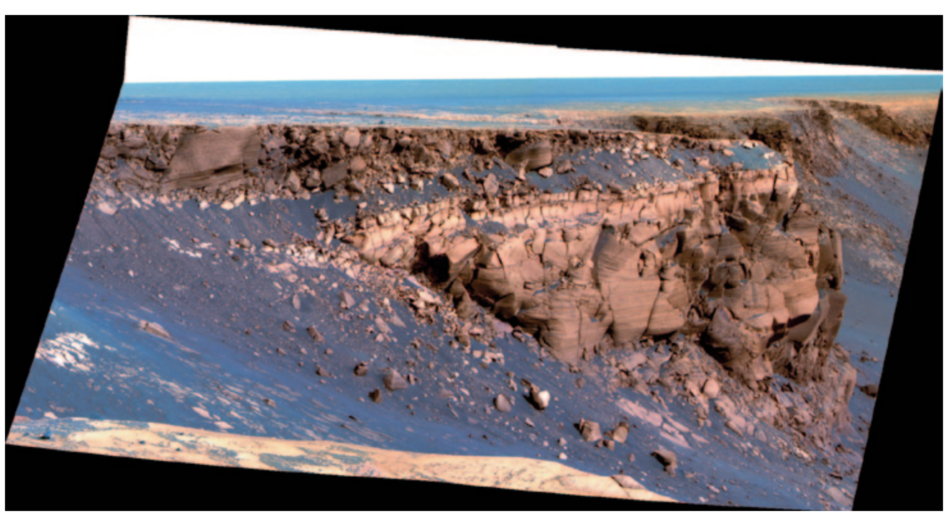
Fig A.5 Mountains in Winter (1919) by Ernst Ludwig Kirchner (1880–1938), a woodcut by the artist who virtually invented German expressionism. (Sprengel Art Museum, Hannover: Wikimedia Commons, uploads7.wikiart.org/images/ernst-ludwig-kirchner/mountains-in-winter-1919.jpg)

We have chosen planetary landscapes to illustrate this book that are grounded in reality. They represent the view that you would have if you stood on the distant world—to some degree! The landscapes have been possible thanks to technology, even where they have actually been made, as with some photographs of lunar scenery, in a camera with an Apollo astronaut's finger on the shutter release.

We have given each landscape illustrated a reality grade, as indicated above, ranging from **AAA** for the most realistic to **C**. The reality grade depends on how the picture was made, and here are the issues behind it:

1. *Color photograph on film.* Commercial color photography on film was developed in order to depict scenes as they are remembered to have been seen (e.g., on holiday), with colors perhaps slightly more vivid than they really were, especially with slide (reversal) film. Color balance was usually optimized for flesh tones, to which the human eye is especially sensitive, and the films were designed for short "snapshot" exposures, usually in earthly daylight, where the sunlight has been filtered through the atmosphere. The film consists of three layers each sensitive to different band-passes, red (R), green (G) and blue (B). After processing into a picture, and viewed either as a slide or as a print, the three layers produce images in the eye that stimulate three kinds of photoreceptor cells in the human retina. These are known as "cones," and are sensitive to three colors approximating to red, green and blue parts of the visible spectrum. The brain takes the stimuli generated by the light-sensitive cones and makes what we conceive as a color picture. Films of different types vary in respect of their depiction of colors, but within a range that we have learned to accept as realistic. The color film process relies on returning the film to Earth, and the only planetary landscapes made in this way (apart from those showing landscape features on Earth) were made by Apollo astronauts on the Moon. Reality grading: **AAA**.
2. *Color pictures made by a conventional digital or video camera, including broadcast television.* The same criteria were implemented for the realism of pictures made digitally as for film. The images can be relayed by data transmission techniques, and so

Fig A.6 Cape St. Vincent. (Opportunity: NASA/JPL/Cornell.) AA



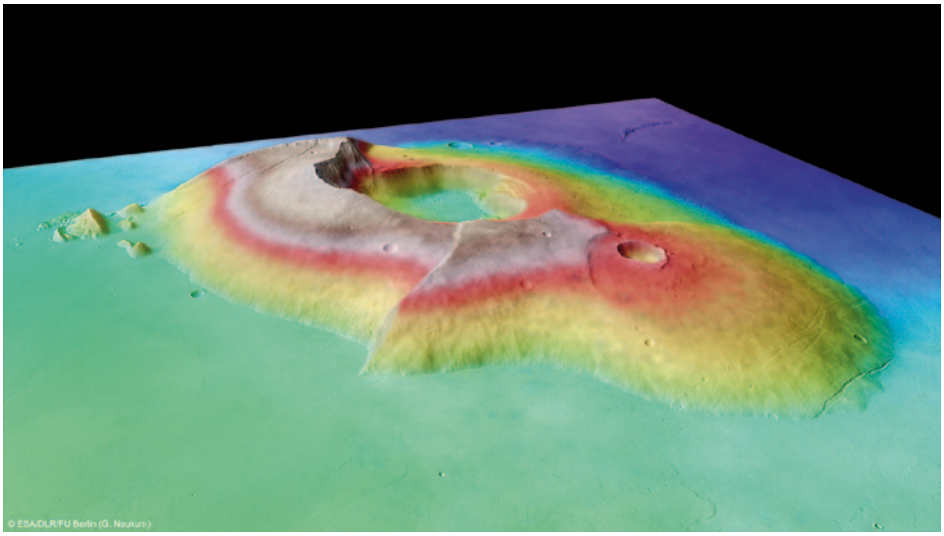


Fig A.7 A false color picture of an extinct volcano. The Martian volcano is shown here colored to show contours of height, and the perspective is stretched vertically. Tharsis Tholus is large by terrestrial standards, towering 8000 m (26,000 ft) above the surrounding terrain, with a base stretching about 150 km (90 miles). On Mars, it is just average-sized. Martian volcanoes build up more easily because of the low gravity there—about 38 % of Earth's. The volcano is dominated by an almost circular caldera, 33 km (21 miles) in diameter. The caldera floor lies as much as 2700 m (8900 ft) below the caldera rim. The volcano emptied its magma chamber in stages after eruptions, producing the stepped ring effect. As the lava ran out, the chamber roof was no longer able to support its own weight, so the volcano collapsed, forming the large caldera. This was not, however, the end of the story. At least two large sections of the volcano have collapsed around its eastern and western flanks during its 4-billion-year history. These catastrophes are now visible as scarps up to several kilometers high. (Mars Express: ESA/DLR/FU Berlin, G. Neukum.) C

could be made by robotic spacecraft. However, if the planet (or moon) has a thick atmosphere such as those covering Venus or Titan, the sunlight filtering to the surface could have a distinctly different hue compared to terrestrial daylight. The eye naturally adapts to this; for instance we do not normally notice the large color shifts as we move from daylight to artificial light indoors, or in the landscape in twilight, but cameras need to be readjusted. (Some digital cameras have settings for tungsten or fluorescent lighting, as do most TV cameras.) The Japanese Selene spacecraft made landscapes of the Moon in this way from an altitude of about 100 km (60 miles), with a sideways-looking high-definition color TV camera: **AAA.**

3. *Black and white photograph on film or with a video camera.* Clearly, black and white photography is unrealistic in so far as its color rendition is concerned. Nevertheless black and white pictures show the structure of the scenery because the most sensitive type of the photoreceptor cells in the retina, the "rods," can operate on their own (at low light levels when the cones are not activated) and the human eye-brain combination has learned to accept the image as a real rendition of the brightness range and textures in the scene. Black-and-white photography was used by the lunar orbiter spacecraft as they surveyed the Moon for the Apollo program, and by the Apollo astronauts, with some examples in this book. Because the lunar surface is almost colorless, the lack of color rendition hardly matters. The early Mariner spacecraft had black and white video cameras to image the surface of the planets to which they were sent. Grade: **AA.**
4. *Digital images made by adding three color images in color bands that approximate to those of the human eye.* Science cameras usually record their data by imaging the scene through colored filters whose band passes are chosen according to some scientific diagnostic. A group of three images can be superimposed to produce pictures that approximate the RGB band passes of conventional color film and the retinal cones. The images can be very realistic. However, they might not be in the exact colors that would actually be seen by a human observer at the scene, because the relative balance of the reconstructed RGB images might be subject to uncertainty, or it could be altered in a way that is driven by the science goals of the imaging program. The Viking landers, the HiRise Camera on board the Mars Reconnaissance Orbiter, and many other space-imaging devices make pictures of this kind. The art has been brought to a high state of perfection by Jim Bell's Pancam cameras made for the Mars exploration rover missions (Opportunity and Spirit). Here is Bell's own explanation of his color postcards from Mars:

> The two Panoramic cameras (called Pancams) on each of the Mars exploration rovers work somewhat like a pair of human eyes. Each camera's light sensitive "cells" are called pixels, and they are part of a light detecting "eye" called a charge coupled device, or CCD. However, unlike the human eye, the Pancams only measure one single wavelength or color at a time. In front of each camera is a filter wheel with eight different filters (seven colors plus one filter for looking at the Sun), each of which allows only certain wavelengths to hit the CCD. The filter wheel in front of the camera in the left Pancam eye of each rover has six filters that span the colors that we can see, from blue to green to red. The other filters can detect colors of light that we cannot see, called "infrared." When we want to take a "true color" picture of Mars, we actually take six pictures of the same exact spot—once with each of the six filters on the Pancam's left eye. Afterwards, we use computer software to combine the separate pictures and to calculate the proportions of primary colors—red, green, and blue—that the rover was seeing. We then combine these three "RGB" images into a single picture that your computer can then display as an estimate of the actual colors that you would see if you were there on Mars. Digital cameras that you can buy in stores work in a similar way, except that the filters are bonded directly onto the CCD, and the RGB images through the different filters are combined automatically for you by the camera's electronics.The detailed math and computer processing that goes into this process is described in the next section. It's important to point out that this is only an estimate of the true color of each of these scenes from Mars. As mentioned above, everyone perceives color differently, and different computer monitors and printers display color differently. The colors also vary with time of day, and even from day to day because of different amounts of dust and clouds in the Mars atmosphere. And there are also sometimes small calibration problems with the images that can cause errors in the true color calculations. We've done the best job that we can to estimate the colors. Ultimately, the true test of color success will probably have to await the judgment of the real experts: the first astronauts who go there and see the place for themselves sometime in the next few decades…

Bell's modest claims for his pictures conceals the skill with which they have been constructed, and his pictures are at the "more realistic" end of the range of Reality Grades that I have assigned to pictures made by three color addition, namely **AA** to **A**.

5. *Two color digital images.* On occasions, for some operational reason (running out of time, perhaps, or a telecommunications failure that lost data), a digital image has been made by recording only two color images in color bands that approximate that of the human eye. A third color band can be synthetically generated by averaging the other two, and the three images can be used as if RGB. This works best if the synthesized image is green, i.e., between B and R. If only the B and G bands or the G and R bands are available there is less information available, and strong color casts are likely, as in 3D pictures made by red and green images viewed through eyeglasses with one red and one green lens. **BBB** to **B.**
6. Digital images may be made by adding three color images in color bands to at least one of which the human eye is not sensitive (perhaps the infrared or ultraviolet). It is common for cameras on space satellites to obtain infrared or ultraviolet images. Cameras are readily sensitive to these wavebands even if human eyes are not, and the bands contain important scientific information. One can imagine extraterrestrial creatures (or indeed terrestrial animals) to whom such pictures would be real. Although they are not very realistic for us, they do tell a truth and are certainly scientifically valuable: **B**.
7. A number of landscapes in this book have been constructed from datasets that represent the heights of elements of the surface of the scene, as measured by some sort of

altimeter as on the Mars Odyssey orbiter, where the altimeter was a laser system that scanned the terrain. The altimeter could also be a stereo camera, like the High Resolution Stereo Camera (HRSC) on board Mars Express. The HRSC is imaging the entire planet in full color, and in 3D. A perspective landscape can be computer-generated from the data, with each colored point projected onto the landscape picture by means of rays that radiate from any chosen viewing point. These landscapes can be very realistic, even if the viewing point is unreachable: **A**.

8. *A number of landscapes produced by method 7 above can made with an exaggerated height scale.* The pictures produced by the HRSC science team are routinely of this sort. Regarding them as similar to color pictures made with exaggerated colors, we give these a Reality Grade of **A**. However, sometimes the height data are reproduced from a range of colors that bear little or no relation to reality, to exaggerate the height scale or to reveal specific features in high relief, in the same way that geographical maps reproduce altitudes and ocean depths (1D data on a 2D plot) in a range of colors as well as contours, to make the maps more readily interpretable to the eye—white for a mountaintop, green for a low-lying valley. The colors make the maps more realistic (and attractive) than contours on their own, but, really, the colors are notional. The actual ground of a low-lying area might be covered by asphalt, not grass. Some of the HRSC perspective landscapes are presented in this way. The reality grade for these is **BBB**.
9. Landscapes of Venus from the Magellan satellite have been constructed in the same way as in 8 above from radar data, using the radar as an altimeter. The radar data contain information, not about color, but about the texture of the surface. This data is used as a brightness scale to create the impression of gross surface relief. This gives what is equivalent to a black and white image. Then the ground is colored orange to look like images made by the Russian Venera landers of the surface of Venus. Finally, the vertical scale has been considerably exaggerated, by a factor of twenty. The reality grade is questionable: **C**. (Note: This low "reality grade" is a criticism of the scientific quality or usefulness of the data and images; it is just an assessment of how much the picture resembles the scene to look at.)

Table A.1 in the Introductory chapter summarized this grading scheme.

APPENDIX 2

Space Exploration Missions

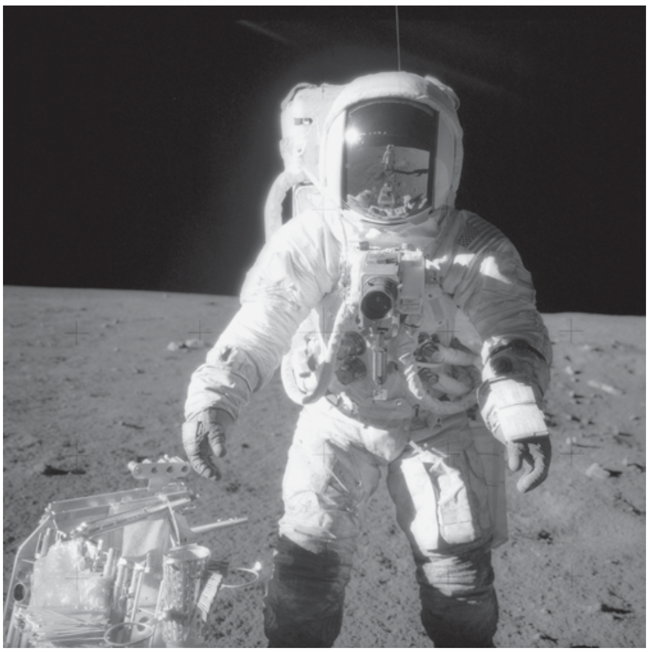


Fig. A.8 Bean walks on the Moon. Astronaut Alan L. Bean, Lunar Module pilot, shows off his chest-mounted Hasselblad camera during the Apollo 12 spacewalk on the Moon. Commander Charles Conrad, Jr., who took the black-and-white photo, is reflected in Bean's helmet visor. (Apollo 12: NASA.) **AA**

A program to explore a planet starts with a flyby—a quick look as a spacecraft zooms past—and then positions an orbiter spacecraft to fly repeatedly around the planet and make sustained investigations remotely from orbit. Based on what the orbiters find, probes might then be plunged into the planet's atmosphere (if it has one) and onto the planet's surface, either crashing swiftly through the atmosphere or floating down for a longer descent on a parachute. In subsequent tries, the probes can be made to land softly, swinging to the surface under parachutes or slowed by retro-rockets; such spacecraft are called landers and can investigate their surroundings close up, determining the geology on the surface, making long term observations of wind speeds, temperatures, etc.

Landers are stationary on the surface and sample only one site. The next scientific capability comes from rovers, which can explore the area around the landing site, moving about seeking out interesting things to investigate, until they get stuck under a rock or bog themselves down in sand, until they run out of motive power, or until something important fails. Only after an extensive reconnaissance like this could it be considered safe to send human beings to land on another planet.

The landscapes discussed in this book are from the following space missions. A complete list of the missions that have successfully landed on other worlds is given in Table A.1 at the end of this appendix.

Apollo

NASA's Apollo program was a series of missions initiated in 1961 by President John F. Kennedy to land a man on the Moon and return him safely to Earth. It accomplished its goal in stages, starting with unmanned missions as tests of the Saturn rockets and manned orbital flights. *Apollo 8* (1968) was the first manned space mission to orbit around another celestial body, the Moon. *Apollo 10* was a "dress rehearsal" for the first Moon-landing by *Apollo 11* in 1969. *Apollo 12* through *17* followed, with the *Apollo 13* landing aborted due to a near-fatal equipment malfunction. The last lunar landing in the program and to date was *Apollo 17* in 1971. At that time 12 men had walked on the Moon, the only people to have experienced the lunar landscape from the Moon's surface.

The Apollo missions were equipped with TV cameras. Some were fixed on the outside of the orbiter and the landing module, positioned to record key moments such as the first step onto the Moon. Others were on transportable tripods that could be positioned for staged moments such as the flag ceremony. The astronauts also had Hasselblad still cameras with magazines loaded with 70 mm color and black-and-white film (digital photography did not exist at that time). The astronauts used the still cameras to record the lunar scenery, including not only in shots from the windows of the orbiting spacecraft but also in pictures taken while the astronauts were on the lunar surface. The photographs that the astronauts took on the surface documented their activities, including scientifi-

P. Murdin, *Planetary Vistas,* DOI 10.1007/978-3-319-15242-4

cally important details such as the places from which geological samples had come. The Hasselblad data camera, adapted from a production model called the EDC, was fitted with a reseau plate. The glass plate was mounted inside the camera just in front of the film plane and engraved with crosses to form a grid (or “reseau”). The crosses were recorded on every exposed frame (as in Fig. 5.12) and provided the scale of the photographs.

It was impossible in a helmeted spacesuit to look through the viewfinder of a camera and equally impossible to handle the camera in bulky gloves, so the astronaut took pictures by operating remotely a camera attached to the outside of the suit on the astronaut’s chest (Fig. A.8). Astronauts were trained to make panoramas by turning stepwise in a fixed angle to provide a series of overlapping photographs that could be pasted together. Decades after the missions had ended, the individual frames on film were digitized and assembled into panoramas by computer methods at NASA’s Information Resources Directorate, Johnson Space Center.

Cassini

NASA’s Cassini spacecraft was a large “bus” equipped with an array of instruments to study the Saturn system—planet, rings, and moons. Cassini launched in October 1997, carrying the European Space Agency’s Huygens probe as a hitchhiker. On arrival near Saturn in December 2004, Cassini discharged the probe to land on Titan’s surface (see “Huygens,” below) and proceeded itself to fly around the planet and its moons in an extended study.

Cassini’s camera was the Imaging Science Subsystem, consisting of two cameras, a Wide Angle Camera (3.5° field) and a Narrow Angle Camera (0.35° field). Both cameras produced CCD images 1024 by 1024 pixels in size. Each camera had two overlapping filter wheels (17 and 23 filters, respectively) chosen to bring out various scientifically important spectral features from the ultraviolet to the near-infrared. Altogether, in combination, the filters allowed the scientists to identify scores of band passes in an image of Saturn or its moons. Considering that human beings have to get by with only three band passes, it is surprising that our vision has so much scientific scope. The cameras are fixed to the spacecraft on a pallet, and all instruments on the pallet point in the same direction, so the Wide Angle Camera provided the context for the higher resolution Narrow Angle Camera and other instruments.

Chang’e 3

Following two successful lunar orbiters, China launched Chang’e 3, which soft-landed on the Moon on December 14, 2013, and deployed a robotic lunar rover, Yutu (Jade Rabbit). The lander carried three panoramic cameras, looking over the Moon’s surface in different directions, as well as a downward-looking descent camera, a lunar-based ultraviolet telescope for astronomy, an ultraviolet sensitive camera to investigate Earth’s magnetosphere, and a soil probe. The lander deployed a lunar rover with two panoramic cameras and two navigation cameras on a mast, 1.5 m (5 ft) high, as well as equipment to investigate the nature of the lunar soil. The rover mechanically failed after its first experience of the cold lunar night.

Curiosity

See Mars Science Laboratory.

Dawn

NASA’s Dawn spacecraft was launched in 2007 to its first target, the asteroid Vesta, arriving in 2011; its second target is the asteroid (or dwarf planet) Ceres. It carries a CCD camera (in fact, because the camera is also used to navigate the spacecraft, two identical cameras, for redundancy) with filters to be able to image in 8 band passes, from the blue to the infrared. The camera system permits images to be obtained with resolutions down to 50–70 m on the asteroids’ surfaces.

Galileo

The main target of NASA's Galileo spacecraft was the planet Jupiter and its moons. It was launched by the space shuttle in October 1989, arriving at and being injected into orbit around Jupiter in December 1995, after passing near Venus and the asteroids 951 Gaspra and 243 Ida. It recorded the impact of Comet Shoemaker-Levy 9 with Jupiter as it approached Jupiter in 1994. Its mission at Jupiter was extended to 8 years and was terminated in September 2003, by vaporizing the spacecraft in Jupiter's atmosphere. Galileo's main imager was the Solid State Imager (SSI), one of the first CCD cameras used in a planetary exploration spacecraft. The SSI's CCD had 800 by 800 pixels, fewer than is common nowadays in a mobile phone camera. The camera has a filter wheel that rotated any of eight filters into the light beam to obtain images at specific wavelengths, with color images constructed by computer processing on Earth.

Hayabusa

Japan's Hayabusa mission. Hayabusa means "Peregrine falcon." The spacecraft reached the asteroid in September 2005 and maneuvered into orbit alongside it.

Huygens

Released from the Cassini spacecraft, ESA's Huygens probe parachuted on January 14, 2005, through the atmosphere of Saturn's moon Titan. It transmitted data that included overlapping images of the landscape, obtained by three downward-looking multifunctional wide-angle cameras in the instrument called the Descent Imager/Spectral Radiometer (DISR). Its scientific purpose was to determine the properties of Titan's atmosphere and surface by looking at the spectrum of the light from them. The DISR made measurements and took pictures for 2 h from the slowly spinning probe on its descent through the hazy atmosphere of Titan and, for two more hours (while the batteries lasted), from its surface. It took 700 images during the decent and landing, but 350 of them were lost in a radio communications failure.

Kayuga

See Selene.

Luna 9

The Soviet Union's Luna series of space missions (1958–1976) consisted of over 40 missions of different sorts, of which about half were successful to 1° or another. In Soviet style, the successful ones were numbered in a series, while the unsuccessful ones were put to one side and forgotten about. In fact the program had nothing to apologize about. It notched up an impressive series of "firsts," including *Luna 2,* the first manmade object to reach the Moon; *Luna 3,* which took the first photographs of its far side; and *Luna 9,* the first soft landing on another world. *Luna 17* and *Luna 21* carried Lunokhod ("Moonwalker") rovers that roamed around on the Moon's surface. *Luna 16, Luna 20* and *Luna 24* collected in total 300 grams of rock samples from the lunar surface, successfully returning them to Earth. These outstanding space achievements had surprisingly little impact in the west, falling into the category of "nine-day wonders," and the scientific impact was muted even in Russia, although the public impact was considerable.

Luna 9 was launched on January 31, 1966, and landed on the Moon three days later. It proceeded to make three scans around the landing site with a TV-type camera. The camera was a single photocell with an optical scanning device that delivered the scene point by point, line by vertical line, onto the sensor and transmitted the picture seamlessly. The camera captured an image that was sharp between 1.5 m and the horizon, but with a low resolution by today's standards of 500 pixels per line.

Lunar Orbiter

NASA's lunar orbiter program (1966–1967) consisted of five spacecraft sent to skim the lunar surface at a height of 45 km (30 miles) to survey the Moon for possible astronaut landing sites. The lunar orbiter's job was to image the candidate sites in detail and in general to map the Moon's surface. The lunar orbiters were robotic photographic laboratories, with black and white film developed on board, scanned line by line and transmitted by radio to Earth, like a fax transmission, and recaptured on film at the receiving station. This cumbersome analog process, fraught with the danger that the film-transport mechanism might jam, was used because the airless Moon has very high contrast, with no air scattering to soften the shadows and highlights. Black and white film had both a greater tolerance to this and much better resolution than the analog TV systems of the day.

Lunar Reconnaissance Orbiter

Launched in 2009, the NASA Lunar Reconnaissance Orbiter orbited the Moon at 50 km (30 miles) altitude to map the Moon at meter scales, with an eye to the return to the Moon of human explorers in the future. Its camera system, the Lunar Reconnaissance Orbiter Camera (LROC), had two narrow-angle black-and-white cameras looking at 0.5-m (20-in.) scales over a 5 km (3 miles) swathe of the Moon, and a wide angle camera to provide images at a scale of 100 m (350 ft) in seven band passes.

Magellan

NASA's Magellan spacecraft was launched in May 1989, and reached Venus in August 1990; it remained in orbit around Venus until October 1994. It carried a radar system to penetrate the dense and opaque atmosphere of Venus. The radar system produced an image of the surface of the planet, with the rougher areas of the planet producing brighter reflections, and a map of the height of the surface features (altimetry). The data was combined to develop a three-dimensional map of the surface, held in a computer file. Rays cast in the computer from a hypothetical viewpoint intersect the surface and can be used to create a three-dimensional perspective view of scenery on Venus. The resulting landscapes use simulated colors that are based on those recorded directly from the surface by the Soviet *Venera 13* and *14* spacecraft.

Mariner 9

In November 1971 NASA's *Mariner 9* entered orbit around Mars, the first space probe to orbit another planet. It carried a 2-in. Vidicon television camera to image the surface of the planet, a primitive instrument by today's standards. The camera could take filtered, wide-angle pictures and broadband (unfiltered) narrow-angle pictures, with resolutions of between 500 and 50 m per TV line. The images were radioed back to Earth not startlingly faster than the speed a human operator would send the pictures in Morse code. No wonder the images, amazing as they were at the time as the first images of planetary surfaces, now look terribly indistinct!

Mars Exploration Rovers: Spirit and Opportunity

In January 2004, the NASA twin Mars exploration rovers named Spirit (MER-A) and Opportunity (MER-B) landed on the surface of Mars. They parachuted through the thin Martian atmosphere under vast parachutes. When they reached the right height, the parachutes were cut free to drift clear of the rovers. The rovers were dropped onto the land, bouncing inside inflated airbags to cushion the impact. Opportunity bounced and rolled right inside a small crater, much to the delight of the mission scientists. A crater exposes rocks from below the surface, a variety of Martian rocks with which the scientists could experiment. The Spirit rover (MER-A) ceased operating in 2010 after six years, when its batteries completely discharged in the Martian winter, and it could not be restarted. The Opportunity rover operated in excess of 30 times longer than its design lifetime and has already (by 2013) traveled in excess of 35 km (23 miles) from its landing site. Each rover had cameras for navigational purposes and for imaging the terrain for scientific purposes. The latter camera is known as Pancam, derived from Panoramic camera.

Pancam was a binocular pair of high-resolution CCD cameras mounted on a mast above the rover at a height of 1.5 m (5 ft) above the ground. The camera could point in any direction. The cameras are mounted side by side and produce stereo images. Each camera has an eight-position filter wheel with a range of filters with band passes from the near ultraviolet to the near infrared. A color calibration target had a vertical mast to cast a shadow to test color differences between direct sunlight and indirect sunlight from the sky; the target was inscribed “Two worlds, one Sun.”

The truest color pictures from Pancam are made by combining seven individual color exposures. They are integrated by computer software that blends the pictures into red, green and blue colors, forming these into a color picture.

Mars Express

ESA’s Mars Express mission reached Mars in 2003. It carried the *Beagle 2* lander, which was lost during its approach and descent to the ground. The satellite carried the High Resolution Stereo Camera. Nine CCD imagers were arranged in strips, and swept one after another like brooms across the Martian landscape. Two pairs of imagers formed two stereo cameras. One channel of each pair looked a little ahead, the other a little back from the satellite, so between the moments at which each sees a given strip of the surface of Mars the satellite has moved. The two images form a stereo pair, which position each pixel of the image to a few tens of meters to make it possible to create a map of the height of the terrain. Other imagers were sensitive to different colors and in combination produce a color image of each pixel. The maps can be supplemented by maps measured by a more accurate altimeter called MOLA, Mars Orbiter Laser Altimeter, on board NASA’s Mars Global Surveyor spacecraft.

Mars Global Surveyor

NASA’s Mars Global Surveyor went into orbit around Mars in 1997. The mission lasted ten years, and contact was lost with the probe in 2006. The spacecraft carried the Mars Orbiter Camera (MOC), a camera built and operated by Malin Space Science Systems, San Diego, CA. The MOC camera was actually three cameras in one, a black-and-white narrow-angle camera and two wide-angle cameras (one red, one blue) feeding CCDs; they could resolve features on Mars between 2 m (6 ft) and 7 km (5 miles) in dimension. The cameras provided scans of swathes of Mars under the spacecraft’s track.

Mars Odyssey

In its full name, 2001 Mars Odyssey was a tribute to science fiction author Arthur C. Clarke’s famous book and movie *2001*. It was launched in April 2001 and entered Mars orbit at the end of that year. It carried a camera called THEMIS (Thermal Emission Imaging System), for determining the distribution of minerals, particularly those that can only form in the presence of water. In the infrared spectrum, THEMIS used 9 spectral bands to differentiate minerals such as carbonates, silicates, hydroxides, sulfates, hydrothermal silica, oxides and phosphates. Using visible imaging in five spectral bands, the experiment also took 18-m-resolution images to see how the land was formed. These data were used to identify potential landing sites for the Mars exploration rover missions.

Mars Pathfinder: Sojourner

NASA’s Mars Pathfinder was a scientifically equipped lander, the Carl Sagan Memorial Station named after the planetary scientist, that also carried a rover called Sojourner, after an American civil rights pioneer, Sojourner Truth. It landed in the *Ares Vallis* on Mars in the summer of 1997, in a relatively flat floodplain that contained a variety of rocks for the rover to seek out and investigate. It parachuted to a height above the ground, then the parachute was cut free and the lander dropped to the ground on airbags. The airbags were deflated, the lander righted itself and the rover rolled down a ramp to the surface.

The lander took pictures with a stereoscopic camera on a pole (the Imager for Mars Pathfinder, IMP), and the rover also had stereo cameras, two black-and-white cameras and one for color pictures. The IMP was used to select targets for the rover to investigate, and the rover's cameras were used not only for scientific investigations at a millimeter scale but also to navigate the rover.

Mars Reconnaissance Orbiter

NASA's Mars Reconnaissance Orbiter was launched in 2005 to orbit Mars later that year. Its instruments are investigating the geology and weather, and include three cameras. The HiRISE camera (High Resolution Imaging Science Experiment) is a veritable telescope, the largest ever flown on a planetary exploration mission, with an 0.5 m primary mirror, the planetary science equivalent of the Hubble Space Telescope. It produces very close up images of the Martian surface with a 0.5–1 m resolution. The CTX (Context Camera) provides wide-area views to help provide the context of the high-resolution analysis of key spots on Mars. MARCI (Mars Color Imager) monitors clouds and dust storms. HiRISE images the ground in three color bands, green, red and infrared. It uses CCD detectors that sweep along the surface underneath the track of the satellite and produce images that are 4048 to 20,048 pixels wide and, in principle, indefinitely long, although the on-board computer memory limits the length in practice. 28 Gbyte pictures are possible, with 500–2500 megapixels. Stereo pictures are possible. The HiRise team's mission statement on its website is "Explore Mars, one giant picture at a time," a mission being achieved.

Mars Science Laboratory: Curiosity

NASA's Mars Science Laboratory landed the rover named Curiosity in Gale Crater on Mars in August 2012. The SUV-sized rover was parachuted to the landing site and lowered to the ground on a "sky crane" that hovered a few meters above the ground. As the mission name implies, Curiosity is a comprehensive laboratory for the physical and chemical examination of Mars rocks, intended to show whether the conditions revealed by the geology would have supported life on Mars in the past. In addition to more exclusively scientific instruments, Curiosity carries 17 cameras of which 12 are engineering cameras to avoid hazards and to navigate the vehicle. The five science cameras use large CCD chips as recorders and several filters. They obtain scenic geological information as well as close-up pictures of the mineralogy of the rocks.

Near-Shoemaker

Near-Earth Asteroid Rendezvous-Shoemaker (NEAR-Shoemaker, or just NEAR) visited the asteroid Eros in 2001, and examined it for nearly a year. At the end of its mission, the spacecraft was lowered to the surface of the asteroid, touching down on February 12, 2001. The impact was on the scale of a terrestrial fender-bender car crash. The asteroid is small and its gravity is weak. The spacecraft carried a Multi-Spectral Imager, a camera to provide visible and near-infrared images of the asteroid surface. An eight-position filter wheel covering the wavelength ranges from 450 to 1100 nm, i.e., the near ultraviolet to the infrared. Its detector was a CCD.

Opportunity

See Mars Exploration Rover B.

Phoenix

NASA's Phoenix Mars lander descended onto the northern polar region of Mars on May 25, 2008. It carried no rover, in part to save money and in part because the region was considered so uniform that there was little value in exploring a wider area. The landscapes produced by Phoenix seemed to have borne this out (Fig. 8.8). The lander operated for longer than its planned lifetime but could not survive its first Martian winter. It carried a camera called the Phoenix Surface Stereo Imager (SSI), a stereo camera with properties that are comparable to the Mars Pancam.

Rosetta

The European Space Agency's Rosetta spacecraft was launched in 2004 and travelled via the planet Mars and asteroids 21 Lutetia and 2867 Šteins to comet 67P/Churyumov–Gerasimenko, where it arrived in late 2014. On 12 November 2014, Rosetta landed a small spacecraft called Philae on the comet's surface.

Unfortunately Philae landed on a irregular part of the comet in the shadow of a cliff. It operated on battery power for a short period but was unable to recharge from its solar cells. It carried a complex of cameras called CIVA, the Comet Nucleus Infrared and Visible Analyser, a group of seven identical cameras arranged on the sides of the lander at 60° intervals. Each camera has a 1024×1024 pixel CCD detector. They would have been used to take panoramic pictures of the comet surface, but even on battery power the camera was so badly tilted that it was unable to take scenic views.

Rosetta itself remained alongside the comet, executing repeated flybys in triangular patterns: it is unable to enter into orbit around the comet since its gravitational pull is so small. The spacecraft carries instrumental cameras called OSIRIS and VIRTIS. OSIRIS is a high resolution imaging camera comprising a wide field and a narrow field components. VIRTIS (the Visible and Infrared Thermal Imaging Spectrometer) maps and provides information on the nature of the physical conditions of the comet. Rosetta also carries a navigational camera (NAVCAM) with a 5 degree field of view and 12 bit 1024x1024 pixel resolution to facilitate visual tracking on each of the spacecraft's approaches to the comet. Most of the pictures released by early 2015, when this book went to press, were from this camera.

Selene

Selene was the Moon goddess in Greek mythology. The Japanese lunar exploration spacecraft was named the SElenological and ENgineering Explorer with her name in mind as the acronym. Launched in 2007 in an 18-month mission, the spacecraft was also called Kayuga, a name chosen by popular vote. Kayuga is the name of a princess in Japanese folklore, who came from and returned to the Moon.

The spacecraft carried two panchromatic (black and white) cameras, one looking slightly forward and one backwards of the nadir (the point directly down), to sweep over the lunar landscape and image it at a resolution of 10 m. In an unusual collaboration between the Japan Aerospace Exploration Agency (JAXA) and the Japanese national broadcaster, NHK, the satellite also carried two high-resolution color TV cameras with CCD detectors to view the landscape as the satellite passed over the Moon at a height of 100 km (60 miles). Later, as the mission was due to end, mission controllers allowed themselves to risk reducing altitude to 50 km (35 miles). The TV cameras, one wide angle, one narrow angle, looked forward and back at an angle of about 20° below horizontal, giving views like those that an astronaut would have looking out the windows of a space vehicle skimming over the Moon's surface. A video sequence from Selene lasted 1 min.

It is possible to make still images from the HDTV video by using single frames, but more impressive images can be made by using the whole video sequence. Two methods were evolved by the mission scientists. A video sequence contained 1800 frames, each exposed for 1/30th of a second as in a standard (U. S. specification) video camera, and consisting of 1080 lines with 1920 pixels. The mission scientist selected one specific line and made a stack of 1800 of them, the same line from each frame. The aspect ratio of the image was adjusted to produce a still image as if made by a still camera looking down. In the other method, the scientist selected a number (seven or eight) frames equi-spaced through the video sequence. The bottom part of the image continuously disappears as the spacecraft moved forward. Each bottom strip was connected spatially to the next image and adjusted in scale so that the features lined up at the join. The piecing together of the 8 strips produced a still image with a stepped outline, with the terrain seen in perspective in swathes 100 km (60 miles) wide that stretch all the way to the curved lunar horizon.

Spirit

See Mars Exploration Rover A.

Venera

"Venera" is Russian for Venus, and the Venera series of spacecraft constituted the Soviet Union's program to explore Venus between 1961 and 1984. There were 26 spacecraft in the series of which about two-thirds were successful. After two flybys, *Venera 3* and *4* were sent into Venus' atmosphere and were crushed by the unexpectedly high atmospheric pressure (up to 80 atmospheres). *Venera 5* and *6* survived in the atmosphere for nearly an hour each, transmitting data about the atmosphere as they descended. *Venera 7* survived a hard landing on the surface but not without problems; although it fell over, it was able to transmit some data from the surface of Venus, the first spacecraft to do so. *Venera 8* landed and transmitted data successfully for an hour, but had no camera. *Venera 9* and *10* in 1975 carried two cameras each, although one camera failed in each case; they were the first spacecraft to return images (in black and white) from the surface of Venus. *Venera 11* and *12* landed successfully, but the cameras failed. *Venera 11* showed how the sky became increasingly orange near to the surface of Venus, due to the thick atmosphere and its composition. *Venera 13* and *14* were perhaps the most successful Venus landers. *Venera 13* operated for 2 h on the surface, *Venera 14* for an hour, returning color images from cameras designed along the same lines as the camera on *Luna 9* (q.v.).

The typical Venera mission, including *Veneras 13* and *14,* was a lander spacecraft taken to Venus on a larger spacecraft called, generically, a "bus." When they reached the planet the two spacecraft separated, and, while the main space bus continued its orbit above, the lander descended to the surface, slowed enough for a safe impact by air braking and by parachutes. The landers took measurements of the properties of Venus' atmosphere on the way down, and deployed cameras and other instruments to measure the properties of the surface when they arrived there, including arms that scooped up soil samples for on board analysis. No lander lasted long in the hot (450 °C), dense (84 Earth atmosphere's pressure), acidic atmosphere. The landers transmitted data to their mother bus, which relayed data, including pictures of the landscape, to Earth.

Voyager

NASA's Voyager program consisted of two unmanned spacecraft, *Voyager 1* and *Voyager 2,* launched in 1977. In what came to be known as the Voyager Grand Tour, they used a very favorable alignment of the planets that enabled the craft to cruise effectively to Jupiter in 1979 and Saturn in 1980–1981, with one of them, *Voyager 2,* able to go on to Uranus (1986) and Neptune (1989).

The navigation engineer for *Voyager 1* was Linda Morabito, a young graduate in her first job. She had to use background star images to locate the moons of Jupiter in space and the position of the spacecraft relative to them, so that the spacecraft could be safely piloted through the Jupiter system and so that the images that it took could be accurately focused on the surface of the planet and its moons. During the encounter with Jupiter, Morabito was working 14 h a day in the Voyager navigation area in the Control Center in JPL—"data was falling down on us like rainfall and the images were coming in at all hours of the day and night." On the morning of March 9, Morabito began processing several images taken by the *Voyager 1* spacecraft as it was looking back over its shoulder for one last view of the Jovian system. One image, taken from a distance of 4.5 million km, had been put up on the monitors for everyone to see. Morabito "stretched" the image—increased its contrast to look for a particular, dim star—and noticed what no one had been able to see on the ordinary picture. It was an anomaly to the left of Io, just off the rim of that world. It was extremely large with respect to the overall size of Io and crescent-shaped. Careful scientist that she was, Morabito began considering whether it could be an artifact, blemish, or a "feature" of the camera. When everything had been eliminated, only one possible explanation remained—the anomaly had something to do with Io. Io itself was overexposed on the image, and it took some work to locate the anomaly over Io's surface. It proved to be located over a large heart-shaped feature on Io. It was a plume from a volcano, and the heart-shaped feature was the volcano itself, with its slopes, ejecta and lava flows.

Viking

The 1975 NASA launches of the Viking program consisted of two orbiters, each having a lander; both landers successfully touched down in 1976. *Viking 1* remained operational for six years, *Viking 2* for three. The Viking landers relayed color panoramas of Mars and the orbiters mapped the surface so well that the images remain in use.

The first landers on Mars were the Viking landers, taken to the Red Planet by orbiters that acted as scout missions for the landing sites and as radio relays. The two almost identical missions were both launched in the summer of 1975 and arrived at Mars the following year. The orbiters determined that both landing sites that had been selected before the spacecraft left Earth were unsafe, with large rocks or hills within the landing zone. New ones were chosen. Both were on plains on the equator of Mars. The landers were deployed by the end of the year, and both successfully landed. One of the primary functions of the landers was to take pictures. The resulting landscapes could be transmitted back to Earth directly, or relayed via an orbiter. *Viking 2* successfully operated for 3½ years until its battery failed, *Viking 1* for 6 years, until human error in a software update caused the radio antenna to fail and communication was lost.

Yutu

The Jade Rabbit rover—see Chang'e 3.

Table A.1 Successful landings on other worlds. (Source: Wikipedia)

Body	Mission	Country or agency	Date of landing or impact	Notes
The Moon				
	Luna 9	USSR	February 3,1966	First successful soft landing; first pictures from the surface of the Moon
	Surveyor 1	USA	June 2, 1966	Soft landing
	Luna 13	USSR	December 24, 1966	Soft landing
	Surveyor 3	USA	April 20, 1967	Soft landing
	Surveyor 5	USA	September 11, 1967	Soft landing
	Surveyor 6	USA	November 10, 1967	Soft landing
	Surveyor 7	USA	January 10, 1968	Soft landing
	Apollo 11	USA	July 20, 1969	First manned landing
	Apollo 12	USA	November 18, 1969	Manned mission
	Luna 16	USSR	September 20, 1970	First successful robotic sample return
	Luna 17	USSR	November 17, 1970	Robotic lunar rover, Lunokhod 1

Table A.1 Successful landings on other worlds. (Source: Wikipedia)

Body	Mission	Country or agency	Date of landing or impact	Notes
	Apollo 14	USA	February 5, 1971	Manned mission
	Apollo 15	USA	July 30, 1971	Manned mission; lunar rover
	Luna 20	USSR	February 21, 1972	Robotic sample return
	Apollo 16	USA	April 21, 1972	Manned mission; lunar rover
	Apollo 17	USA	December 7,v1972	Manned mission; lunar rover
	Luna 21	USSR	January 8, 1973	Robotic lunar rover, Lunokhod 2
	Luna 24	USSR	August 18, 1976	Robotic sample return
	Chang'e 3	China	December 14, 2013	Robotic lunar rover, Yutu (Jade Rabbit)
Venus				
	Venera 7	USSR	December 15, 1970	First soft landing on another planet; transmitted from surface for 23 min
	Venera 8	USSR	July 22, 1972	Soft landing; transmitted from surface for 50 min
	Venera 9 lander	USSR	October 22, 1975	Soft landing; transmitted from surface for 53 min. First pictures from surface of Venus
	Venera 10 lander	USSR	October 25, 1975	Soft landing; transmitted from surface for 65 min
	Pioneer Venus Multiprobe	USA	December 9, 1978	One of four atmospheric probes survived impact and continued to transmit for 67 min
	Venera 12 lander	USSR	December 21, 1978	Soft landing; transmitted from surface for 110 min
	Venera 11 lander	USSR	December 25, 1978	Soft landing; transmitted from surface for 95 min
	Venera 13 lander	USSR	March 1, 1982	Soft landing; transmitted from surface for 127 min
	Venera 14 lander	USSR	March 5, 1982	Soft landing; transmitted from surface for 57 min
	Vega 1 lander	USSR	June 11, 1985	Soft landing; instruments failed to return data
	Vega 2 lander	USSR	June 15, 1985	Soft landing; transmitted from surface for 57 min
Mars				
	Mars 3 lander	USSR	December 2, 1971	First soft landing on Mars. First images from surface. Sent signal for only 20 seconds after landing
	Mars 6 lander	USSR	March 12, 1974	Contact lost after landing
	Viking 1 lander	USA	July 20, 1976	Successful soft landing
	Viking 2 lander	USA	September 3, 1976	Successful soft landing
	Mars Pathfinder lander and Sojourner rover	USA	July 4, 1997	First air bag landing on Mars and first Mars rover
	Mars Exploration Rover-A: Spirit	USA	January 3, 2004	Mars rover
	Mars Exploration Rover-B: Opportunity	USA	January 25, 2004	Mars rover
	Phoenix	USA	May 25, 2008	Landed in the northern polar region and investigated whether conditions there are suitable for life to have evolved
	Mars Science Laboratory: Curiosity	USA	August 6, 2012	Mars rover. Landed in Gale Crater to investigate the geology and mineral-ogy there

Table A.1 Successful landings on other worlds. (Source: Wikipedia)

Body	Mission	Country or agency	Date of landing or impact	Notes
Other bodies				
Eros (asteroid)	Near Earth Asteroid Rendezvous Shoemaker	USA	February 12, 2001	Designed as an orbiter, but an improvised landing was carried out on completion of the main mission. Transmission from the surface continued for about 16 days
Titan (moon of Saturn)	Huygens probe	ESA/ USA/ Italy(ASI)	January 14, 2005	Successful soft landing. Transmitted data for 90 min following landing
Itokawa (asteroid)	Hayabusa	Japan	November 19, 2005	Accidentally stayed for 30 min
			November 25, 2005	Stayed for 1 sec. Sample return (very small amount of dust successfully returned to Earth)
Comet 67P/ Churyumov–Gerasimenko	Philae	ESA	November 2014	Forecast date of landing from the Rosetta spacecraft (author: update)

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