Planet Mars

Story of Another World

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Springer

Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

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Original French edition: *La Planète Mars*
Published by © Éditions Belin 2006
Ouvrage publié avec le concours du Ministère français chargé de la culture – Centre national du livre
This work has been published with the help of the French Ministère de la Culture – Centre National du Livre

Translator: Bob Mizon, 38 The Vineries, Colehill, Wimborne, Dorset, UK

SPRINGER–PRAXIS BOOKS IN POPULAR ASTRONOMY
SUBJECT *ADVISORY EDITOR*: John Mason B.Sc., M.Sc., Ph.D.

ISBN: 978-0-387-48925-4 Springer Berlin Heidelberg New York

Springer is a part of Springer Science + Business Media (*springer.com*)

Library of Congress Control Number: 2007931635

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Cover design: Jim Wilkie
Typesetting: BookEns Ltd, Royston, Herts., UK

Printed in Germany on acid-free paper

Table of Contents

Welcome to Mars! 2
Introduction 4
Martian landscapes 9
Chronology of Mars 12

PART 1
BIRTH OF A PLANET
–4.6 to –3.8 billion years 17
1 Before Mars and the other planets 18
2 Very rapid protoplanetary growth 21
3 Formation of the core, crust and mantle 24
4 The evolution of Mars, the Earth, Venus and Mercury 27
5 What Martian meteorites tell us 30
6 The origin of atmospheres and water 33
7 Meteoritic bombardment 36
8 The enigma of the 'north-south dissymmetry' 39
9 The primordial dynamo and magnetic field 42
10 The moons of Mars: captured asteroids? 45

PART 2
A YOUTHFUL MARS
–4 to –3.5 billion years 49
1 Rivers on Mars! 50
2 The source of Mars' rivers 53
3 The mystery of the lakes 56
4 Traces of water 59
5 A history of many chapters 62
6 In search of a lost ocean 65
7 The mystery of Mars' past climate 68
8 The theory of life on Mars 71
9 Hunting for fossils 74
10 A unique witness: 4 billion years old 77
11 The end of an oasis: Mars loses its atmosphere 80
12 Life on Mars today 83

PART 3
THE SLOW METAMORPHOSIS
–3.8 to –0.1 billion years 87
1 A sub-surface motor: convection in the mantle 88
2 Giant volcanoes on Mars 91
3 Olympus Mons: the solar system's biggest volcano 94
4 Lava flows and lava plains 97
5 Ridges and cracks on the surface 100
6 Valles Marineris: the valley of wonders 103
7 A permanently frozen sub-surface 106
8 The mystery of the chaotic terrains 109
9 Outflow channels 111
10 A drive around the mouth of Ares Vallis 114
11 A second Siberia 117

PART 4
CLIMATES AND STORMS
Mars today 121
1 Seasons and temperatures 122
2 The atmosphere of Mars 125
3 Martian winds 128
4 Martian meteorology 131
5 Dunes, ergs and erosion: footprints of the winds 134
6 The dust cycle: ever-orange skies 137
7 The dust cycle: planet of storms 140
8 The dust cycle: whirlwinds of dust 143
9 The dust cycle: global storms 146
10 The water cycle: vapour, frost and ice – water on Mars 149
11 The water cycle: clouds and fogs 152
12 The CO_2 cycle: seasonal polar caps 155
13 The CO_2 cycle: an atmosphere which solidifies 158
14 The CO_2 cycle: the vagaries of carbon dioxide ice 161
15 The CO_2 cycle: the residual southern polar cap 164
16 Climate change: when Mars rocks on its axis 167
17 Climate change: ancient glaciers on Mars 170
18 Climate change: surface ice at high latitudes 173
19 Climate change: intermittent water flows 176
20 Climate change: polar sediments, evidence of past climates 179

PART 5
EXPLORING MARS
1650–2050 183

1 Telescopic voyages 184
2 First visitors: the Mariner probes 187
3 Soviet setbacks 190
4 Viking 192
5 A difficult exploration 195
6 New American initiatives 198
7 Spirit and Opportunity: wheels on Mars 201
8 Europe joins in: Mars Express 205
9 The future of European Mars exploration 208
10 Imagination serves exploration 211
11 The Grail: returning samples 214
12 Astronauts on Mars 217

Epilogue 220

Index 225

Acknowledgements

We thank all those who have lent their support, and especially Nicolas Mangold, Michel Capderou, Thérèse Encrenaz, Emmanuelle Gautier, Azar Khalatbari and Sandrine Maïsano.

We are grateful for the many new images incorporated into this edition: sources include ESA and the HRSC and OMEGA teams, NASA (JPL and GSFC), and the associated teams of Malin Space Science Systems, Arizona State University, Cornell University, and the Lunar and Planetary Laboratory.

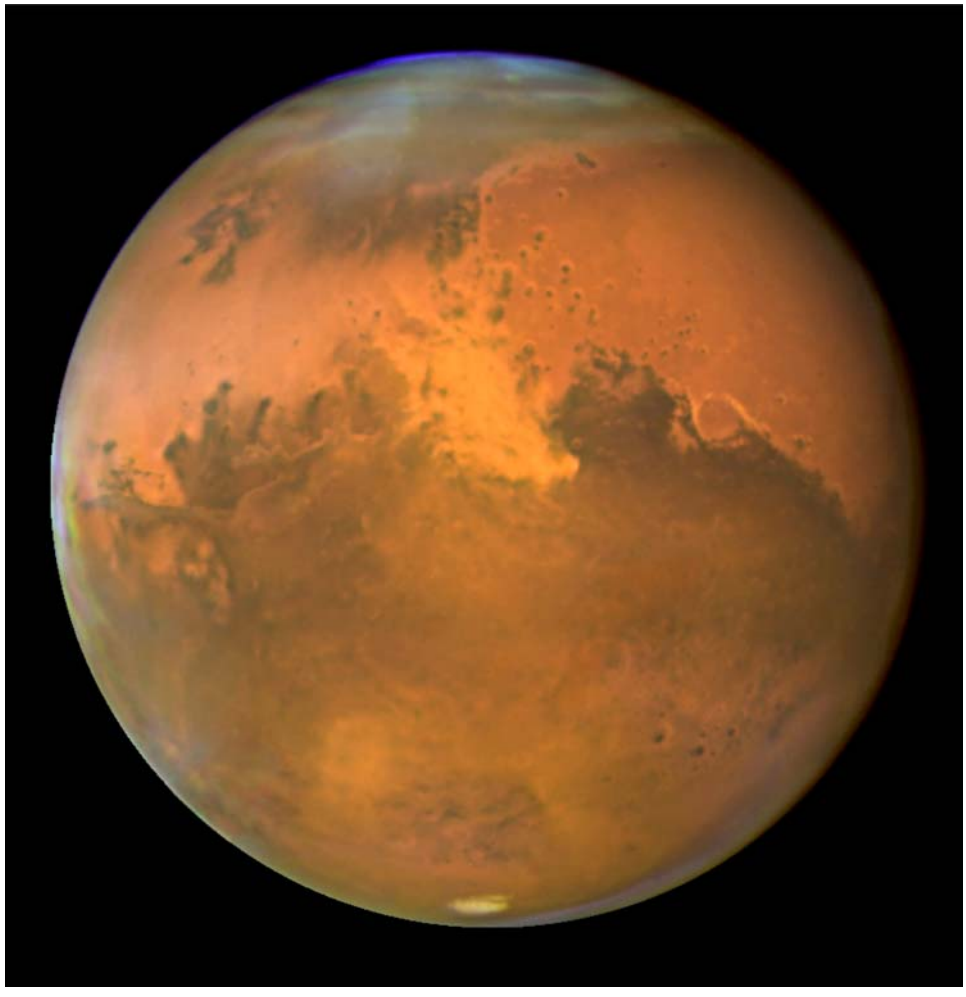
We also thank D. Andersen, B. Harris and D. Hardy, for allowing the use of their illustrations, and special thanks go to Kees Veenenbos, who reworked some of his extraordinary images (see www.space4case.com) especially for us. We are grateful to Luce Delabesse for technical assistance.

We express our gratitude also to the team at Éditions Belin, and notably Roman Ikonicoff and Yolande Limousin, for their remarkable work on the realisation of the French edition of this book – not forgetting the contribution of Christelle Sauvage to its origins. During the preparation of the first edition, the authors were privileged to be able to work in the marvellous conditions provided by the Fondation de Treilles.

We are grateful to Clive Horwood and Praxis Publishing for their support and encouragement, and to Bob Mizon for the excellent translation work.

Lastly, we must thank our laboratory colleagues, researchers, engineers and technicians, and all those who have worked alongside us with the aim of bringing to fruition a European Mars exploration programme. It is to be hoped that their efforts will realise the dream of an international presence on Mars in the twenty-first century.

The publishers thank Roman Ikonicoff, who re-read and edited the text.

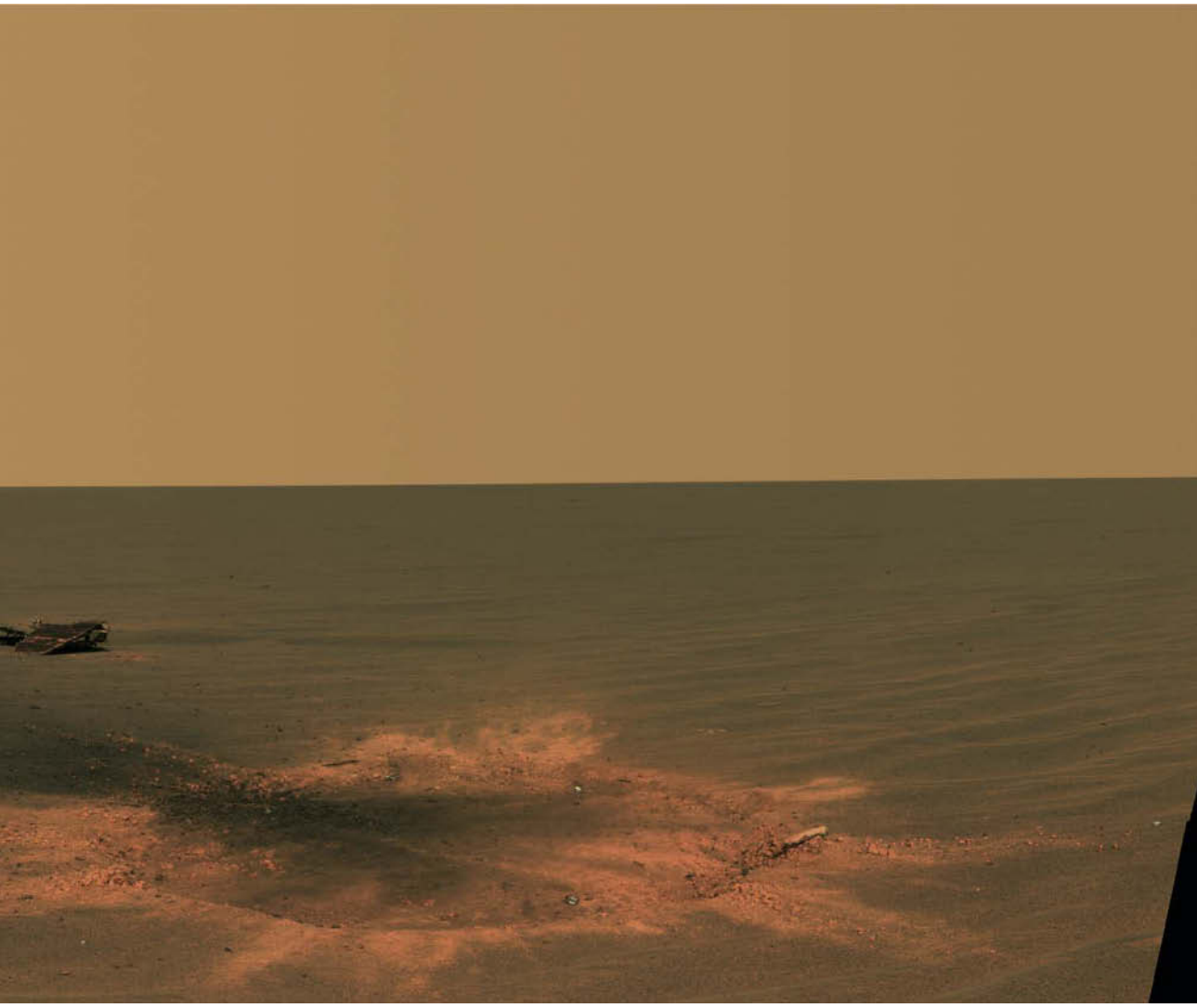


NASA's Hubble Space Telescope snapped this picture of Mars on 28 October 2005, within a day of its closest approach to Earth. A large regional dust storm, about 1500 km across, appears as the brighter, redder cloudy region in the middle of the planet's disk. The south polar ice cap is much smaller than normal because it has largely sublimated with the approach of southern summer. Bluish water-ice clouds can also be seen along the limbs and in the north (winter) polar region at the top of the image. (Courtesy NASA, ESA, The Hubble Heritage Team (STScI/AURA), J. Bell (Cornell University) and M. Wolff (Space Science Institute).)

Welcome to Mars!

After a journey of 300 million kilometres from Earth, the heat shield of the Mars Exploration Rover Opportunity crashed onto the surface of Mars on 25 January 2004. The shield had protected the precious payload as it entered the

atmosphere, before being detached. Opportunity parachuted down, landing a few hundred metres away. One year on, Opportunity, on its way southwards, encountered its protector, and transmitted this image. (Courtesy NASA, JPL (Jet Propulsion Laboratory), Cornell.)



Introduction

A simple red dot observed in the sky by our ancestors, or the planet across which our modern robots trundle in their explorations: however we see it, Mars never ceases to thrill.

Earth's sister planet, that other world which may harbour extraterrestrial beings, leading lives parallel to ours. . . Such a view of Mars was indeed the fruit of over-stimulated imaginations and a few sparse data, and today's probes, revealing the true nature of the planet, have dashed most of the ancient myths. However, recent findings have sprung their own surprises, and Mars is, if anything, an even more fascinating place than it was before.

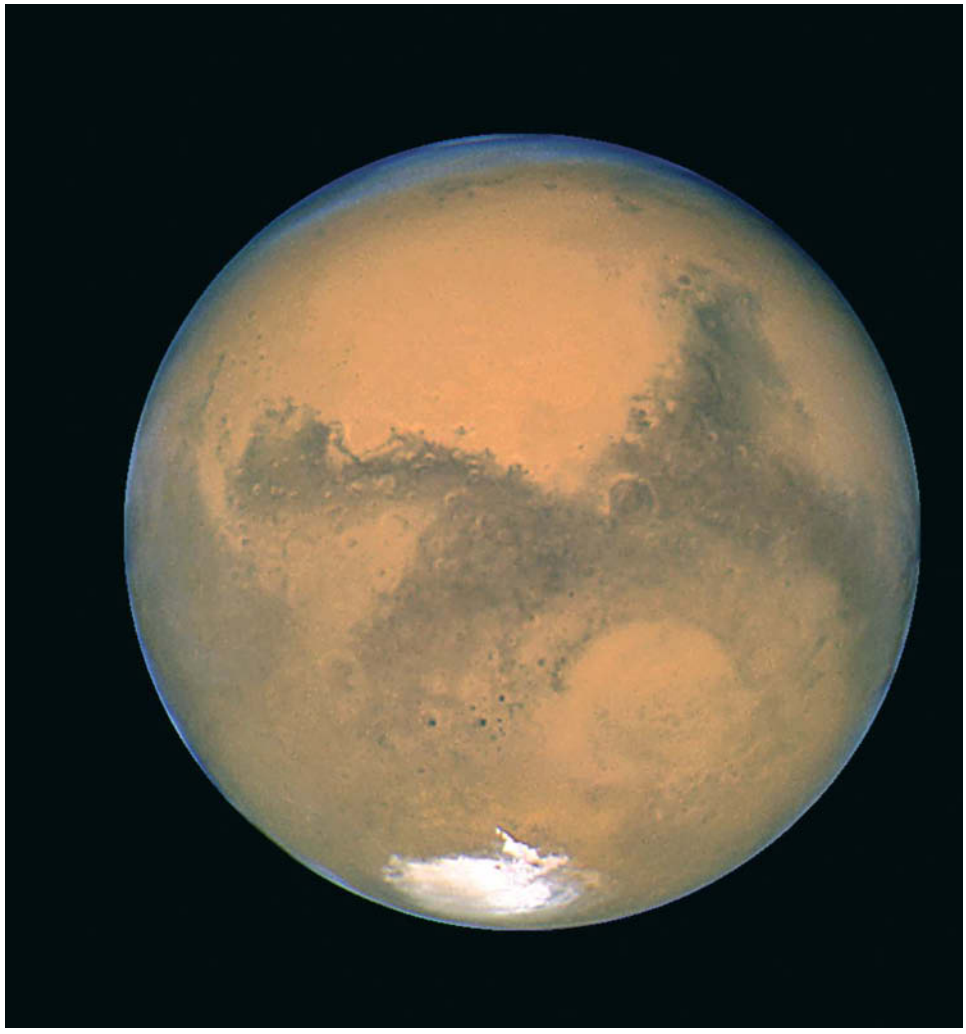
What have we learned from the Mars probes? Mars, like planet Earth, is a world, a complex and vast world with a long history. This book will confirm these ideas, going as it does to the heart of current planetary research, with all its doubts (and occasional certainties). We present many images, some of them previously unpublished. Although Mars is a beautiful place, a book about it need not be a mere photo album. The images will be markers along the way as we reveal this new world which, although it has many echoes on our planet, is nonetheless quite 'extraterrestrial'.

We shall discover Olympus Mons*, more than 20,000 metres high and the solar system's biggest volcano. Beside Olympus, Everest would rank as just a foothill. At Mars' poles, glaciers, formed from thousands of fine strata, are evidence of past climatic fluctuations. Entire plains bear the marks of cataclysmic flooding. Everywhere, strange dunes whisper the story of the winds that shaped them. . .

Imagine a day spent somewhere on Mars. As dawn breaks, night frosts give way to mists and fogs which, in their turn, disperse to reveal the orange sky. At the warmest part of the day, dust devils patrol the surface. At dusk, a tiny, oddly shaped moon takes just a few hours to cross the sky. And tomorrow, will the whole planet be veiled beneath a global dust storm, as happens sometimes in the winter?

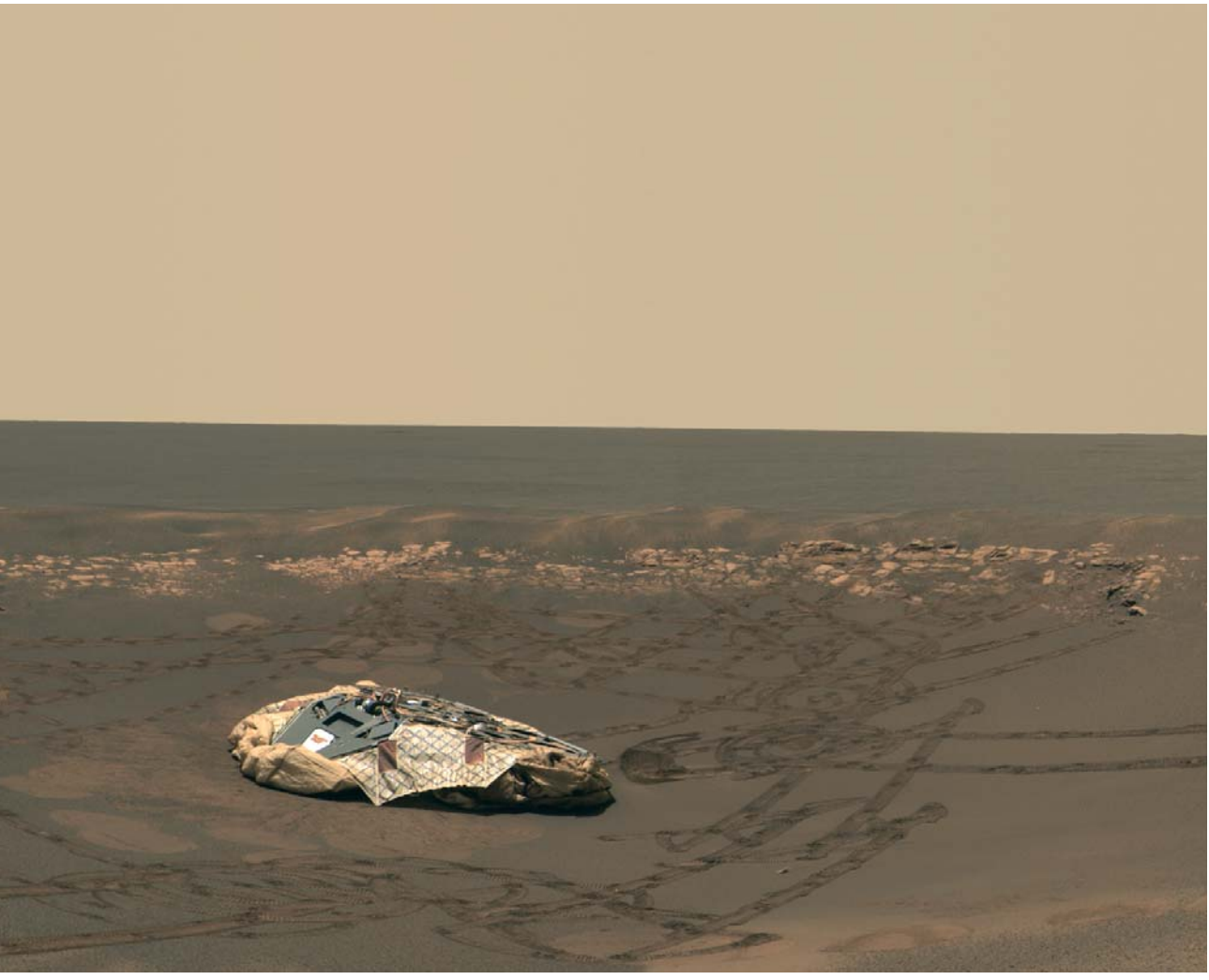
Beyond the magnificent scenery, there is a new world to understand, and the workings of the planet to reveal. How was Mars formed? Why has its evolution followed a different path to that of Earth? What do its river beds, volcanoes and glaciers tell us about its past? Could life have existed there? Does it exist there now? What processes 'drive' Mars today?

* Most of the places mentioned in the text are shown on the map of Mars at the end of the book.



Mars as seen from 55.8 million kilometres by the Hubble Space Telescope in orbit around the Earth on 26 August 2003. On that day, Mars was closer to the Earth than it had ever been during the whole of human history (in fact, since 60 000 years ago). It is the end of spring in the southern hemisphere of Mars. The last deposits of frozen carbon dioxide, accumulated during the winter around the south pole (bottom), are subliming in the spring sunshine. At the near edge, a tongue of ice dubbed the 'Mitchell Mountains' (though there is nothing mountainous about it) projects from the ice cap. In the southern hemisphere, spring is a relatively warm season, and few clouds are present in the atmosphere. Only the north polar region (at top) is shrouded in haze. (Courtesy NASA, J. Bell (Cornell U.) and M. Wolff (SSI).)

Of all the planets of the solar system, Mars is the one that most closely resembles ours. Geologists, meteorologists and many other scientists possess a vast 'laboratory' to test out their comprehension of the phenomena which occur on the terrestrial planets. Mars has the added advantage of having preserved the



A nest on Mars. The little crater 'Eagle' in the Terra Meridiani region. The six-wheeled rover Opportunity fortuitously landed in the middle of this crater on 25 January 2004. Sixty days later, after descending from its landing platform (left of centre) and investigating nearby rocks and soil, Opportunity leaves the nest and sets off for new adventures (see pages 201–204). (Courtesy NASA, JPL, Cornell.)

traces of its distant past. The same cannot be said of the Earth. Our planet's surface is constantly renewed: erosion and the phenomenon of plate tectonics have erased the archives of four-fifths of Earth's history. There remain almost no clues to what the Earth was like when the first micro-organisms made their appearance, before carbon chemistry was so widely exploited by living things. Mars can remind us of our own past, and perhaps tell us how life began. To understand Mars is, in a sense, to understand our own origins.

Let us leave Mars for a moment and return to Earth. All over the world, hundreds of researchers and engineers have but one aim in mind: bringing to fruition future Mars missions. In the last decade, more than ten space probes and their robot explorers have been sent to the red planet; the next twenty years will see more and more voyages from Earth to Mars. There will be new probes, and samples of Martian surface material will be brought back. Perhaps people too will make the journey.

The five parts of the present book trace the history of this active planet. Part 1 examines its formation, together with that of the solar system itself, from the ashes of dead stars, more than 4.5 billion years ago. Part 2 takes us through its early and turbulent youth. Part 3 traces the gradual, 3.5-billion-year long metamorphosis which created the great planetary structures. Part 4 explores Mars as we find it today, with its dust storms, water features and atmosphere, and we see that Mars is subject to continual climatic change. Finally, in Part 5, we recount the story of the recent exploration of Mars, and look at what is going on in laboratories and space agencies in preparation for the missions of the next twenty years.

This new edition offers a synthesis of our current knowledge about Mars, revisited with the aid of the multitude of images and discoveries made by Mars Express, the first European probe, and by NASA's robot geologists, the indefatigable Mars Exploration Rovers.

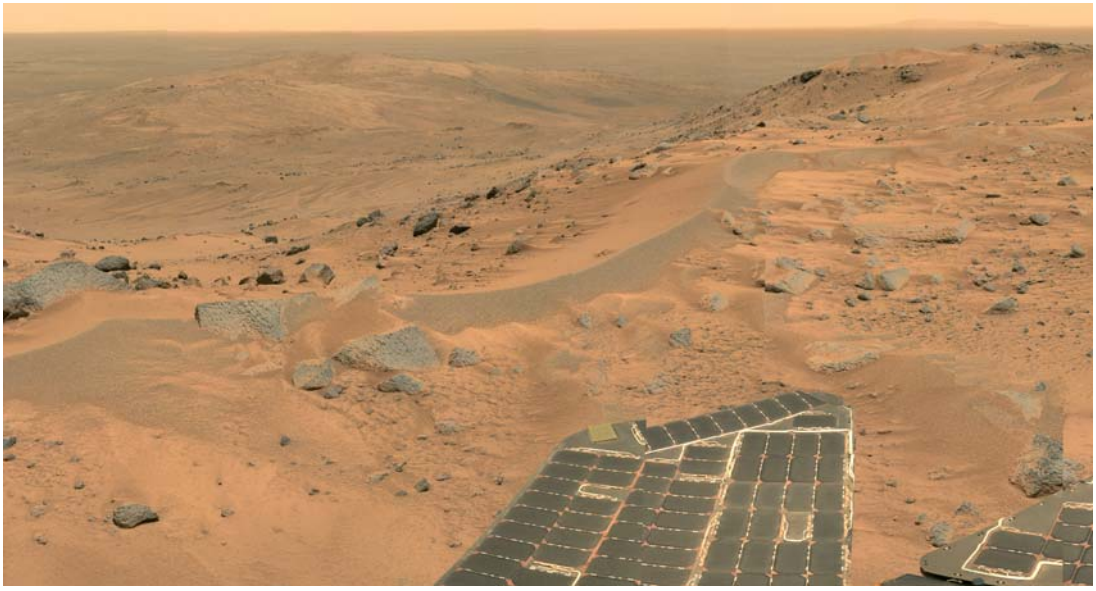
So, *bon voyage*, Mars traveller: don't forget that Mars still holds many secrets, laying down a challenge for generations to come...

Comparison of Mars and the Earth

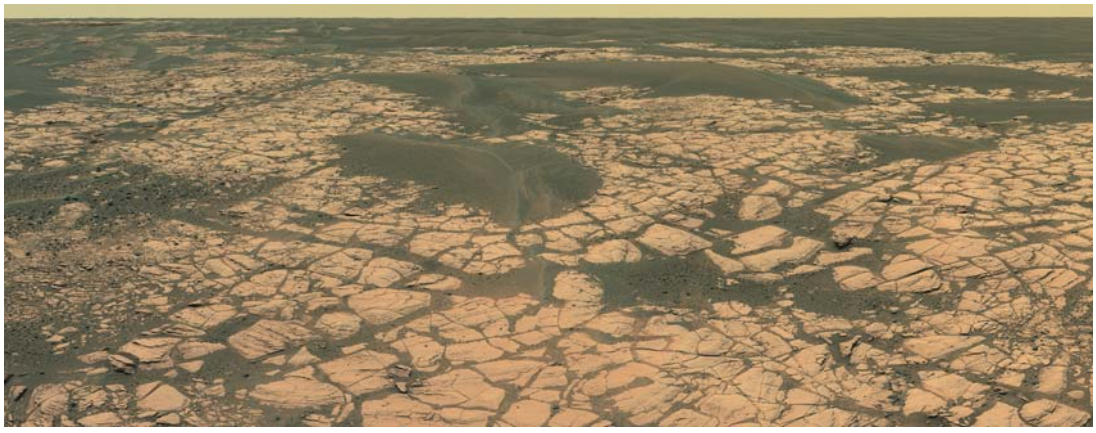
	Mars	Earth
Size (mean diameter)	6779 km	12742 km
Age	Formed 4.5 bn yrs ago 50% of surface more than 3.8 bn years old	Formed 4.5 bn yrs ago 99% of surface less than 2 bn years old
Position	Eccentric orbit Distance from Sun: 1.384–1.664 AU*	Near-circular orbit Distance from Sun: 0.983–1.017 AU
Data	**Mass**: $6.42.10^{23}$ kg (0.107 Earth mass) **Surface gravity**: 3.72 $m.s^{-2}$ (0.38 Earth's) **Day length**: 24h 39m 35s **Year**: 669 Mars days (=687 Earth days)	**Mass**: $5.97.10^{24}$ kg **Surface gravity**: 9.81 $m.s^{-2}$ **Day length**: 24h **Year**: 365.25 Earth days
Atmosphere	**Colour**: orange **Composition**: CO_2 95.3%, N 2.7%, Ar 1.6%, O 0.13% **Mean surface pressure**: ~6 hPa **Other**: assorted mineral dust in suspension Some water-ice & CO_2 clouds	**Colour**: blue **Composition**: N 78.1% O 20.9%, Ar 0.93%, Water vapour ~1% **Mean surface pressure**: 1000 hPa **Other**: many water clouds Protective ozone layer
'Family'	2 small satellites: Phobos (size: $27 \times 22 \times 18$ km, 5990 km above Mars' surface) Deimos (size: $15 \times 12 \times 10$ km, 20,100 km above Mars' surface)	One large satellite: the Moon (diameter: 3476 km, approx. 378 000 km from Earth)

*1 AU (Astronomical Unit) = 149.6 million km
(Data taken from NSSDC, NASA Goddard Space Flight Center)

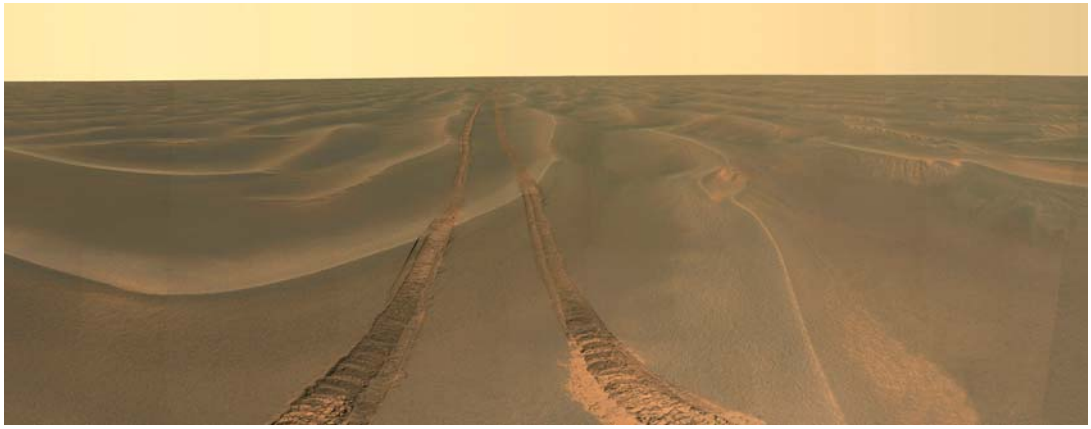
Martian landscapes



The plain within Gusev Crater, seen from the Columbia Hills by the Mars Exploration Rover Spirit in August 2005. (Courtesy NASA, JPL-Caltech, Cornell.)

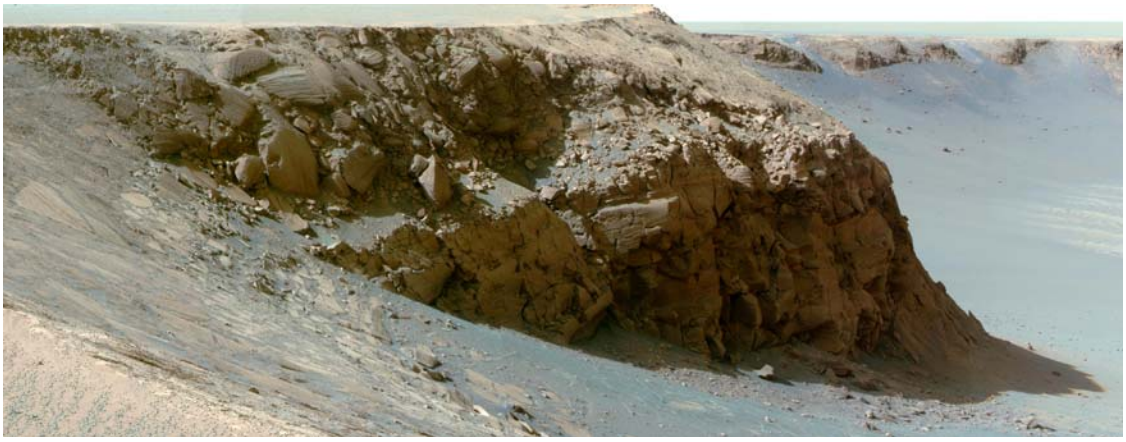


Outcrops of rock rich in sulphate salts, in the Terra Meridiani region, photographed by the Mars Exploration Rover Opportunity in September 2005. (Courtesy NASA, JPL-Caltch, Cornell.)



An expanse of sand traversed by Opportunity in May 2005. (Courtesy NASA, JPL, Cornell.)

The flank of Endurance Crater, surveyed by Opportunity, June-December 2004. (Courtesy NASA, JPL, Cornell.)



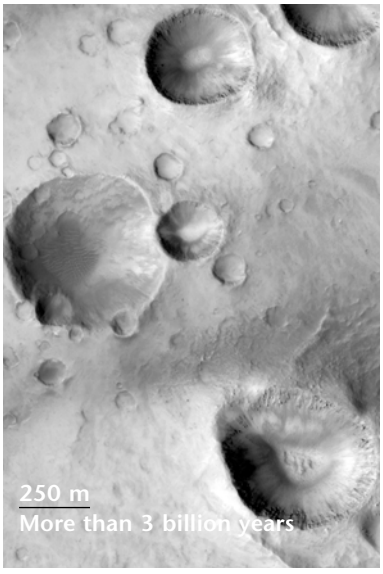
A cliff of layered rocks on a promontory called Cape St. Mary, examined by the Opportunity rover as part of its investigation of the rim of Victoria crater. This view combines several images into a false-colour mosaic that enhances subtle colour differences in the rocks and soil. (Courtesy NASA, JPL-Caltech, Cornell.)

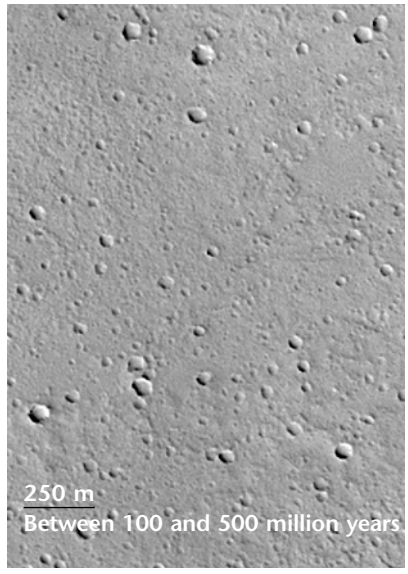
Left: Victoria crater, an impact crater on Meridiani Planum, viewed from the HiRISE camera on Mars Reconnaissance Orbiter. The crater is approximately 800 metres in diameter. It has a distinctive scalloped shape to its rim, caused by erosion and downhill movement of crater wall material. (Courtesy NASA, JPL-Caltech, University of Arizona.)

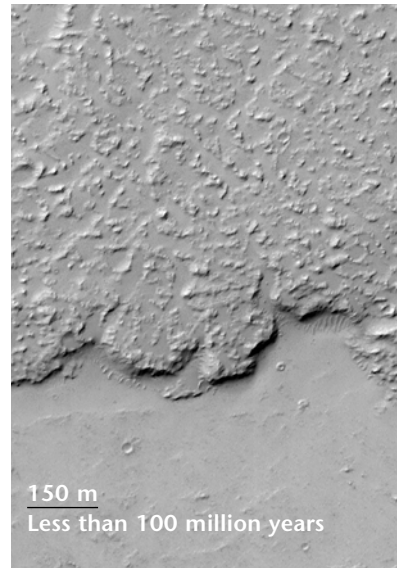
Chronology of Mars

To date Martian terrains, geologists count meteorite impacts . . . and visit the Moon

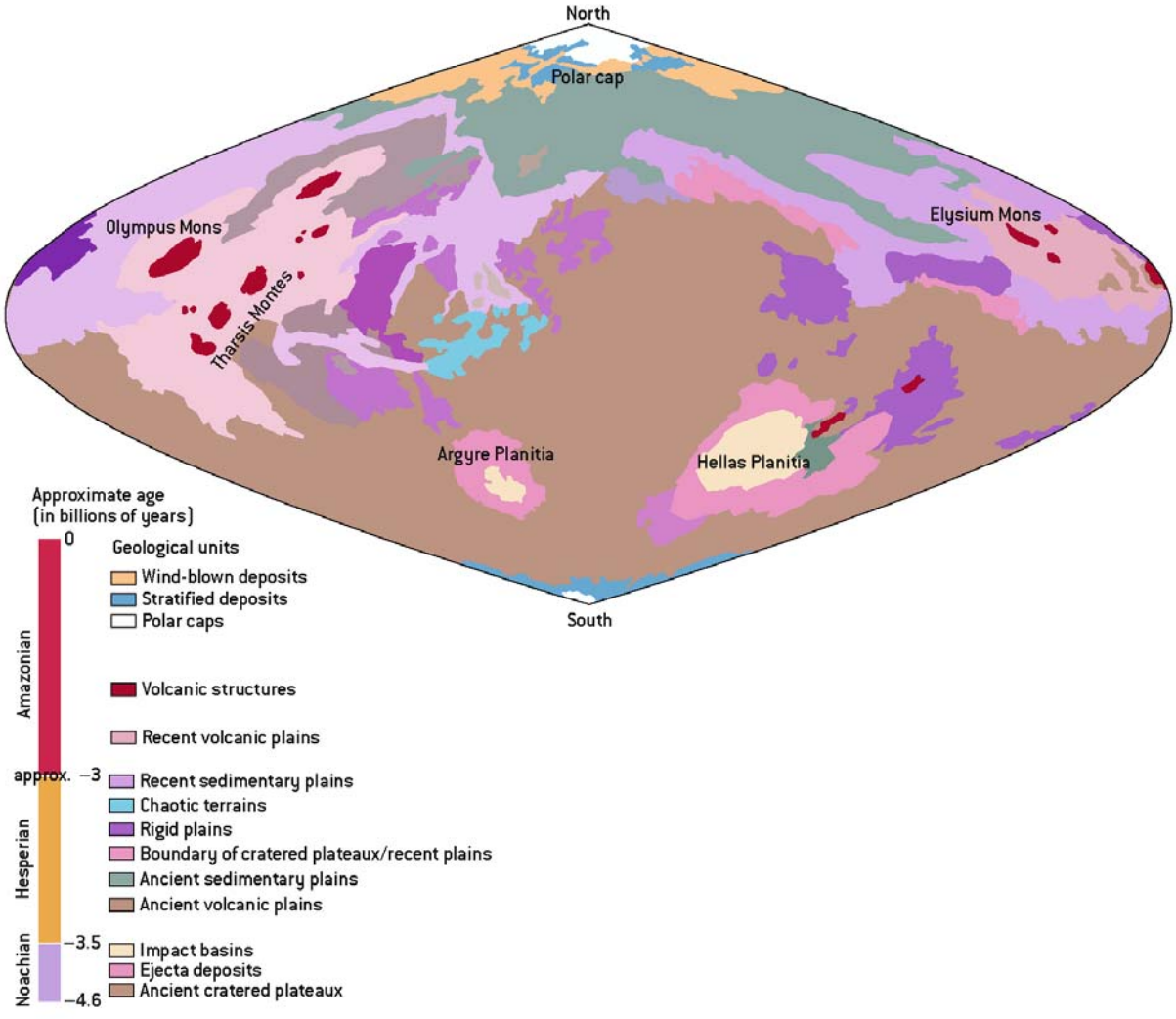
Before undertaking any in-depth study of the geophysical evolution of a planet, scientists must possess a time-scale within which to classify the various structures observed. How, though, can we date the Martian terrains if we have no samples of the surface? The answer lies in counting craters, formed over long periods by incoming meteorites. All dates for geological structures used in the present book are based on this principle.





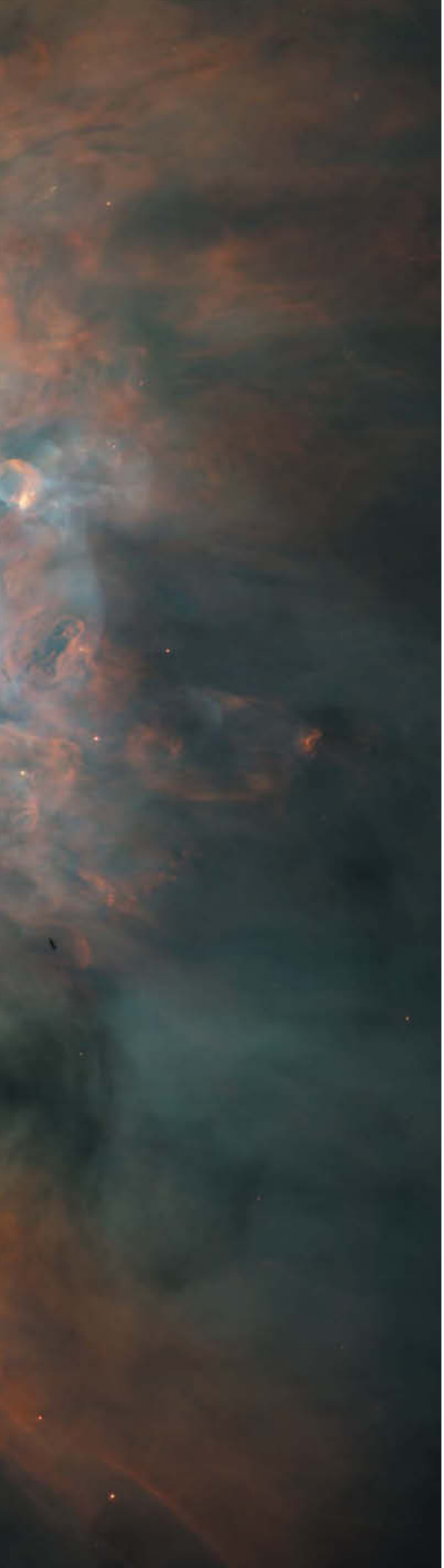


Unequal cratering. Left: a surface peppered with impact craters in Terra Arabia, exposed for the last three billion years. Many craters hundreds of metres in diameter are seen. The smallest craters have been eroded or covered in sediments. **Centre**: the surface of the caldera (volcanic crater) of the volcano Arsia Mons, in the Tharsis region. The innumerable small craters suggest an age between 100 million and 500 million years. **Right**: high-resolution image of a recent lava flow (at top) in the region of Daedalia Planum, to the south-west of the volcano Arsia Mons. Note the absence of impact craters, suggesting that this is a relatively young surface, less than 100 million years old. Illumination is from the left on all three images. (Courtesy NASA, JPL, Malin Space Science Systems.)



Map of the principal geological areas on Mars. Dating by cratering has led to the definition of the three main geological eras of the planet. The most ancient surfaces on Mars, such as the cratered plateau of its southern hemisphere, date from the Noachian era (–4.5 to about –3.5 billion years). The Hesperian era saw the formation of the northern plains and certain areas of the cratered plateau. The most recent era was the Amazonian, represented by the plains where the last phases of volcanic activity occurred, and by polar caps and channels. The date of transition between the Hesperian and the Amazonian remains controversial, but lies somewhere between 2 and 3.2 billion years ago.

Not long after it was formed, 4.5 billion years ago (see Part 1), Mars was subjected to a continuous meteoritic bombardment. Intense until 3.8 billion years ago, this process rapidly diminished thereafter (the impactors decreasing in both number and size), and stabilised over the last billion years. This decrease in the frequency of impacts over time allows geologists to establish a relative chronology from calculations involving the density of craters per unit area on the surface. For example, the heavily cratered plateau of the southern hemisphere, which will be referred to quite often and especially in Part 2, has large numbers of craters of considerable diameter. It must therefore be older than any lightly cratered surface such as is found in the plains of the northern hemisphere. However, counting craters gives only the relative age of a region compared with another. So although we might say that the high plateau in the south is 'definitely' older than the northern plains, to know its exact age, we would need a sample from the Martian surface in order to be able to date it by measuring radioactivity (see page 31). Although it is not currently possible to return the precious samples, future space missions will be programmed to do this, as will be shown in Part 5. Meanwhile, planetologists have to resort to a kind of 'short-cut', involving lunar samples brought back by the Apollo astronauts. Our own natural satellite also possesses, of course, a 'cratering curve'. The lunar samples serve to calibrate this curve, substituting absolute dating for relative dating. Mars specialists have been able to do the same thing, calibrating their calculations for the ages of areas on Mars using lunar samples, and adding 'correction factors' which take into account the position of Mars relative to the Sun, Martian gravity, the presence of an atmosphere, etc. Until we possess a better method, this extrapolation is sufficient for our purposes, even if absolute estimates differ a little from each other according to the values allotted to the corrections, and the models used.



Birth of a planet

–4.6 to –3.8 billion years

Our history of Mars begins in the darkness of past time, at an epoch when almost nothing of the solar system that we know existed – not even the Sun. But the universe was old even then, some 10 billion years old, two-thirds of its present age. All the matter that would form the Sun, Mars, the Earth and living things was still floating as gas and dust.

Suddenly, in just a few tens of millions of years, the blink of an eye on the cosmic time-scale, the solar system came into being. What followed would forever leave its mark on the destiny of the red planet.

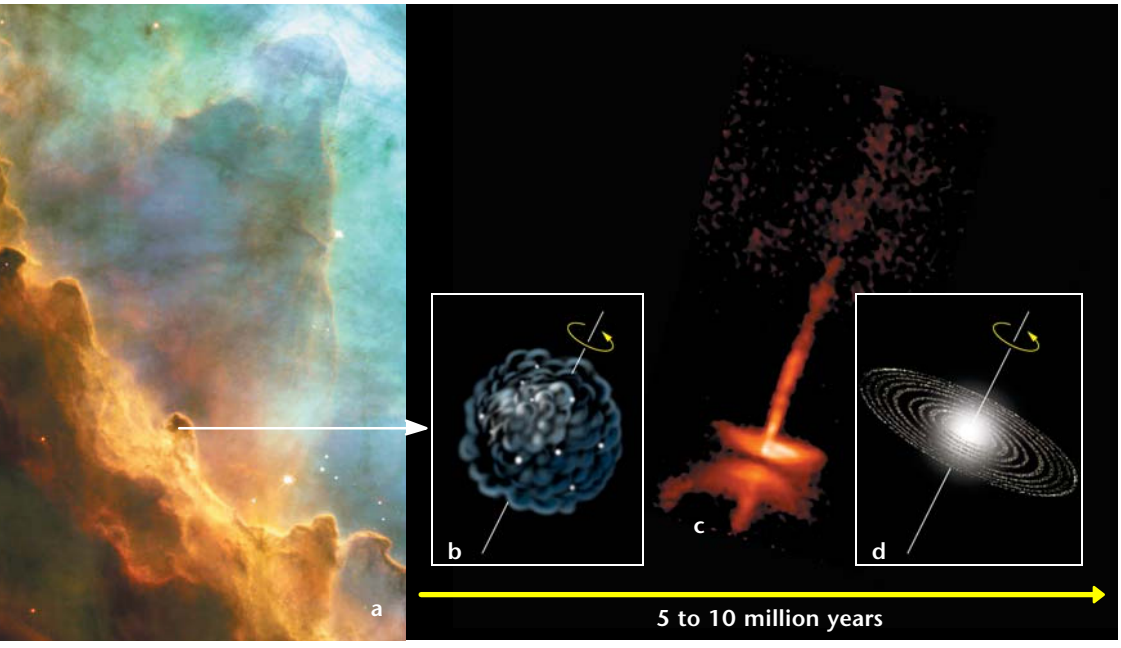
The Orion Nebula, photographed by the Hubble Space Telescope. This immense cloud of matter may resemble the nebula which gave birth to our Sun, and to Mars and the other planets of the solar system. The Orion Nebula is about 1500 light-years away from the Sun, in the same spiral arm of our galaxy, the Milky Way. In the heart of the nebula, more than 150 recently-formed 'protoplanetary' discs, a few million years old, have been identified. Some of these will possibly give rise to Mars-like planets. The image is about 2.5 light-years across. (Courtesy NASA, STScI, C.R. O'Dell and S.K. Wong, Rice U.)

1 Before Mars and the other planets

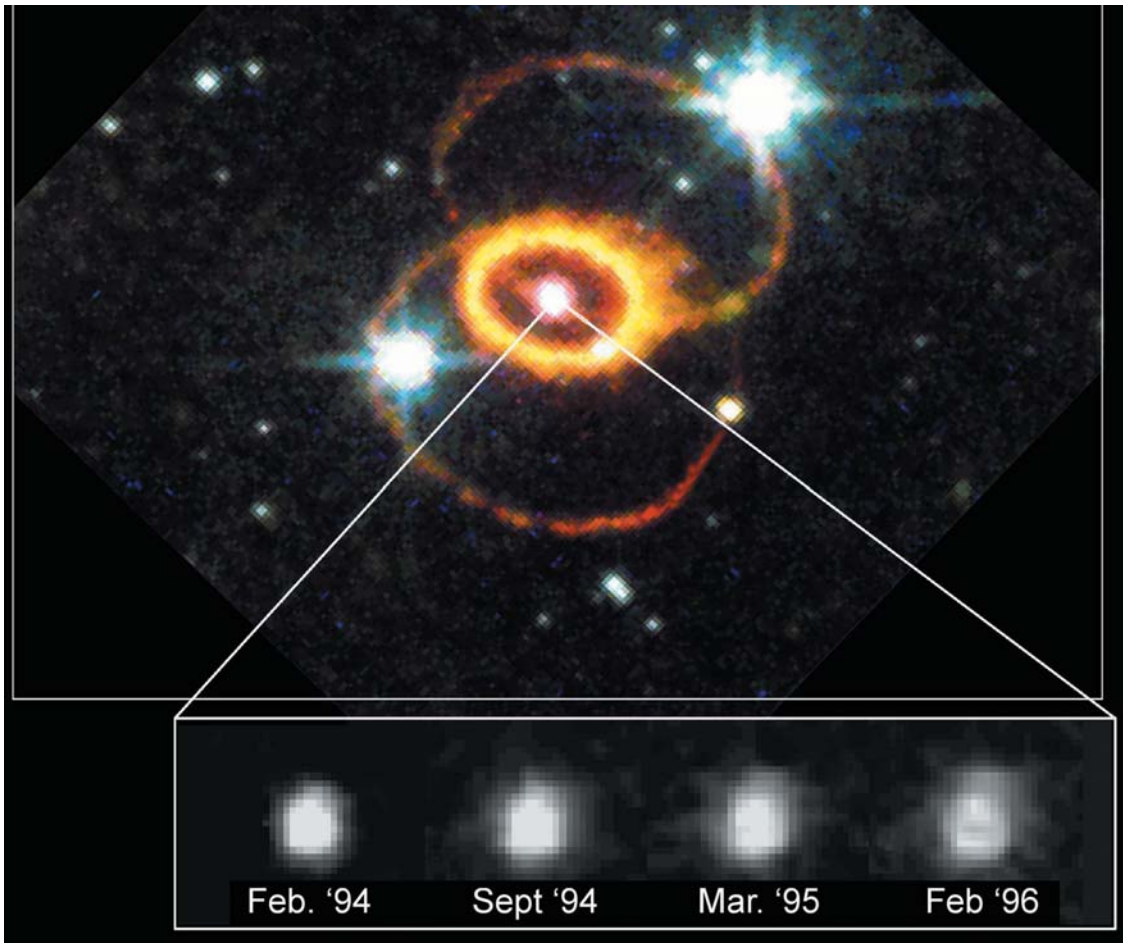
What is the origin of the matter which formed the planets of the solar system?

Like the other 'terrestrial' planets, Mercury, Venus and the Earth, Mars is made principally of the so-called 'heavy' chemical elements, such as oxygen, magnesium, silicon and iron.

These elements were not created by the Big Bang, the singularity which marked the birth of the universe some 13.7 billion years ago. This primordial



Stellar nurseries. Image (a) shows part of the 'Omega' or 'Swan' Nebula (M17). (Courtesy NASA, ESA and J. Hester (ASU).) This cloud of dust and gas is a veritable 'nursery' of stars. When temperature and pressure locally reach a critical threshold, embryonic stars appear. Then, starbirth proceeds, in three stages. Diagram (b): still surrounded by a residual disc of gas and dust, the young star continues to draw in matter though its own gravity, and then (c) begins to eject particles in a direction perpendicular to the plane of the gaseous disc, within an intense magnetic field. This phenomenon slows down the rotation of the star. Here we see the example of HH30, less than half a million years old: its disc of matter appears dark, and its perpendicular jet bright. (Courtesy C. Burrows (STScI & ESA), the WFPC 2 Investigation Definition Team, and NASA.) In (d), the disc, containing only a fraction of its initial mass, now possesses most of the rotational energy (angular momentum). Now, planetary formation may begin...



A cosmic tidal wave. Supernova SN1987A, photographed by the Hubble Space Telescope. The supernova occurred in the Large Magellanic Cloud, a satellite galaxy of our own Milky Way. In 1997, ten years after it exploded, SN1987A's expanding wave of material had travelled more than 750 billion kilometres (5000 times the distance of the Earth from the Sun), at an average velocity of 2500 km/s. Scientists believe that a wave of matter such as this triggered the formation of the solar system 4.56 billion years ago. This wave is rich in very unstable radioactive elements, such as aluminium-26. Now, within the most ancient meteorites in the solar system, magnesium-26, a by-product of the disintegration of aluminium-26, has been discovered. In this way, a link has been established between the formation of the solar system and the explosion of a supernova. (Courtesy Chun Shing, Jason Pun (NASA/GSFC), Robert P. Kirshner (Harvard-Smithsonian Center for Astrophysics), and NASA.)

explosion produced only the very lightest elements, such as hydrogen, helium and a little lithium and deuterium. So where did the planet-forming elements originate?

One very early hypothesis claimed that the heavy elements in planets were made by the Sun. This idea is thought to have originated in the mind of the

Greek philosopher Anaxagoras (500–428 BC), who said that the existence of iron meteorites proved that the Sun was nothing but 'a mass of red-hot iron'.

Nowadays we know that the Sun is composed essentially of hydrogen and helium, but the idea that the Sun provided the material for the formation of the planets is not such an absurd one, because those heavy elements are indeed present within it. What is more, they are present in proportions quite close to those in the primitive meteorites that built the planets. For example, in the Sun (just as in these meteorites), carbon atoms are eleven times more numerous than silicon atoms. However, the hypothesis of a solar origin for the planets encounters one major objection: it cannot account for the disparity of the amount of light elements, especially deuterium, lithium and boron. For when the planets formed, the Sun was deficient in these elements, since it was burning them (and it still is) – and planetary material does not exhibit such deficiency.

Today we can give a better answer to the question of the origin of planets, thanks to our analysis of ancient solar system meteorites. The Sun and its planets owe their heavy elements to the explosions of massive stars at the end of their lives. As a star enters the final stage of its life, having transformed all its hydrogen into helium, it produces heavy elements: helium is transformed into carbon, oxygen and nitrogen, and these in their turn become still heavier elements as fusion processes continue. In stars with sufficient mass, this chain of creation ends in a supernova explosion, involving the ejection of all these elements into space. They will then participate in the formation of new stars and planets.

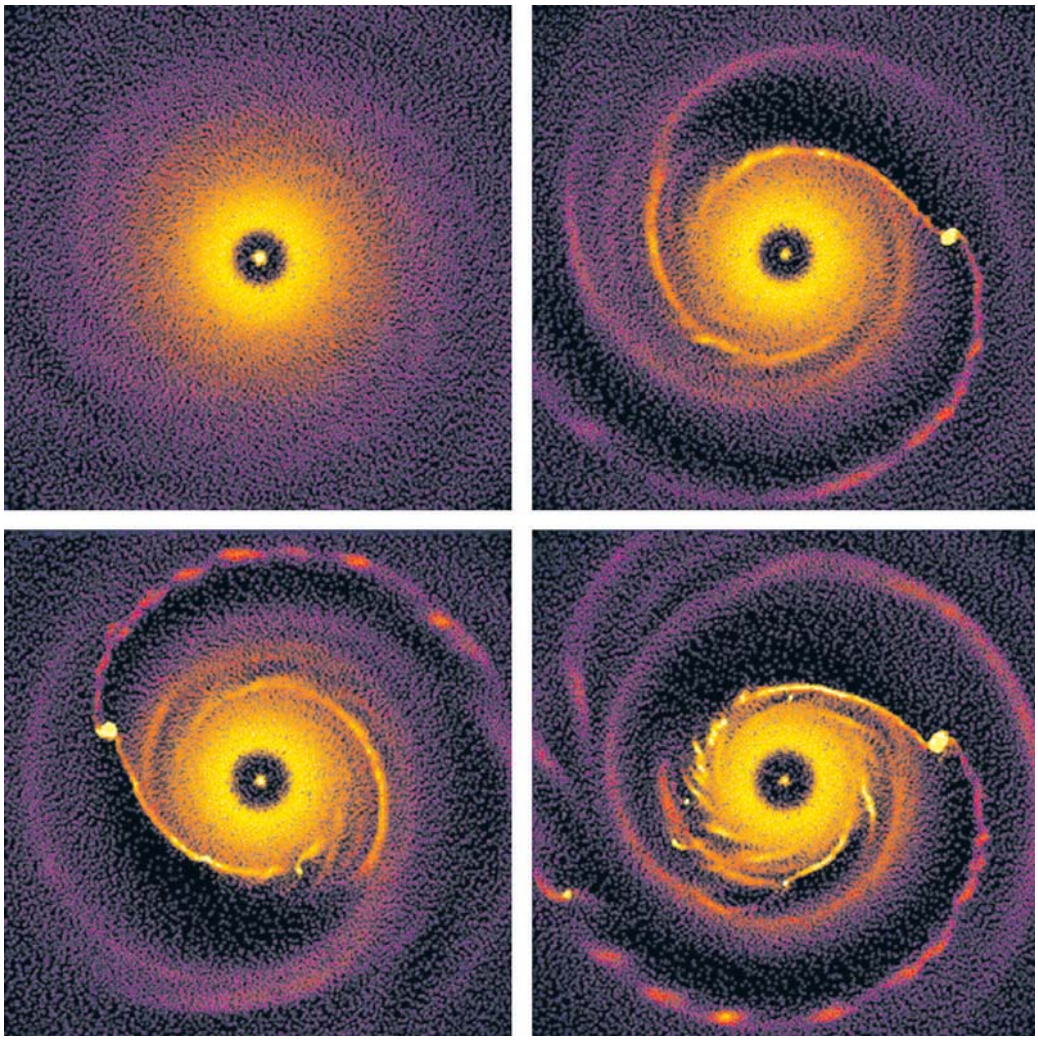
2 Very rapid protoplanetary growth

From stardust to planet in 100 million years

4.52 billion years ago, the Sun began to shine within a disc of gas and dust. Near it, the temperature was so high that water and other volatile elements were in a gaseous state. Only compounds which were not very volatile, such as oxides of silicon and magnesium, and metallic elements, were able to remain in solid form. Dust particles collided and adhered to form porous agglomerates, about a metre in diameter. In their turn, these bodies collided with each other, until they became kilometre-sized 'planetesimals', the building blocks of future planets.

After a fairly tranquil 'infancy', the Sun entered a violent adolescent phase at about the age of 10 million years. For the first time since their formation, gases and volatile materials reversed their movement, now being ejected towards the edge of the solar system due to the buffeting of the solar wind, an intense stream of particles issuing from the Sun's corona.

In the Orion Nebula, the young star LL Ori (at the centre of the image) suggests what the Sun probably looked like during the 'T Tauri' phase of its adolescence. This phase is characterised by the existence of a fierce solar wind, and the ejection of a quantity of matter of the order of one percent of a solar mass every million years. These phenomena can be from 100 to 1000 times more intense in the so-called 'FU Ori' phase. The bright zone of the nebula (to the right of LL Ori in this image) corresponds to a region where hydrogen, oxygen and nitrogen atoms are being excited most strongly by the solar wind. (Courtesy NASA and The Hubble Heritage Team (STScI/AURA).)



The role of Jupiter. A computer simulation by P. Armitage, of the University of Toronto, illustrates the process of planetary formation. 60 000 small bodies were initially 'placed into orbit' around a 'Sun'. As shown in figure (a), without the presence of a massive planet, the configuration evolves very slowly (the simulation represents a period of ten million years). If a Jupiter-type planet of mass one-thousandth that of the Sun is introduced into the system, the configuration after the same length of time corresponds to figure (b): the small bodies are concentrated as much between 'Jupiter' and the 'Sun' as outside the orbit of 'Jupiter'. The other figures represent the process of aggregation after phase (b), over two million (c) and four million (d) years. The embryos of future planets are evident. If the simulation were pursued, we would notice that 'Jupiter' prevents any further formation of large planets within the asteroid belt, and limits the growth of a 'Mars' to its present size. In summary, in the absence of Jupiter, Mars might have become a little bigger, but the Earth and Venus would probably not have been able to attain their current dimensions. What might then have become of these planets? (Courtesy P.J. Armitage and B.M.S. Hansen, *Nature* No 402, 9 Dec. 1999, p. 20.)

As matter flowed outwards, water vapour migrated to regions where temperatures were lower. At about 820 million kilometres from the Sun (5.5 times the present distance between the Earth and the Sun), water vapour condensed into particles of ice. The ice came together with dust to form a planet several tens of times more massive than the current mass of the Earth. The gravitational field around this massive body drew in large quantities of hydrogen: Jupiter was born, and it had taken less than 10 million years.

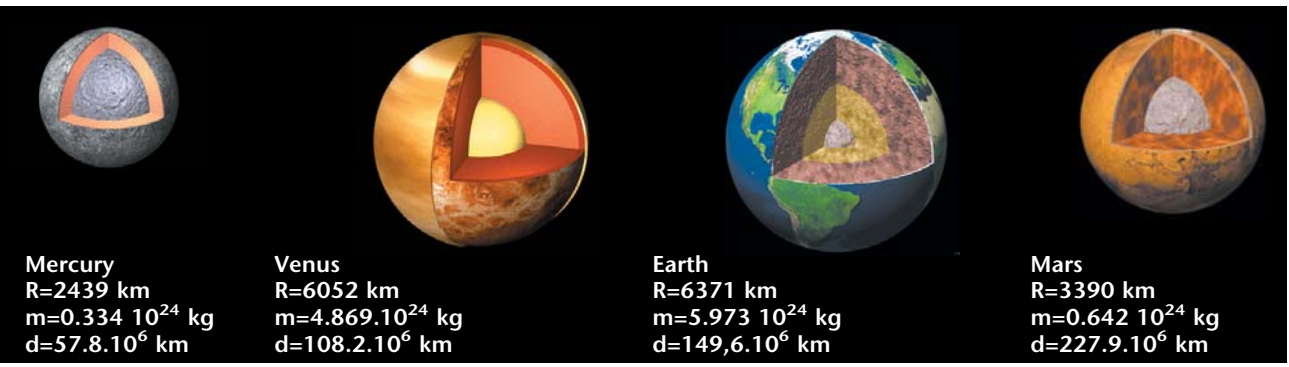
Saturn took twice as long to form, at a distance from the Sun (about 1250 million kilometres) where its orbital period was twice that of Jupiter. Uranus and Neptune were born in similar circumstances, devouring icy planetesimals at a distance from the Sun more than twice that of Saturn.

Nearer to the Sun, planetesimals continued to attract each other and collide. In the course of about 10 million years, embryonic planets grew into the smaller planets of the early solar system. Some were the same size as Mars, about 7000 kilometres in diameter, about 10 of them resembled Mercury (5000 kilometres), and there were many hundreds similar in diameter to our Moon (3500 kilometres). So, between 4.47 and 4.44 billion years ago, the 'modern' phase of the history of the solar system began. As the last cataclysmic collisions between planets occurred, the Earth and Venus gathered in most of the existing material. Another planet, as big as Mars, had formed, and collided with the Earth. From this impact was born the Moon. Later, Jupiter moved closer to the Sun, causing Saturn and, further out, Uranus and Neptune, to move away. Since then, the planets have maintained the orbits which they pursue today.

3 Formation of the core, crust and mantle

The physics of the blast furnace at the heart of planets

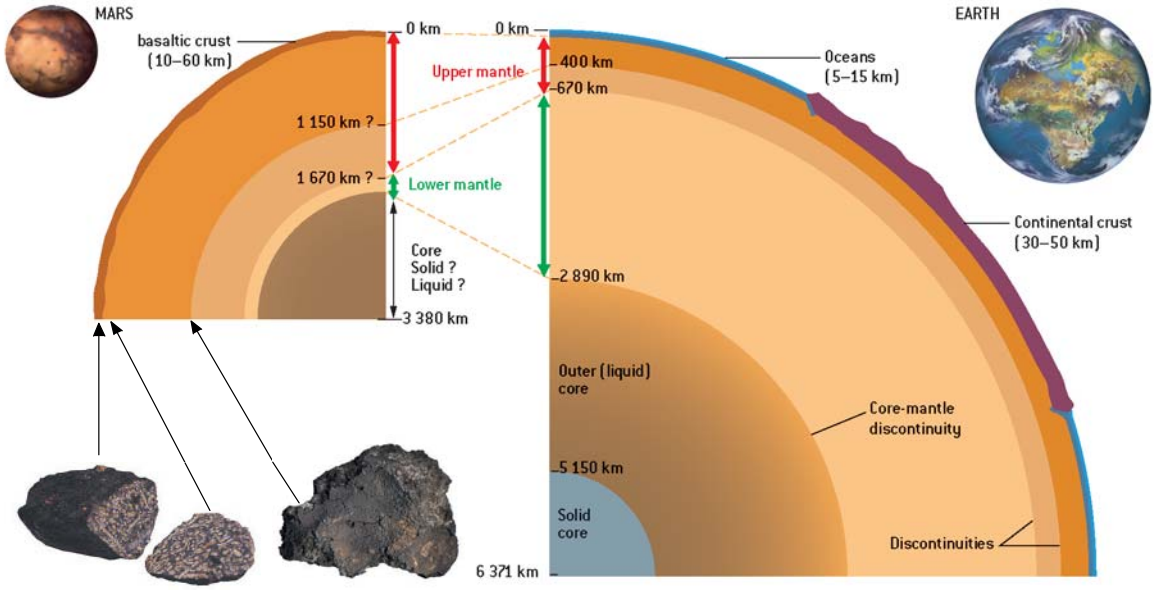
The 'terrestrial' planets (Mercury, Venus, the Earth and Mars) were formed from a disorderly crowd of planetesimals. However, these planets now exhibit an iron core surrounded by a rocky mantle, which is not so dense, and above this lies an external crust. This differentiation could not have happened unless the interior of the primitive planets had melted, and followed the same process of refinement as occurs in high-temperature industrial furnaces. During the 1970s, most planetologists thought that, in the case of Mars, this process took a billion years, which is the time required to accumulate a sufficient quantity of heat created by the disintegration of radioactive elements within the planet. However, analysis of Martian meteorites during the 1980s (see pages 30–32) revealed a much more rapid scenario. In these meteorites, which bear witness to the formation of Mars' crust, certain elements known for their readiness to associate with iron ('siderophilic' or iron-loving elements), and which are found with iron even within the core, were not present in the expected quantities. This gave credence to the idea that iron had largely migrated from the crust of Mars towards the core as the planet accreted, the core having formed in fewer than 50 million years, and possibly only 20 million years.



Mercury, Venus, the Earth and Mars: the four terrestrial planets all possess a metallic core, a mantle and an external crust. They are represented here with details of their radii (R), masses (m) and mean distances (d) from the Sun. The comparatively enormous core of Mercury is exceptional. This planet was probably involved in a vast collision towards the end of its formation, in the course of which the core of the impactor penetrated the mantle of the proto-planet and fused with its core. Most of the fragments of the mantle were ejected. (Courtesy Calvin J. Hamilton.)

During the accretion phase of a planet, the impacts of planetesimals liberate vast quantities of energy. An object 10 metres in diameter, crashing into the Earth at 20 kilometres per second (a typical impact velocity for a meteorite), liberates energy equivalent to 100 000 tonnes of TNT, or about 7 times the energy of the Hiroshima bomb. What would be the effect of a 1-kilometre planetesimal? The greatest impacts may convert up to 30% of their kinetic energy (energy of motion) into heat. This heat would be sufficient to melt the surface of a planet to a depth of several hundred kilometres. (Illustration by David A. Hardy.)

In fact, it was accretion itself that produced sufficient heat, not only on Mars but also on the Earth, Venus and other terrestrial bodies, to refine the elements from the original mixture present within the planetesimals, in the manner of a blast furnace. In the heart of a blast furnace, oxygen, carbon and iron oxides react to form iron and carbon dioxide: within the magma of a planet, iron oxides and graphite from meteorites known as carbonaceous chondrites react to form metallic iron and carbon dioxide. The molten iron sinks towards the centre of the planet, gaining a little more heat as it falls. Conversely, 'refractory' oxides, and in particular aluminium oxide and calcium oxide, rise to the surface as a kind of scum: the 'primary crust'.



How big is the core of Mars? And what is it made of? The depth of Mars' core-mantle boundary has not yet been directly measured. However, we can have some indication by comparing meteoritic fragments of the Martian crust (such as the Chassigny meteorite) with meteorites with a composition supposedly comparable to that of planetesimals, such as the carbonaceous chondrite which fell near Ivuna, in Tanzania, in 1938. The core of Mars, which is about 1500–1900 km in diameter (about half the diameter of the planet), is probably composed of about 70-80 percent iron, with some nickel and sulphur. Having studied the SNC meteorites (see pages 30–32), Heinrich Wänke, of the University of Mainz in Germany, concluded that the sulphur content was 14 percent and the nickel content 8 percent. One of the consequences of the presence of sulphur in Mars' core is to decrease by nearly 300°C the solidification temperature of the iron-nickel-sulphur amalgam. So, because of the presence of sulphur, Mars could still, even today, possess a completely liquid core. Recent geodesic measurements by Mars Global Surveyor tend to confirm this. (Illustrations courtesy Sté Labenne Meteorites, France (left) and INSU, CNES (right).)

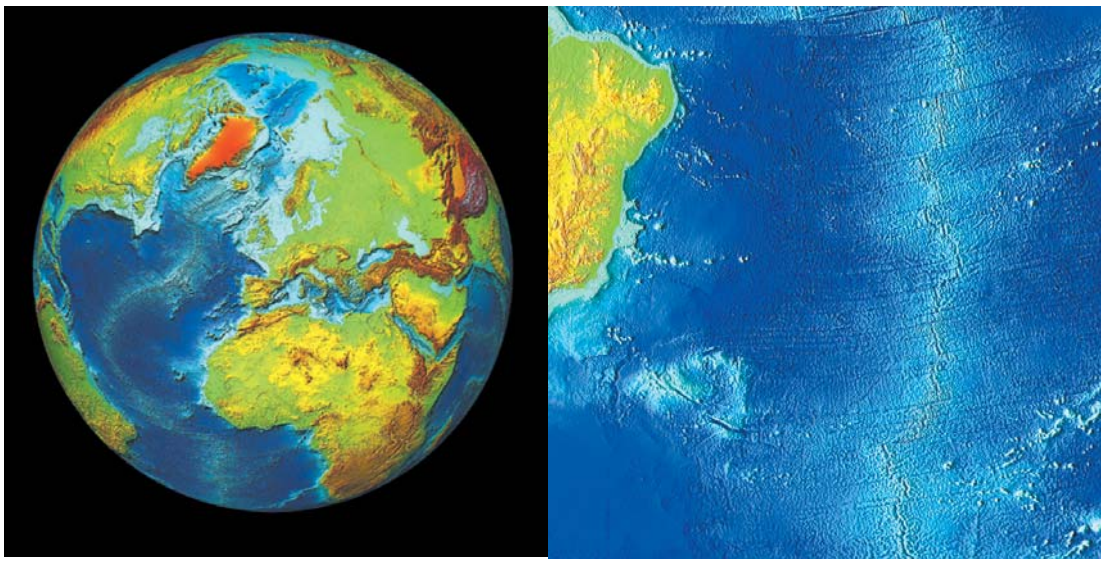
4 The evolution of Mars, the Earth, Venus and Mercury

Born at the same time – but their paths are so divergent

Various factors can be invoked to explain the evolutionary differences of the four terrestrial planets. Among these factors are initial size, the history of (cataclysmic) cratering, and the process of heat loss from within.

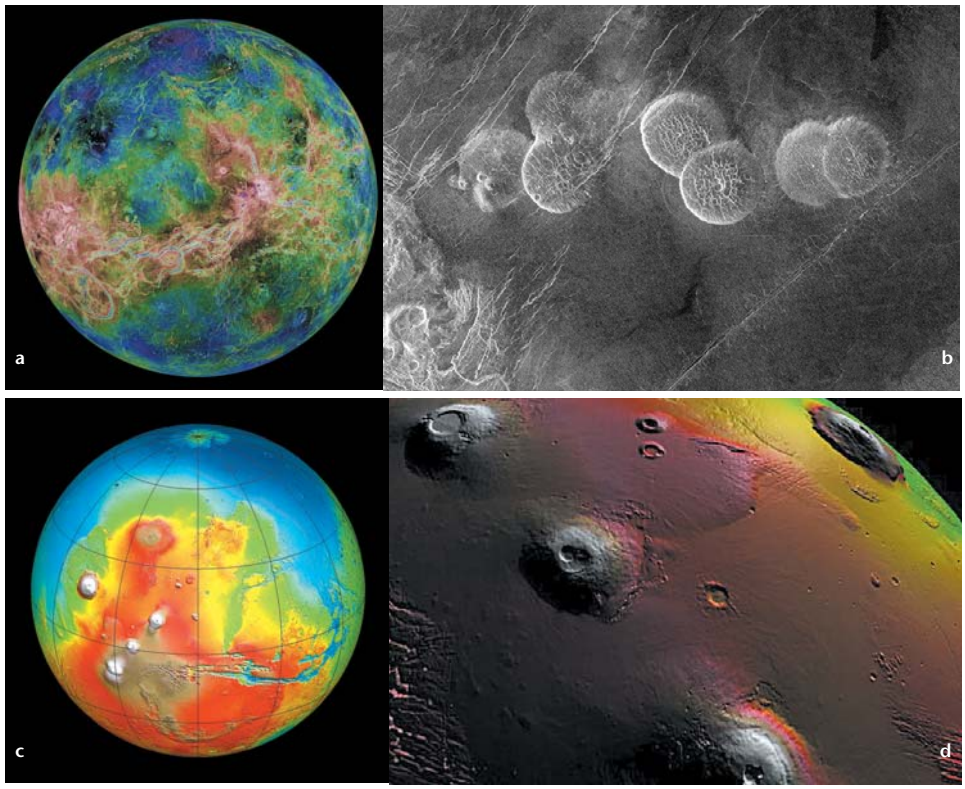
Initial size

By the end of the period of accretion, a little more than 4.45 billion years ago, Mars was half the size of Venus or the Earth, and about ten times less massive. This difference would prove decisive, in more ways than one, for the quantity of energy stored within the planets. The more massive a planet is, the greater is the



On Earth ... The Earth is characterised by plate tectonics, its continental and oceanic ('lithospheric') plates moving at a rate of a few centimetres per year. This movement at the surface is associated with convection currents within the mantle. This phenomenon accounts for two-thirds of the heat loss from the mantle and core. It is in the volcanic zones of oceanic ridges that the plates move apart, allowing hot matter from the depths to emerge and form new crustal material at the rate of 3 square kilometres of oceanic crust per year. On the left is shown the Atlantic Ridge, and on the right, an enlargement of its southern part. This ocean ridge volcanism extends for more than 60 000 kilometres. In subduction zones, the ancient crust falls back into the mantle, to be recycled. (Courtesy NOAA, Satellites and Information.)

gravitational acceleration towards it of planetesimals, and the harder they impact as accretion proceeds. Also, the bigger the planet, the greater the quantity of radioactive elements stored within it. What is more, large planets conserve heat better, since their stronger gravity can maintain dense atmospheres, opaque to thermal radiation and therefore limiting energy loss. This is why, from the beginning, the two smaller bodies, Mercury and the Moon, cooled more quickly. Mars marks an intermediate stage between these two smaller bodies and two larger ones, the Earth and Venus.



. . . And on Venus and Mars. Unlike the Earth, Venus and Mars show no plate-tectonic activity. Their internal heat is probably lost through local up-currents in the mantle (volcanoes), forming cylindrical plumes at the surface. On Venus (image (a)), seven pancake dome volcanoes have attained heights of 750 metres (b) in the Alpha Regio area (Magellan radar image). On this planet, heat accumulated beneath a layer of rigid rock, the lithosphere. In consequence, large numbers of volcanoes erupted between 500 and 300 million years ago, covering most of Venus' surface with lava, and erasing the majority of surface impact features. As for Mars (c), it could well still be volcanic, especially in the Tharsis Region. Image (d) is a false-colour photograph of the topography of the Tharsis region, the vertical scale having been exaggerated by a factor of three. In fact, since the red planet has a very thick lithosphere (of the order of five hundred kilometres), thermally isolating the mantle and the core, it loses its heat much more slowly than does the Earth. Also, unlike the Earth's core, which is already partly solid, Mars' core is probably still in the liquid state. (Courtesy NASA (a) and (b), NASA, MOLA Science Team (c), and NASA, Goddard Space Flight Center, Scientific Visualization Studio (d).)

Cataclysmic cratering

The random process of cataclysmic meteorite impacts played an important part in the internal evolution of planets. Take the example of the Earth, whose mantle absorbed the greater part of the matter and energy involved in the violent impact which gave birth to the Moon, just over 4.48 billion years ago. Compare this with Mercury, which lost most of its mantle to another impact.

The process of heat loss

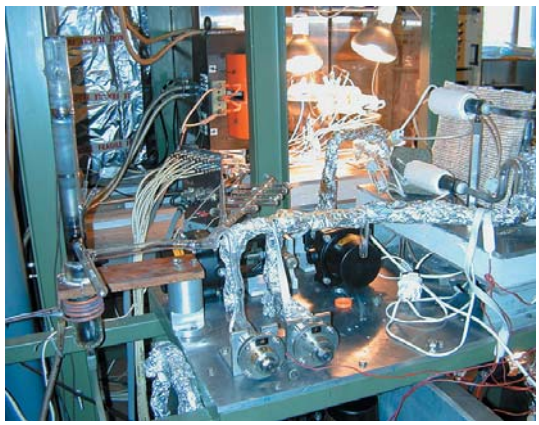
After the phase during which they absorbed material and gravitational energy, the planets radiated away some of their internal heat, including the heat slowly released by the radioactivity of the rocks. What mechanisms were involved? In the case of a solid, rigid planet, the process will be that of thermal conduction of heat towards the surface. This mechanism causes heat to be lost in proportion to the surface area of the planet, while heat retained is proportional to the volume. So, a large planet will lose relatively less energy than a smaller one. However, this model does not take into account the thickness of the isolating surface layers, volcanism or the movements of material within the mantle. What happens within the seemingly solid mantle is that, over geologic time, the hot rocks are subject to deformation, and material from deep within, hot and less dense, can come to the surface, where it cools. This phenomenon, known as convection, is much more efficient than conduction at transporting and releasing heat. The Earth is today the terrestrial planet with the strongest convection, almost up to the surface at the mid-oceanic ridges, while mantle convection has probably ceased in the Moon and Mercury. Again, Mars is in-between, with a mantle hot enough to convect weakly or at least, especially beneath the large volcanoes, with zones of partial melting, generate volcanism in the last hundred million years.

5 What Martian meteorites tell us

Stones reveal the secrets of the planet and its history

In the morning of 3 October 1815, the inhabitants of the village of Chassigny, in eastern France, were startled by some very unusual detonations: a 'stone' had fallen from the sky nearby. This 4-kilogramme meteorite intrigued generations of researchers, seeming to have come straight from the mouth of a volcano!

Of all the tens of thousands of meteorites found on Earth, only about thirty are of the 'Chassigny' type. These are known as the SNC meteorites, referring to the initial letters of the places where the first three were found: Shergotty in India, Nakhla in Egypt and Chassigny in France. Only in the 1980s was it finally discovered that these meteorites originate on Mars. They are characterised by their 'isotopic' oxygen content. Oxygen has various isotopes: its nucleus has



Discovered in the Antarctic, dated in the laboratory. Many Martian meteorites (e.g. EETA 79001) have been found on the ice of Antarctica (left), where they are easily seen. (Courtesy Antarctic Search for Meteorites Program (William Cassidy).) Their composition can be readily discovered by means of mass spectrometry (the right-hand photo shows equipment at the Institut de Physique du Globe in Paris).

To determine their origin, and more particularly the date at which they solidified from magma, geochemists rely on the phenomenon of the radioactive disintegration of potassium-40 into argon-40. As soon as the rock is molten, the argon present due to the disintegration of potassium-40 can escape. As soon as it has solidified, the argon accumulates within the rock. By comparing the content of different isotopes of potassium and argon with their initial values (their concentration in the Martian atmosphere), the time of crystallisation can be deduced. In the case of EETA 79001, the value is 180 million years. It is therefore quite a recent rock, given the age of the planet.

Clues to the differentiation and solidification of a planet. Isotopic geochemistry provides global data about a planet from only a few grammes of rock, using the properties of the many chemical elements in that rock. The basis of this analysis relies on two physical phenomena.
1: chemical elements (whatever their identity) usually possess several isotopes, i.e. atoms whose nuclei have the same number of protons but different numbers of neutrons. Certain isotopes are unstable, because of the number of neutrons within them. These will disintegrate more or less rapidly into other, more stable chemical elements.
2: certain chemical elements are fixed in rocks at the time of their formation. Others are produced in the interior of the rocks as a result of radioactive disintegration of elements present since the origin of the rocks.
Example: the dating of the Martian crust. In a meteorite which has come from Mars' crust, we find two isotopes of neodymium: Nd-142 and Nd-144. We know that the Nd-142 present in the meteorite was produced by the disintegration of samarium-146 (Sm-146) which had been fixed in the crust since its formation, and of which only traces now remain. Its half-life (the time required for half the atoms of Sm-146 to disintegrate into Nd-142) is 'only' 100 million years. However, Nd-144 is not a product of any disintegration, and we know in what proportion the Nd-144 and Sm-146 occur at the time of their formation in the supernova which gave birth to the solar system (see pages 18–20).
Also, the proportion of Nd-142 compared with that of Nd-144 today allows us to deduce the proportion of Sn-146 relative to that of Nd-144 at the time of the formation of the crust. By comparing the latter to the initial proportions (in the supernova), we can work out the time which has elapsed since the birth of the solar system and the formation of the Martian crust. According to this analysis, the crust was probably formed 100 million years after the birth of the solar system. (Courtesy LPI, Houston and Calvin J. Hamilton.)

eight protons, but the number of neutrons can differ. The isotopic composition and the relative abundance of different isotopes are the same in all the SNC meteorites, providing a distinctive signature. Another identifying feature of SNCs is that they are relatively young, mainly magmatic or volcanic rocks. Isotopic

dating reveals that the youngest of them crystallised less than 200 million years ago.

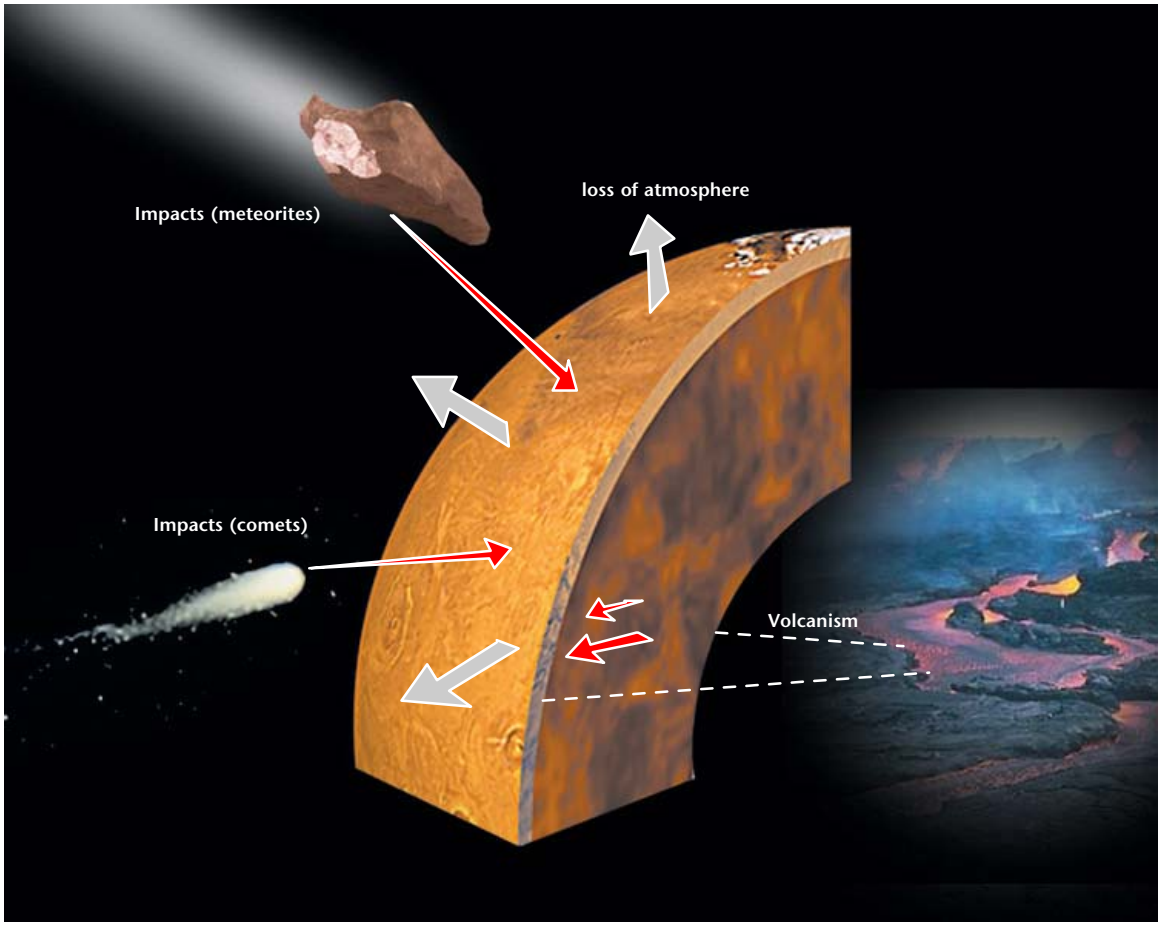
How was it discovered that SNC meteorites come from Mars?
Dating and analysis revealed only part of the scenario: the fact that they once belonged to a single, far-off parent body big enough to have produced magma and volcanism. Was it Mars? Venus? Or an ancient planet destroyed during the formation of the solar system? The SNCs had been ejected into space probably as the result of a violent asteroid impact, but relatively recently, so only existing planets can be considered. Finally, the most convincing evidence of a Martian origin came from one of these meteorites: EETA 79001. This object was collected in Antarctica in 1980. Inside it were bubbles of gas, trapped within dark flecks of basaltic glass. The glass had been formed at the time of the enormous impact which detached the rock from its planet. It was concluded that these gaseous inclusions were almost identical in composition to Mars' atmosphere, as analysed *in situ* by the Viking landers in 1976. On this basis, SNC meteorites are considered by many researchers to be true fragments of the red planet, and clues to its formation.

6 The origin of atmospheres and water

A composite and elusive origin

Mars, the Earth and Venus all have atmospheres essentially composed of nitrogen, oxygen, carbon dioxide, water vapour and rare gases such as helium, argon, neon, krypton and xenon. These atmospheres are distinguished from each other by the relative proportions of the various gases, and by their global pressures. For example, the pressure at the surface of Mars is between 100 and 150 times lower than on Earth, which in its turn has an atmospheric pressure 90 times lower than that on Venus.

Mars (left) and Venus (right) as seen through the Earth's atmosphere from the space shuttle Discovery. (Courtesy NASA.)



The origin of Mars' water and atmosphere. Most of Mars' water and carbon dioxide was released into the atmosphere during accretion, having been trapped within chondrites. Later, more was released during volcanic episodes. According to Roger Phillips, of the University of Washington, the creation of the Tharsis bulge and its volcanoes would have involved some 300 million cubic kilometres of lava, sufficient to liberate enough water to form a global ocean 120 metres deep and an atmosphere 50 percent denser than Earth's. After the accretionary phase, impacts of water-bearing comets and meteorites would also have contributed to the formation of the primitive ocean and atmosphere. (Courtesy NASA, JSC, JPL, and Calvin J. Hamilton.)

To discern the original composition of the planetary atmospheres, planetologists need to put in a lot of detective work: the compositions have been vastly changed by chemical and physical interactions of the volatile elements, the solid crust and the liquid oceans, and by volcanic activity. Looking for atmospheric constituents which have persisted unchanged for four billion years requires, paradoxically, that those elements which form today's atmospheres have to be left out of the analytical equation. For example, oxygen, nitrogen and carbon

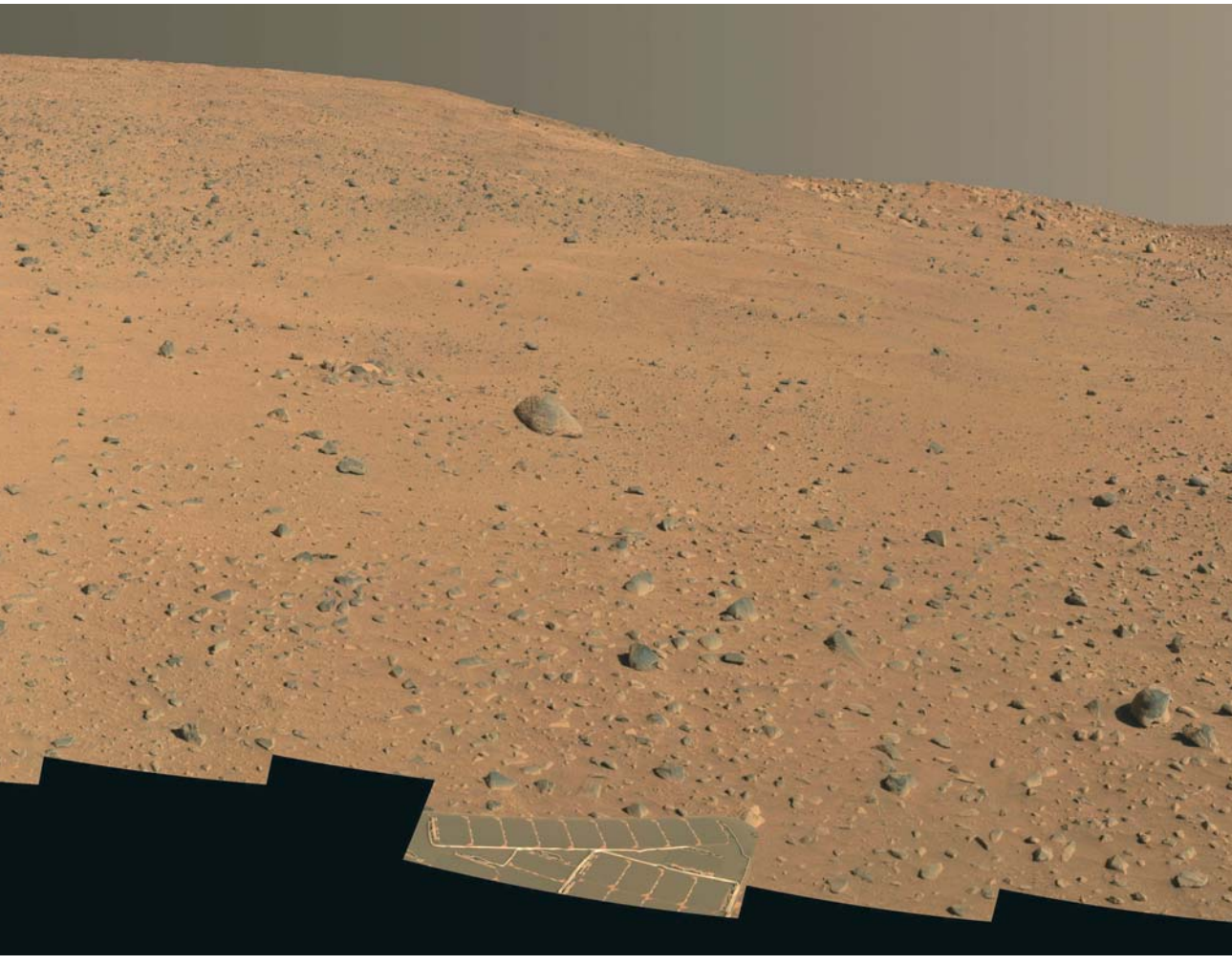
form carbonates and nitrates which are incorporated into the crust; deuterium and hydrogen may be products of the decomposition of water in oceans and ice deposits. There remain only the rare gases, characteristically chemically inactive (hence their alternative name of 'inert' gases), and more particularly their isotopes (atoms of the same chemical element which differ both in the number of neutrons in their nuclei, and in their masses).

In 1976 the Viking probes took measurements, indicating that these rare gases make up just over 1.6 percent of Mars' atmosphere. Most of this is argon-40, an isotope produced by the radioactive disintegration of potassium-40 in the rocks, and there are some traces (less than 5 parts per million) of neon, krypton and xenon.

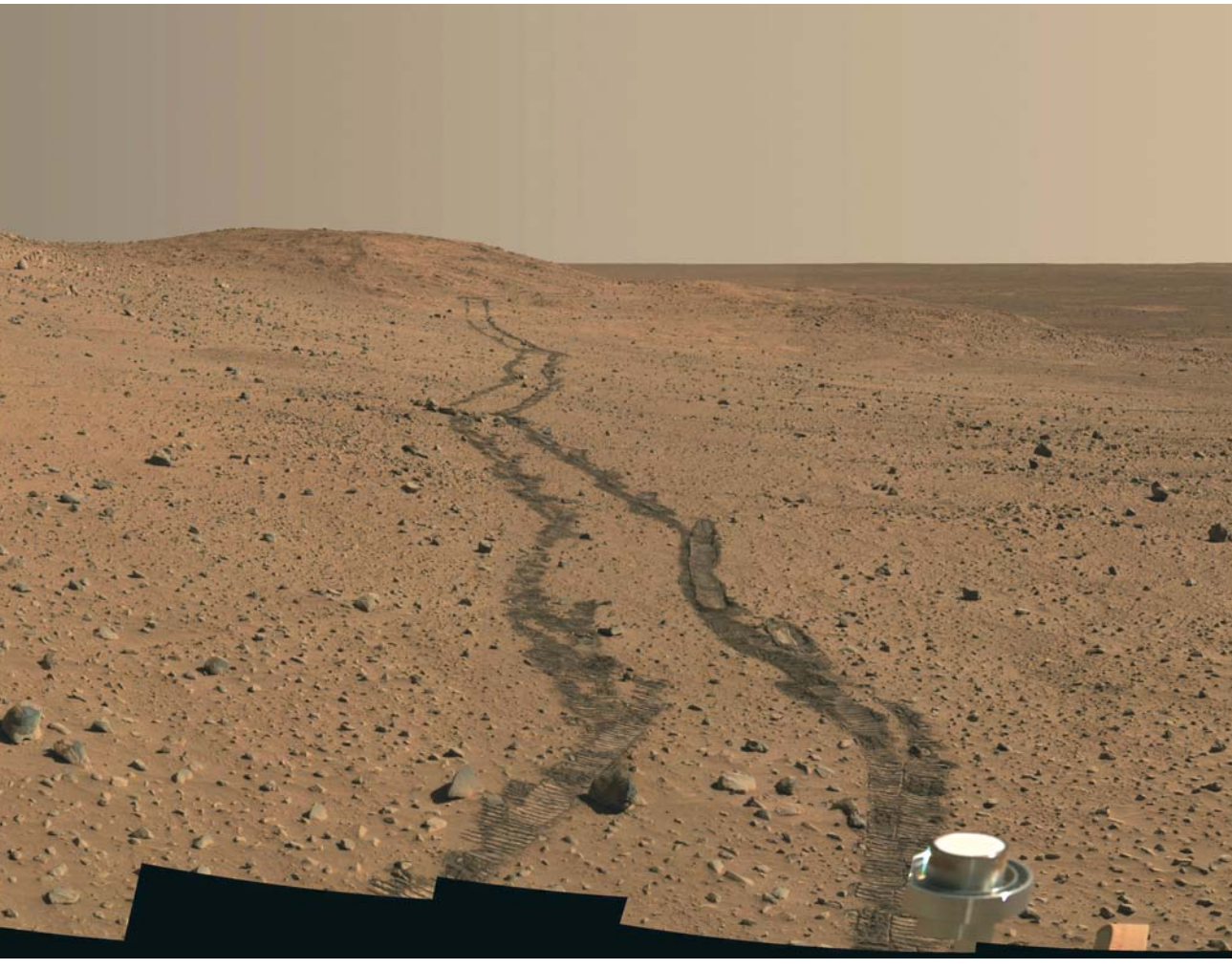
Describing the origin and history of the Martian atmosphere is made even more difficult by the planet's low gravity, lack of a magnetic field (see pages 42–44) and still unknown history of volcanic activity. These two factors are responsible for the loss of most of the primitive atmosphere, which was stripped away as a result of meteoritic impacts and the action of the solar wind.

As for Mars' initial quantity of water, it may well have been greater than that in the Earth's oceans. We know now that after an early phase of accretion when part of the core and mantle were formed, the process continued with the arrival of planetesimals rich in volatile elements and water (forming as much as 10 percent of their mass). Analyses of meteorites originating on Mars seem to indicate that half of the planet is composed of such material. Most of the water has certainly disappeared, but some remains in the crust in the form of ice (see Parts 2 and 3), and in the planet's mantle, although quite how much of it now exists is a matter of debate.

Epilogue



A new road on Mars, travelled by the rover Spirit in November 2004. (Courtesy NASA, JPL-Caltech, Cornell.)



As the first edition of this book was nearing completion, one of the authors received a gift of another book: *Physique de la Planète Mars*, written in 1951 by Gérard de Vaucouleurs, one of the most famous astronomers of the twentieth century, and a great expert on the red planet, and on galaxies. The book was published in English in 1954 with the title *Physics of the Planet Mars*. In his book,

Sunset over the rim of Gusev Crater, photographed by the rover Opportunity. On Mars, atmospheric dust surrounds the white Sun with a bluish halo. (Courtesy NASA, JPL-Caltech, Texas A&M, Cornell.)

de Vaucouleurs presented a rigorous overview of all the available observations of Mars, drawing upon the best current knowledge of planetary physics in order to '*summarise those things which are already known through serious consideration*'. Fifty-two years after its publication, the book made edifying reading: because nearly everything in it was wrong! We read, for example, that '*the permanent atmosphere of Mars can be constituted only of nitrogen, and a small quantity of argon*', though we now know that the Martian atmosphere is essentially carbon dioxide. According to de Vaucouleurs, '*. . .the surface pressure on Mars is 85* $\pm$ 8 millibars' – the value in reality is 6 millibars. Again, '*we can now confirm that the polar caps are like those on Earth, made of frozen water*', and the author adds in a footnote '*we shall not linger here over a detailed discussion of the reasons why the hypothesis involving frozen carbon dioxide is no longer tenable*' – on the contrary, the caps do indeed contain considerable amounts of carbon dioxide snow.

A message to Earth? This heart-shaped depression on the flank of the volcano Alba Patera was photographed by the MOC camera, on Mars Global Surveyor, in 1998. The feature, 2.3 km wide, was created by stretching of the Martian crust within a trench of the 'graben' type (see pages 100–102). (Courtesy NASA, JPL, Malin Space Science Systems.)

Far from deriding this famous author, we realise that the traps laid by Mars at the feet of the best scientists of the past teach us caution today. We now have direct measurements taken on the Martian surface, and the finest remote-sensing instruments are mapping the planet from every angle. However, contrary to what the title of the present work might suggest, and although we have done our best to draw together current knowledge, we are far from being able to tell the real story of Mars. The only thing that is certain is that our book too will be subject to debate: less than three years passed between the first edition, and the writing of the revised edition now before you – and already, discoveries made by Mars Express and the Mars rovers led us to rewrite whole sections. There is no doubt that, in time, some of the theories that we have laid out in these pages will be contradicted.

Are we pessimistic? Not a bit of it! The aim of this book is none other than to invite you to take part in this great scientific and technological adventure – the exploration of the red planet, and the search for its origins and mechanisms. We hope that we have succeeded in conveying the wonder awaiting us, as Mars continues to offer up more discoveries and surprises.

Index

accretion 24–5
Acheron Fossae 100
Acidalia Planitia 66, 70, 99
aircraft 212–13
Alba Patera 92, 93, 100, 223
ALH84001 77–9, 81
Alpha Regio area 28
Amazonian era 13
ammonia 70
Antarctic lakes 75
Apollinaris Patera 92, 93
Arabia Terra 56, 170
Arcadia Planitia 66
ARES 213
Ares Vallis 112, 113, 114–16
argon 30, 34, 69, 126, 127
Argyre Basin 66
Arsia Mons 12, 91
Ascraeus Mons 91, 98
ASPERA instrument 205
asteroids 46
astronauts on Mars 217–19
Athabasca Vallis 112, 113
atmosphere 8, 186
  carbon dioxide cycle 158–60
  composition 8, 125–7, 220
  dust in 137–9, 140
  loss of 35, 80–2
  origin of 33–5
aureoles 95, 96
Aureum Chaos 110
Aurora programme 208–10

Bakhuysen crater 54
balloons 199, 213
barchans 134
Beagle 2 195, 196, 197, 207, 212
Big Bang 18–19
biomorphic robot explorers 212
blast furnace 25
buttes 39, 40, 109

calderas 95, 96
canals 185
Cape St Mary 11
carbon 20, 33, 76
carbon dioxide 69–70, 125–7
  cycle 155–66
carbon dioxide ice
  clouds 68, 70, 158–60
  polar caps 151, 155–7
  vagaries of 161–3
carbon monoxide 126, 127
carbonate nodules 78–9
carbonates 80–1, 82
Cassini, Giovanni Domenico 185
Ceraunius Tholus 92
chaotic terrains 109–10
chasmata 105
ChemCam 199
chemical anomalies 76
Chryse Planitia 66, 107, 111–12, 137, 194
clays 61, 63–4
clear season 141
climate
  past 68–70
  seasons and temperatures 122–4
climate change 167–81
clouds
  carbon dioxide ice 68, 70, 158–60
  water cycle 149–54
colour 115–16
Columbia Hills 63, 202, 203
compression ridges 101–2
conduction 29, 88
convection 27, 29
  asymmetrical 39
  in the mantle 88–90
core 24–6
  and magnetic field 43–4
craters
  counting for dating 12–14
  lobate-ejecta craters 106, 107

craters (*cont.*)
  meteorite bombardment 29, 36–8
crust 24–6, 90
  north-south dissymmetry 39–41
Cryobot 211, 212

Daedalia Planum 12
dating
  counting craters 12–14
  SNC meterorites 30, 31–2
Deimos 8, 45–7, 185
delta-like structures 57, 58
depressions (low-pressure areas) 131–3
diurnal oscillations 132
dunes 4, 134–6
dust 116, 125
  in the atmosphere 137–9, 140
  cycle 137–48
dust devils 4, 138, 139, 143–5
dust storms 4, 121, 134, 138, 139, 140–2, 189
  global 141, 146–8
dynamo effect 43–4

Eagle Crater 6, 203
Earth 6, 50, 76, 82, 122–3, 133
  Antarctic lakes 75
  atmosphere 8, 33, 80, 81, 126
  comparison with Mars 8
  evolution 27–9
  formation 23, 24
  gullies 177
  Hadley circulation 129
  origin of life on 71, 72, 73
  Scabland area 113
  Siberia 117, 118, 119
  temperature profile 126
Eberswalde Crater 57
Echus Chasma 55
EETA 79001 30, 32
Elysium 91, 93
Endurance crater 10, 59, 136, 203
erosion 55, 69
  in frozen soil 118, 119
  wind 134–6
escape to space process 80, 81–2
European Space Agency (ESA) 205–10, 212, 216
  Aurora programme 208–10
  Mars Express 7, 61, 127, 196, 205–7, 212
  Venus Express 209
ExoMars 208, 209–10, 212
ferric oxide 116
Fesenkov crater 48–9
Flammarion, Camille 184
fogs 152–4
fossils 72, 74–5, 79
frost 150, 151

gamma-ray spectrometer (GRS) 173, 199
gas exchange experiment 84
Genesis 214
geological eras 13
geysers 162, 163
Giotto probe 205
glaciers 4, 168, 169, 170–2
global dust storms 141, 146–8
graben 100–1
gravitational anomalies 40, 41
gravity 81, 215
greenhouse effect 68–70
gullies 51, 176–8
Gusev Crater 9, 62–3, 144, 202, 222
gypsum 181

Hadley cell 129, 131
Hall, Asaph 185
Hayabusa mission 214
heat loss 29, 88–90
heavy chemical elements 18–20
helium 19, 20
Hellas Planitia 38, 65, 66, 171
hematite 59–60, 63, 64
Herschel, William 185
Herschel Crater 135
Hesperian era 13
Holden Crater 57, 75
HRSC camera 96, 205
Hubble Space Telescope 5
Huygens, Christian 185
Huygens probe 205
Hydaspis Chaos 109
hydrothermal circulation 54

ice
  carbon dioxide *see* carbon dioxide ice
  permafrost 106–8, 109–10, 118, 119
  polar deposits and evidence of climate change 179–81

ice (*cont.*)
surface ice at high latitudes 173–5
water flows beneath 176, 178
see also glaciers
ignimbrites 93
impact craters 29, 36–8
intermittent water flows 176–8
IRAM interferometer 185
iron 18, 24, 25, 116
iron oxide 59–60, 63, 64, 116
Isidis Planitia 38, 107, 132
isotopic geochemistry 30–2

Jupiter 22, 23, 198
Juventae Chasma 61

Kasei Vallis 170
Kosmos 419 probe 195, 196

labelled release experiment 84
lakes 56–8, 62–3, 75
landslides 104, 105
launch windows 188
lava 89, 97–9
flows 97–8, 99
plains 98–9
life 71–3
possibility of current 83–5
traces of 74–6, 78–9
linear dunes 134
lithosphere 90
lobate-ejecta craters 106, 107
Lowell, Percival 184, 185
Lowell Crater 37
Lunae Planum 98, 101–2

Ma'adim Vallis 51, 55, 62
magnesium 18
magnetic anomalies 195–6
magnetic field 42–4, 82, 88
magnetite 76
Mangala Vallis 118
mantle 24–6
convection in 88–90
Mariner probes 50, 125, 148, 157, 187–9, 190, 196
Mars Climate Orbiter (MCO) 195, 196, 197, 198, 200, 201
Mars Climate Sounder (MCS) 198
MaRS experiment 205
Mars Exploration Rovers 7, 196, 198, 200, 201–4
Opportunity 2–3, 6, 60, 201–4
Spirit 62–3, 139, 201–4
Mars Express 7, 61, 127, 196, 205–7, 212
Mars Global Surveyor (MGS) 42–3, 148, 158, 173, 176, 195–6, 198, 200
Mars Observer 195, 196, 197, 198–200
Mars Odyssey 173–4, 196, 198, 200
Mars Pathfinder 114–16, 194, 196, 198, 200
Mars Polar Lander (MPL) 195, 196, 197, 198, 200, 201
Mars Reconnaissance Orbiter 196, 198, 200
Mars Science Laboratory 198, 199, 200
MARSIS radar 198, 205, 206
Martian meteorites *see* SNC meteorites
Mercury 24, 27–9
meridional circulation 129
meteorites 29, 40, 73, 80
bombardment by 14, 36–8
SNC meteorites *see* SNC meteorites
see also craters
meteorology 131–3
methane 70, 127
Mitchell Mountains 5
MOC camera 176, 177, 199
MOLA laser altimeter 67, 158, 199
mole, tethered 212
Moon 8, 23, 45, 90, 99
lunar samples 14, 214

Nanedi Vallis 51, 53, 55
NASA 195, 196, 198–204, 212
astronauts to Mars 217–19
Mariner probes 50, 125, 148, 157, 187–9, 190
sample return 200, 214–16
Viking probes *see* Viking probes
see also under individual programmes
neodymium 31
Neptune 23
neutron flux 173, 175
nickel 26
Nirgal Vallis 51, 55
nitrogen 20, 33, 69, 125, 126, 127
Noachian era 13
Noachis Terra 69
north-south dissymmetry 39–41

northern polar cap 150, 155–7
  deposits and climate change 179–81
Nozomi probe 195, 196
nuées ardentes 93, 106

obliquity 122–3, 167–9
  high 167, 169
  low 167–9
  very high 167, 169
ocean 65–7
Olympus Mons 4, 86–7, 91, 94–6, 97, 152, 188
OMEGA mapping spectrometer 61, 160, 165, 205
Omega Nebula 18
Opportunity rover 2–3, 6, 60, 201–4
opposition 186
orbit 122–3
  variations and climate change 167–9
organic material 76
Orion Nebula 16–17, 21
outflow channels 51, 111–13, 117
oxygen 18, 20, 30–1, 33, 126, 127
ozone 84, 126, 127

Paterae 92, 93
Pathfinder lander 114–16, 194, 196, 198, 200
Pavonis Mons 91, 99
permafrost 106–8, 109–10, 118, 119
PFS spectrometer 127, 205
Phobos 8, 45–7, 185
  Soviet Phobos probes 45, 190, 191, 206
Phoenix 198, 199, 200
phosphates 76
planetary rotation 129, 130
planetesimals 21–3, 25
planets
  evolution 27–9
  formation 21–3
  initial size 27–8
  origin 18–20
  structure 24–6
plate tectonics 27, 81, 95
polar hood 154
polar ice caps 5, 150, 151, 220–1
  residual southern cap 157, 164–6
  seasonal 155–7
polar sediments 179–81
polycyclic aromatic hydrocarbons (PAHs) 78–9
polygonal structures 173
'Pot of Gold' 64
pressure, surface 8, 33, 159, 220
protoplanetary discs 17, 21
pyrite 76
pyrolitic release experiment 84

rain 55
rare gases 33–4
reference mission strategy 217, 218
regolith 37
residual southern polar ice cap 157, 164–6
ridges, compression 101–2
rivers 50–2
  source of 53–5
Rock Abrasion Tool (RAT) 201
rock glaciers 168, 171
rotation, planetary 129, 130
'rotisserie' effect 176, 178
Russian exploration programme *see* Soviet exploration programme

saltation 134, 139
sample return project 14, 200, 214–16
satellites 8, 45–7, 185
Saturn 23
Schiaparelli, Giovanni Virginio 184, 185
SCIM mission 215
seasonal polar ice caps 155–7
seasons 122–4
sedimentary deposits 56–64
Shalbatana valley 117
SHARAD radar 198
shield volcanoes 91, 95
Siberia 117, 118, 119
silicon 18
Simud valley 117
size, initial (of planets) 27–8
SNC meteorites 24, 26, 30–2, 116, 214–16
  ALH84001 77–9, 81
Sojourner 114, 116
solar system *see* planets; Sun
solar wind 21, 82
solstices 123
southern polar cap 151, 155–7
  residual 157, 164–6
Soviet exploration programme 213

Mars probes 148, 187, 190–1, 195, 196, 197, 206, 213
Phobos probes 45, 190, 191, 206
Venus 190
SPICAM spectrometer 127, 160, 205
Spirit rover 62–3, 139, 201–4
Stardust 214
stars
end stages 20
formation 18
sterile chambers 215
storms *see* dust storms
stromatolites 72
sublimation 155, 157, 161, 163, 164, 166
sulphates 9, 60–1, 63–4, 105
sulphur 26
sulphur dioxide 70
Sun 19–20, 21, 68
supernovae 19, 20

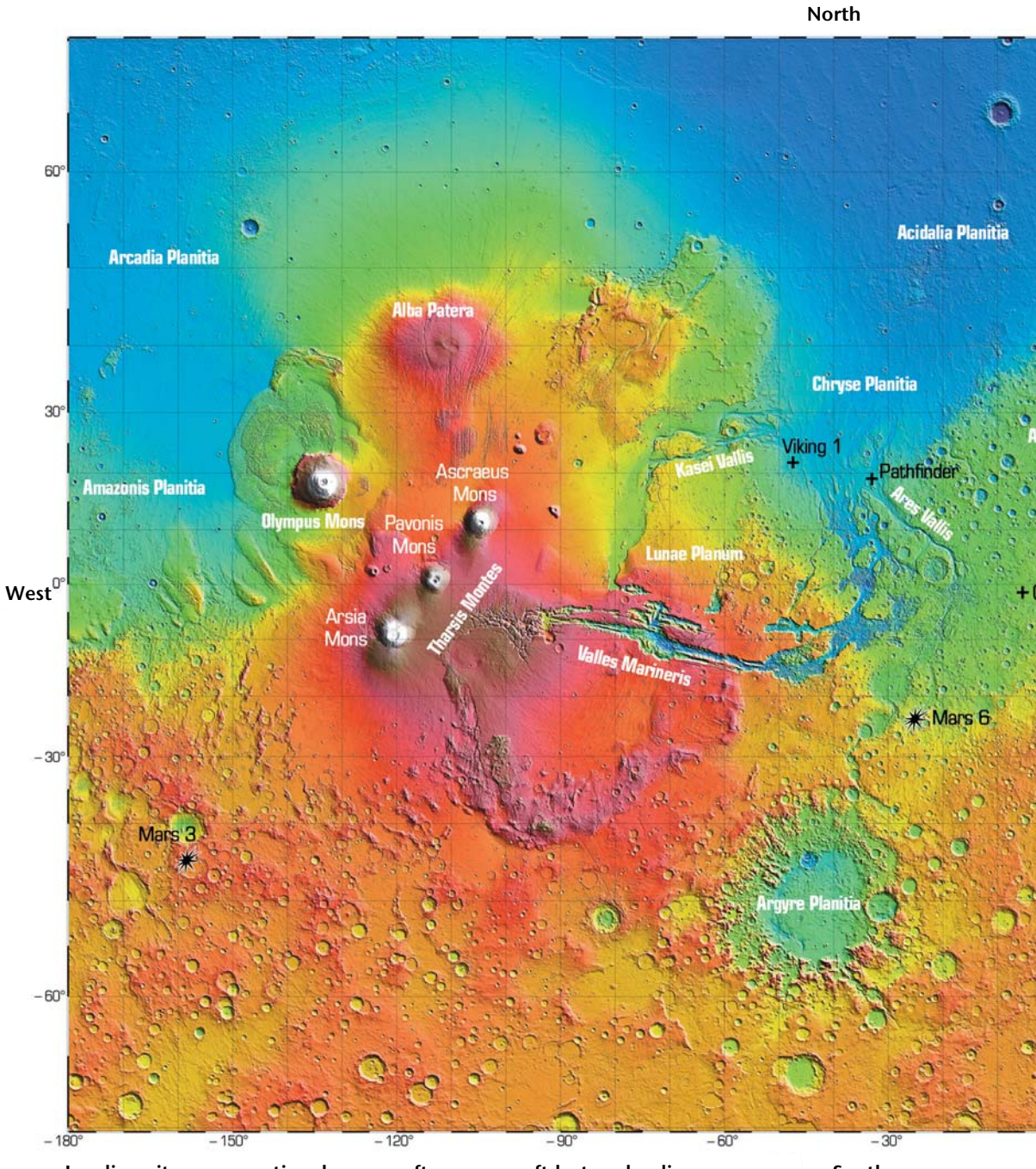
telescopic observations 184–6
temperature 68–9, 107, 118, 126, 139
seasons and 122–4
Terra Arabia 12
Terra Meridiani 6, 9, 59–61
tethered mole 212
Tharsis region 28, 91, 93, 100–2, 103–4
thermal contrasts 128, 129
thermal tidal waves 132
Tholi 92, 93
trade winds 131–2

ultraviolet radiation 82, 84, 126, 127
underground water 176, 178
flows 55, 176, 178
reservoir 113, 172
Uranius Tholus 92
Uranus 23, 185
Utopia Planitia 66, 98, 194

Valles Marineris 61, 65, 103–5, 109
valleys
networks 50–2, 53–5
outflow channels 51, 111–13, 117
Vastitas Borealis 66
Vaucouleurs, Gérard de 221–2
Venera missions 190
Venus 23, 24, 33
evolution 27–9
probes 190, 198, 209
Venus Express 209
Victoria Crater 11, 203
Viking probes 76, 83, 84, 127, 148, 192–4, 196
Viking 1 115, 116, 124, 137–8, 192–4
Viking 2 116, 182–3, 192, 194
volcanoes/volcanism 88, 89, 91–9

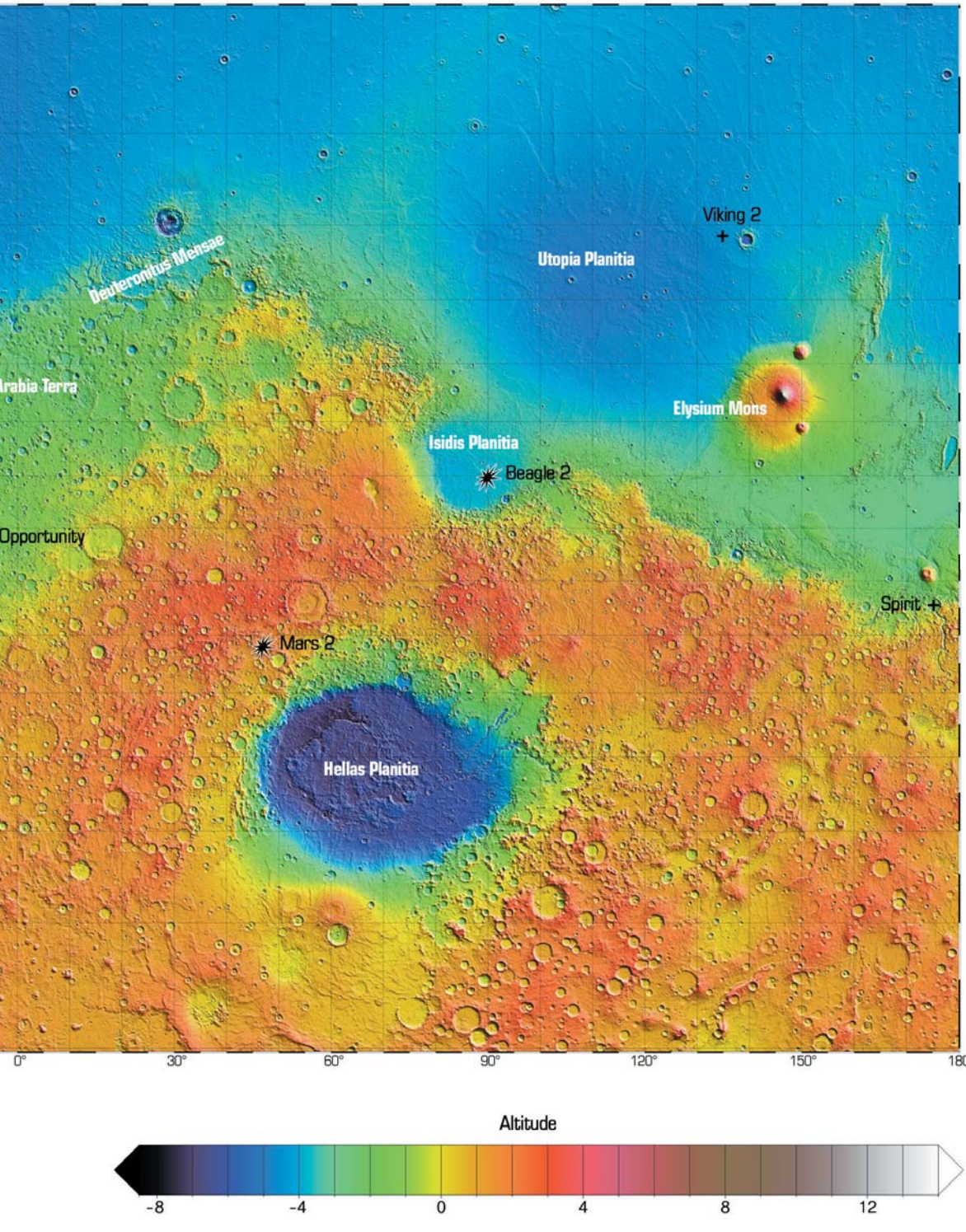
water 85
cycle 149–54
intermittent flows 176–8
origin of 34, 35
sedimentary deposits 56–64
underground *see* underground water
see also ice; lakes; ocean; rivers; valleys
water vapour 69–70, 126, 127, 149–51
winds 58, 128–36
dunes, ergs and erosion 134–6
mechanisms 128–30
meteorology 131–3
wrinkle ridges 101–2

Zubrin, Robert 218



Landing sites: + operational spacecraft * spacecraft lost on landing

A global topographic map of the planet Mars, obtained from data acquired by the Mars Orbiter Laser Altimeter (MOLA) carried by the Mars Global Surveyor spacecraft. Thanks to this instrument, the global topography of Mars is now known to a greater precision than that of the Earth. The major surface features of Mars, referred to in this book, are labelled here: the volcanoes (Mons, Patera), the plains and impact basins (Planitia), the valleys and canyons (Valles). In the absence of oceans, 'zero elevation' on Mars (the equivalent of 'mean sea level' on our planet) corresponds to the planet's average elevation, or the mean radius of the planet. (Courtesy MOLA Science Team.)


Viking 2
Utopia Planitia
Deuteronilus Mensae
Arabia Terra
Elysium Mons
Isidis Planitia
Beagle 2
Opportunity
East
Spirit
Mars 2
Hellas Planitia
0°
30°
60°
90°
120°
150°
180°
Altitude
km
-8
-4
0
4
8
12