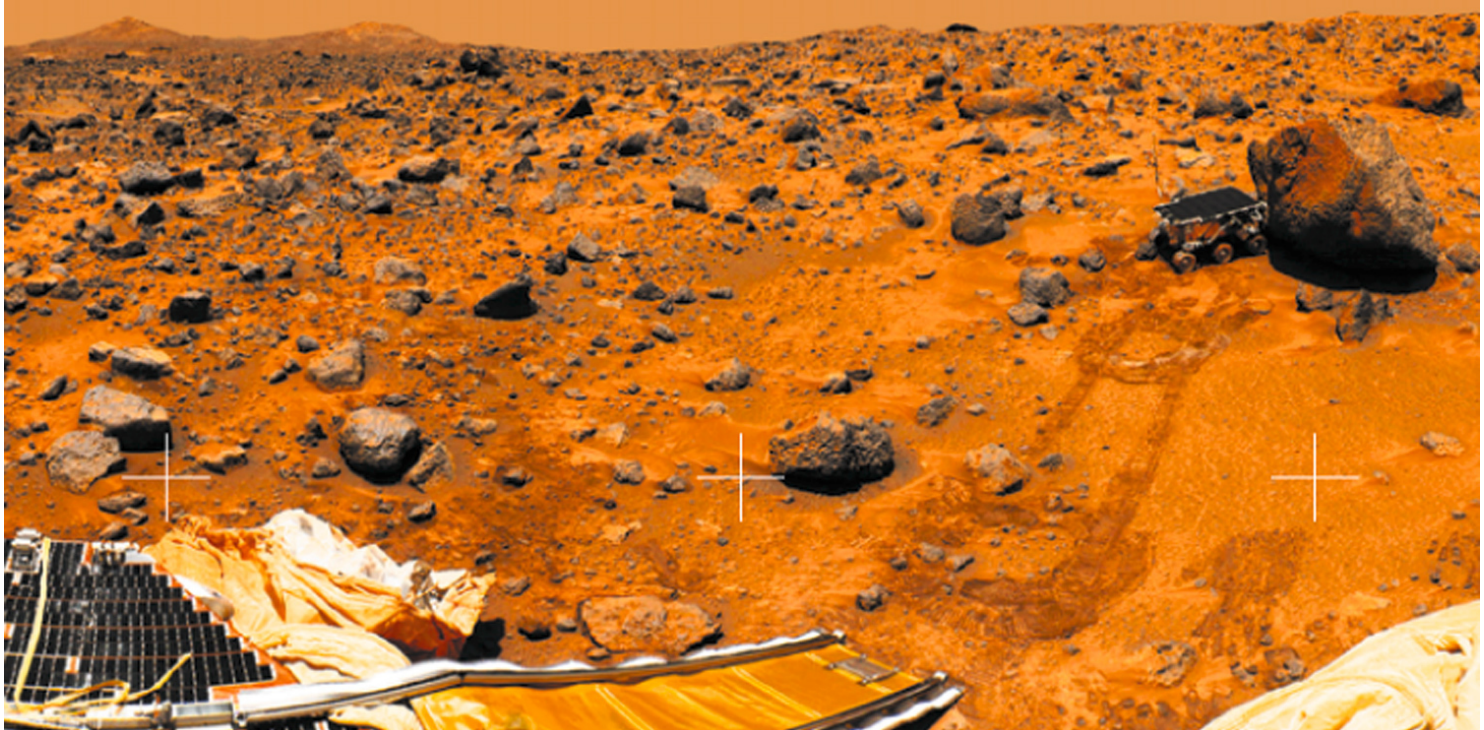
mapping mars

Science, Imagination and the Birth of a World

OLIVER MORTON



Oliver Morton

Mapping Mars: Science, Imagination and the Birth of a World

«HarperCollins»

Morton O.

Mapping Mars: Science, Imagination and the Birth of a World / O. Morton — «HarperCollins»,

A narrative history of the men and women who have explored Mars and mapped its surface from afar, and in so doing conditioned our understanding of our nearest planetary neighbour.The maps of Mars are exquisitely detailed representations of a land as large as all the continents of the earth combined. Yet they are being drawn before any human eye has seen the wonders they contain. In this fascinating mix of science, travel and the history of scientific imagination, Oliver Morton tells the story of the men and women who are mapping a dramatic, mysterious landscape, without having once set foot on its surface. Filled with awe-inspiring detail about volcanoes twice the height of Everest, basins deeper than the Pacific, 'Mapping Mars' is a breathtaking account of a world opening up to the imagination.

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OLIVER MORTON

Mapping Mars

SCIENCE, IMAGINATION AND
THE BIRTH OF A WORLD

Copyright

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Dedication

For Lieutenant Arthur Noel Morton, RNVR

Navigating officer, HMS *Hargood*, 1944–5 Lover of maps, lover of writing and loving father – ‘Round about here, Sir.’

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Preface

‘Are you going to move our stuff?’
‘No, that’s the view. We’re in the picture.’
Exchange between William Fox and Mark Klett
in William L. Fox, *View Finder*

Introduction

There's a world on my wall.

Mountains, canyons, plains and valleys, all a faded pinkish ochre, an even tone as plain as a colour can be without being grey. The sun is to the west – shadows fall gently to the right. There are faults and rifts, ash flows and lava fields. There are creases and stretch marks, straight lines and strange curves. There are circles and circles and circles.

No cities. No seas. No forests and no battlegrounds. No prairies. No nations. No histories and no legends. No memories. Just features, features and names. Argyre and Hellas and Isidis. Olympus and Alba and Pavonis. Schiaparelli and Antoniadi, Kasei and Nirgal. Beautiful double-rimmed Lowell. Names from one world projected on to maps of another. Maps of Mars.

The maps on my wall, painstakingly painted about fifteen years ago, show the surface of Mars from pole to pole. They show volcanoes that dwarf their earthly cousins in age and size. They show the round scars of uncountable asteroid impacts, many far more violent than the one which killed off the earth's dinosaurs. They show a canyon so long and deep it's as if the planet's tight skin has swollen and split. They show featureless plains and pock-marked ones, jumbled hummocky hills and strange creases that swarm together for thousands of kilometres, like the grain in a piece of timber. They show features perfectly earthlike and features so strange the earth has no names for them. There's a world's worth of scientific puzzles here, some of them already tentatively answered, most still mysterious. There's a world's worth of possibilities. But there's no clear place to start the story.

If people had moved across the pinkish ochre – if they had grown vines on the terraces of Olympus, or herded goats through the Labyrinths of the Night; if legends haunted Tempe and the dales of Arcadia, or if in Ares Vallis ancient grudge had broken into new mutiny – then it would be easy. But there are none of those tales to tell. No gardens of Eden, no sacred springs, nowhere to start the story of a world.

Even stripped of people, with their cities and their borders and their histories, a map of earth would not be this unyielding. Global truths and discrete units of geography would draw the eye. River catchments would tile the plains, mountain ranges would stand like the backbones of continents. There would be seas and islands, well defined. But Mars is not like that. It is continuous, seamless and sealess. Its great mountains stand alone; there are no sweeping ranges, no Rockies or Alps or Andes. The rivers are long gone. There are no continents and there are no oceans, and thus there are no shores. Given patience, provisions and a pressure suit you could walk from any point on the planet to any other. No edges guide the eye or frame the scene. Nowhere says: Start Here.

We might begin the story at one of the places that humanity has touched. In 1971 a Russian spacecraft crashed into Hellas, a vast basin in the southern hemisphere, while another landed more decorously on the other side of the planet, somewhere in or around the crater Ptolemaus. Two years later another Russian probe struck the surface somewhere near the dry valley called Samara. None sent back anything by way of a message. In 1976 America's more sophisticated Viking landers lowered themselves gently to sites in the northern plains of Chryse and utopia, sending back panoramas of rock and rubble beneath pink-looking skies. But the Vikings eventually fell silent too, leaving Mars alone again. Preludes, not beginnings.

Twenty years later, NASA's little Pathfinder, cocooned in airbags, bounced to a halt in the rocky fields where Ares Vallis had once spewed out its flood waters. It let loose Sojourner, the first of humanity's creations to travel on its own across the sands of Mars. That was a new beginning, the beginning of a grand age for earth's robots. At the time of writing there have been automatic envoys sending data back from Mars ever since. But Pathfinder's story cannot encompass the whole vast world in front of me. Not yet.

What about beginning on earth? Some places here are very like locations there, perhaps close enough to be tied together by some sort of sympathetic story-magic. Maybe Antarctica, where the driest, coldest landscapes on earth are regularly visited by scientists wanting to get some sense of a smaller, drier, colder world. Or Iceland, where permafrost and lava fight as once they did on Mars. Or the scablands of Washington state, ripped clean by floods like those that scoured Pathfinder's landing site. Or Hawaii's volcanoes, near perfect miniatures of the Martian giants. Or Arizona's Meteor Crater, where earthly geologists first came to grips with what a little bit of asteroid can do to the face of a planet, given enough speed. They are all places where one can learn about Mars, where the trained imagination can almost touch it. But none evokes the whole world.

We could cast our imaginations wider, to those who have tried to speak for all of Mars. To the astronomers looking at it with their telescopes, measuring all the qualities of light reflected from its surface, seeing seasons and imagining civilisations. Or to the writers inspired by those astronomical visions: H. G. Wells and Stanley Weinbaum, Arthur C. Clarke and Robert Heinlein, Ray Bradbury and Alexander Bogdanov and Edgar Rice Burroughs. Their imaginations took a point of light and turned it into a world of experience. But their Mars was never this one, the one which we only saw – which we could only ever see – after our envoys left the earth and went there.

Only after our spacecraft reached its orbit could we see Mars for what it is, a planet with a surface area as great as that of the earth's continents, all of it as measurable, as real as the stones in the pavement outside your door. After millennia of talking about worlds beyond our own, of heavens and hells and the Isles of the Hesperides, humanity now has such a world fixed in its sights, solid and sure. For the moment it is a world of science, untouchable but inspectable and oddly accessible, if only through the most complex of tools. But unlike the other worlds that scientists create with their imaginations and instruments – the worlds of molecular dynamics and of inflationary cosmology and all the rest of them – this one is on the edge of being a world in the oldest, truest, sense. A world of places and views, a world that would graze your knees if you fell on it, a world with winds and sunsets and the palest of moonlight. Almost a world like ours, except for the emptiness.

This book is about how ideas from our full and complex planet are projected on to the rocks of that simpler, empty one. The ideas discussed are mostly scientific, because it is the scientists who have thought hardest and best about the realities of Mars. It is the scientists who have fathomed the ages of its rocks, measured its resemblance to the earth, searched for its missing waters and – always – wondered about the life it might be home to. The stories they tell about the planet must have pride of place. But there are artists in here too, and writers, and poets, and people whose dreams take no such articulated form, but still focus themselves on the same rocks in the sky. They illuminate Mars; Mars illuminates them.

It's common to imagine that the human story on Mars will only start when humans actually get there, when they stand beneath its dusty sky and look around them at its oddly close horizon. I don't know who those people will be, or when they will get there, or where on the planet they will first set their feet. But I know that for all their importance, they will not be a new story's beginning, rather a new chapter. Their expectations and hopes are already being created on the earth today, by the people in this book; the process of making Mars into a human world has already begun. And I know that their landing site is somewhere on the map in front of me, already charted, if not yet chosen.

Back to the maps, then; in particular to the 1:15,000,000 shaded-relief map of the surface published by the United States Geological Survey, its three sheets fixed to my office wall. It represents the planet as well as any single image could. But it's not just the representation of a planet. It's the embodiment of a process, a process that forged links between far-off Mars and the cartographers' drawing board point by point, feature by feature. It embodies links of reason and technology that ran through the cameras of now-dead spacecraft millions of kilometres away, and through the minds of the men who designed and controlled those cameras. Links that ran through empty space, carried by the faintest of radio waves, and through the great dishes that picked up those signals, and through the

computers that wove them back into images. Links that ran through the eyes and minds and hands of the people who assembled the pictures produced by that great scientific adventure into a world they could see in their minds and draw on the paper in front of them, a world precise and publishable.

The maps themselves tell no single story. But the people who put those links together with technology and craft, mathematics and imagination – they have a story, one that lets the maps and the planet they are tied to come to life.

Where to begin to write about Mars? With the making of the maps.

Part I – Maps

'Now when I was a little chap I had a passion for maps. I would look for hours at South America, or Africa, or Australia, and lose myself in all the glories of exploration. At that time there were many blank spaces on the earth, and when I saw one that looked particularly inviting on a map (but they all look that) I would put my finger on it and say, "When I grow up I will go there." The North Pole was one of these places, I remember. Well, I haven't been there yet, and shall not try now. The glamour's off. Other places were scattered about the Equator, and in every sort of latitude all over the two hemispheres. I have been in some of them, and … well, we won't talk about that. But there was one yet – the biggest, the most blank, so to speak – that I had a hankering after …'

Marlow in Joseph Conrad, *Heart of Darkness*

Greenwich

And then, as they sat looking at the ships and steamboats making their way to the sea with the tide that was running down, the lovely woman imagined all sorts of voyages for herself and Pa.

Charles Dickens, *Our Mutual Friend*

Maps of the earth begin a short walk from the flat where I live. Go down the High Road, up Royal Hill towards the butcher's, left along Burney Street and then right on to Crooms Hill. At the corner, if you care for such things, you can see a blue plaque of the sort with which London marks houses where people who have made a significant contribution to human happiness once lived. In this case, it was the poet Cecil Day Lewis; as you climb the hill, you'll pass another one marking the home of Benjamin Waugh, founder of the National Society for the Prevention of Cruelty to Children.

Near the top of the hill sits a grand (but plaqueless) bow-fronted white house, called simply the White House. Walk round the White House's walled garden, down a little alleyway and through a gate in the high brick wall on your right, and you emerge into Greenwich Park. To your right, the beautiful semicircle of the rose garden; to your left a steep path lined by trees. And as you walk out on to the grass, London spread at your feet. As views go, it's not particularly extensive – the horizon is nowhere more than twenty kilometres away and in many directions much closer – but it's vast in association. The once imperial cityscape is woven from threads that stretch throughout the world.

Across the river to the east sits the squat black-glass bulk of Reuters, information from around the globe splashing into its rooftop dishes. Upstream and on the near side sit the long, low workshops where for more than a century men have made undersea cables to tie the continents together. New skyscrapers devoted to global businesses sit in the redeveloped heart of the docks that used to handle the lion's share of the world's sea trade. Within the park itself there are plants from every continent except Antarctica. At its foot sits the old naval college, where generations of Britannia's officers, my late father included, learned to rule the waves.

Through it all the Thames runs softly, looping around the Isle of Dogs, a local feature leading, as Conrad says in *Heart of Darkness*, 'to the uttermost ends of the earth'. Little sails down this umbilicus of empire now – but above it the new trade routes of the sky are sketched out by aircraft arriving and departing from London's four airports, carving their way through the air we all breathe and the stratosphere we shelter under. To the west the Thames beneath them is still daytime blue; to the east it is already evening dark.

Dawn may feel like an intervention by the sun, rising above a stationary earth; sunset reveals the truth of the earth's turning, a slipping away into night. That turning defines two unique, unmoving points on the surface of the earth: the poles, the extremes of latitude. Add one more point – just one – and you have a co-ordinate system that can describe the whole world, a basis for all the maps and charts the sailors and pilots need, a way of deciding when days start and end. And that third point is right in front of you, the strongest of all Greenwich's links to the rest of the earth. In the middle of the park is the old Royal Observatory, a little gathering of domes perched clubbily on a ridge. Within the observatory sits a massive metal construction called a transit circle. The line passing through the poles and through that transit circle is the earth's prime meridian: 0 degrees, 0 minutes, 0 seconds. All earthly longitudes are measured with respect to that line through Greenwich Park.

The English have taken the Greenwich meridian as the starting point for longitudes since the observatory was founded in the seventeenth century. But it wasn't until the late nineteenth century – at a time when its home in Greenwich was under the stewardship of Sir George Airy, Astronomer Royal, the man who had that great transit circle built – that the Greenwich meridian was formally adopted by the rest of the world. With worldwide navigation a commonplace, and with telecommunications making almost instantaneous contact between continents a possibility, there was a need for a single set of co-ordinates to define the world's places and time zones. Over the years a variety of possible

markers to define this prime meridian were suggested – islands, mountains, artefacts like the Great Pyramid or the Temple in Jerusalem. But a meridian defined by an observatory seemed best. In 1884, at a conference in Washington DC, and over spirited French opposition, Greenwich was chosen. Airy's transit circle came to define the world.

Airy was, by all accounts, an uninspiring but meticulous man. He recorded his every thought and expenditure from the day he went up to Cambridge University to more or less the day he died, throwing no note away, delighting in doing his own double-entry bookkeeping. He applied a similar thoroughness to his stewardship over the Royal Greenwich Observatory, bringing to its workings little interest in theory or discovery but a profound concern for order, which meant that the production of tables for the Admiralty (the core of the observatory's job) was accomplished with mechanical accuracy. He looked at the heavens and the earth with precision, not wonder, and though he had his fancies, they were fancies in a similar vein – ecstasies of exactitude such as calculating the date of the Roman invasion of Britain from Caesar's account of the timing of the tides, or meticulously celebrating the geographical accuracy of Sir Walter Scott's poem 'The Lady of the Lake'. This was a man whose love of a world where everything was in its place would lead him to devote his own time to sticking labels saying 'empty' on empty boxes rather than disturb the smooth efficiency of the observatory by taking an underling from his allotted labours to do so for him. After more than forty-five years of such service Airy eventually retired 200 yards across the park to the White House on Crooms Hill, where he died a decade later.

It's a little sad that the White House doesn't carry a blue circular plaque to commemorate Airy's part in the happiness brought to humanity by a single agreed-upon meridian, but surely there are monuments elsewhere. Maybe Ipswich has an Airy Street; he grew up there and remained fond of the place, arranging for his great transit circle to be made at an Ipswich workshop. There must be a bust of him in the Royal Astronomical Society. Or a portrait in some Cambridge common room. And even if there are none of these things, there is something far grander. Wherever else astronomers go when they die, those who have shown even the faintest interest in the place are welcomed on to the planet Mars, at least in name. By international agreement, craters on Mars are named after people who have studied the planet or evoked it in their creative work – which mostly makes Mars a mausoleum for astronomers, with a few science fiction writers thrown in for spice. In the decades since the craters of Mars were first discovered by space probes, hundreds of astronomers have been thus immortalised. But none of them has a crater more fitting than Airy's.

A Point of Warlike Light

'I've never been to Mars, but I imagine it to be quite lovely.'
Cosmo Kramer, in *Seinfeld*
('The Pilot (I)', written by Larry David)

Mars had an internationally agreed prime meridian before the earth did. In 1830 the German astronomers Wilhelm Beer and Johann von Mädler, famous now mostly for their maps of the moon, turned their telescope in Berlin's Tiergarten to Mars. The planet had been observed before. Its polar caps were known, and so was its changeability; the face of Mars varies from minute to minute, due to the earth's distorting atmosphere, and from season to season, due to quite different atmospheric effects on Mars itself. There are, though, some features that can be counted on to stick around from minute to minute and season to season, the most notable being the dark region now called Syrtis Major, then known as the Hourglass Sea. To calculate the length of the Martian day, Mädler (Beer owned the telescope – Mädler did most of the work) chose another, smaller dark region, precisely timing its reappearance night after night. He got a figure of 24 hours 37 minutes and 9.9 seconds, 12.76 seconds less than the currently accepted figure. That this length of time is so similar to the length of an earthly day is complete coincidence, one of three coincidental similarities between the earth and Mars. The second coincidence is that the obliquity of Mars – the angle that its axis of rotation makes with a notional line perpendicular to the plane of its orbit – is, at 25.2°, very similar to the obliquity of the earth. The third is that though Mars is considerably smaller than the earth – a little more than half its radius, a little more than a tenth its mass – its surface area, at roughly a third of the earth's, is quite similar to that of the earth's continents.

When Mädler came to compile his observations into a chart in 1840, mathematically transforming his sketches of the disc of Mars into a rectangular Mercator projection, he declined to name the features he recorded, but did single out the small dark region he had used to time the Martian day as the site of his prime meridian, centring his map on it. Future astronomers followed him in the matter of the meridian while eagerly making good his oversight in the matter of names. Father Angelo Secchi, a Jesuit at the Vatican observatory, turned the light and dark patches into continents and seas, respectively, as astronomers had done for the moon, and gave the resulting geographic features the names of famous explorers – save for the Hourglass Sea, which he renamed the 'Atlantic Canale', seeing it as a division between Mars's old world and its new. In 1867 Richard Proctor, an Englishman who wrote popular astronomy books, produced a nomenclature based on astronomers, rather than explorers, and gave astronomers associated with Mars pride of place. His map has a Mädler Land and a Beer Sea, along with a Secchi Continent. Observations made by the Astronomer Royal in the 1840s – he was interested in making more precise measurements of the planet's diameter – were commemorated by the Airy Sea. Pride of place went to the Rev. William Rutter Dawes, a Mars observer of ferociously keen eyesight, perceiving, for example, that the dark patch Mädler had used to mark the prime meridian had two prongs. (Dawes's far-field acuity was allegedly compensated by a visual deficit closer to home; it is said he could pass his wife in the street without recognising her.) So great was Dawes's influence on Proctor – or so small was the number of astronomers associated with Mars – that his name was given not just to the biggest ocean but also to a Continent, a Sea, a Strait, an Isle and, marking the meridian, his very own Forked Bay.

Proctor's names had two drawbacks, one immediately obvious, one revealed a decade later. The obvious drawback was that an unhealthy number of the people commemorated on Mars were now British. When the French astronomer Camille Flammarion revised Proctor's nomenclature for his own map of 1876, various continentals – Kepler, Tycho, Galileo – were given grander markings. One continental on whom Proctor had looked with favour, though, was thrown off: perhaps influenced by the Franco-Prussian war, Flammarion resisted having the most prominent dark patch on the planet

called the Kaiser Sea, even if Proctor had named it such in honour of Frederik Kaiser of the Leyden Observatory. The Hourglass Sea became an hourglass again, though this time in French: Mer du Sablier.

Proctor's other problem was more fundamental. The features he had marked on his map, whatever their names, did not match what other people saw through their telescopes. In 1877, Mars was in the best possible position for observation; it was at its nearest to the sun (a situation called perihelion) and at its nearest to the earth (a situation called opposition), just 56 million kilometres away. Impressive new telescopes all over the world were turned to Mars and revealed its features in more detail than ever before. The maps based on observations made that year were almost all better than Proctor's; and the map made by Giovanni Schiaparelli, a Milanese astronomer, on the basis of these observations, provided a new nomenclature that overturned all others.

Schiaparelli was not interested in celebrating his peers and forebears; he wanted to give Mars the high cultural tone of the classics. In the words of Percival Lowell, an American astronomer who was to make Mars his life work, it was an 'at once appropriate and beautiful scheme, in which Clio [muse of poetry and history] does ancillary duty to Urania [muse of astronomy]'. To the west were the lands beyond the pillars of Hercules, such as Tharsis, an Iberian source of silver mentioned by Herodotus, and Elysium, the home of the blessed at the far end of the earth. Beneath them, part of the complex dark girdle strung around Mars below its equator, were the sea of sirens, Mare Sirenum, and Mare Cimmerium, the sea that Homer put next to Hades, 'wrapped in mist and cloud'. Then we come to the Mediterranean regions: the Tyrrhenian Sea and the Gulf of Sidra (Syrtis Major, the long-observed hourglass) dividing bright Hellas and Arabia. Along the far side of Arabia sits the Sinus Sabeus, a gulf on the fragrant coast of Araby, home to the Queen of Sheba. Beyond Arabia begins the Orient, with Margaritifer Sinus, the bay of pearls on the southern coast of India, and the striking bright lands of Argyre (Burma) and Chryse (Thailand). Finally, in the dark region others had called the eye of Mars, Schiaparelli placed Solis Lacus, the lake of the sun, from which all dawns begin.

Do not think for a moment that this means a good classical education will help you find your way around Mars. For a start, due to the way telescopes invert images, everything is flipped around: Greece is south of Libya, Burma west of Arabia. What's more, Schiaparelli's geography was often more allusive than topographical. His planet is 360° of free association. Thus Solis Lacus is surrounded by areas named for others associated with the sun; Phoenix, Daedalus and Icarus. The sea of the sirens borders on the sea of the muses, presumably because Schiaparelli wanted to provide opportunity for their earthly feud to continue. Elysium leads to utopia.

For the most part he did not explain his nominal reasoning very exactly, but there are exceptions, most notably right in the middle of the map, at the point where dark Sinus Sabeus gives way to Sinus Margaritifer, somewhere between Arabia and the Indies, a place he called Fastigium Aryn. 'As Mädler,' Schiaparelli wrote, 'I have taken the zero-point of the areographic longitudes there, and following this idea I have given it the name of Aryn-peak or Aryn-dome, an imaginary point in the Arabian sea – which was long assumed by the Arabic geographers and astronomers as the origin of the terrestrian longitudes.'

By the time he was through with Mars, Schiaparelli had given 304 names to features on its surface and though there was a Proctorite resistance – 'Dawes' Forked Bay it will ever be to me, and I trust to all who respect his memory,' wrote Nathaniel Green, who painted a lovely map of Mars after observing the planet from Madeira during the opposition of 1877 – it foundered. Schiaparelli's proper names were triumphant and have in large part lasted until today. It was his common nouns that caused the problems. Schiaparelli saw a large number of linear features on the face of the planet and called them 'canali' – channels. Schiaparelli claimed to be agnostic as to the nature of these channels – they might have been natural, or they might have been artificial. Percival Lowell, his most famous disciple, plumped firmly for the artificial interpretation.

Lowell's reasoning went like this. Mars is habitable, but its aridity makes the habitability marginal; if there were intelligences on Mars, they would do something about this; the obvious thing to do would be to build a network of long straight canals. And since this is what we see when we look at Mars, this is what must have happened.

With this leap of the imagination, Lowell created one of the most enduring tropes of science fiction: Mars as a dying planet. It would live on in the works of H. G. Wells, Edgar Rice Burroughs, Leigh Brackett and many, many others. And if his interpretation of what he saw did not win as much favour among his astronomical colleagues as it did in the popular imagination, it was not because the idea of life on Mars seemed too far-fetched. Observations of the way the planet's brightness and colour seemed to change with the seasons made plant life there seem almost certain; if plants, why not animals and why not intelligence? The most weighty argument against Lowell's Martians was simply that over time other, better observers consistently failed to see the canals as continuous and linear, if they saw them at all. The lack of evidence of engineering, not the implausibility of life on Mars, was what counted against Lowell – a belief in life on Mars was quite commonplace.

Today this easy acceptance seems rather remarkable. At the beginning of the twenty-first century, when the possibility of life elsewhere has become the central preoccupation of space exploration, its discovery is routinely held up as the most important discovery that could ever be made. What accounts for this change?

A large part of the answer lies in the nature of astronomy. Copernicus's proposal that the earth was not the centre of the solar system changed the way that astronomers looked at the sky. If the earth was no longer the fixed centre, then it was a wandering star like the five which shuffled back and forth across the zodiac: a planet. Previously unique, now it was one member of a class and must have similarities to its classmates. The world had become a planet and so the planets must become worlds, a process accelerated by the Galilean discovery that, like the earth, the planets were round and had features. In this context it was quite normal to believe that one of the things that the planets had in common was life, especially since, after Copernicus, many astronomers tended to go out of their way to deny the earth any special attributes. As Lowell put it in *Mars* (1896), 'That we are the only part of the cosmos possessing what we are pleased to call mind is so earth-centred a supposition, that it recalls the other earth-centred view once so devoutly held, that our little globe was the point about which the whole company of heaven was good enough to turn. Indeed, there was much more reason to think that then, than to think this now, for there was at least the appearance of turning, whereas there is no indication that we are sole denizens of all we survey, and every inference we are not.' A Copernican stance could easily lead astronomers to the assumption of life, not lifelessness, as the status quo.

Another part of the answer is that in Lowell's day a belief in life on Mars was largely without consequences. As Alfred Lord Tennyson noted as early as 1886, our astronomical observations of planets and our dreams of what might transpire on them were separated by a vast gulf:

Hesper – Venus – were we native
to that splendour or in Mars,
We should see the Globe we groan in,
fairest of their evening stars.
Could we dream of wars and carnage,
craft and madness, lust and spite,
Roaring London, raving Paris,
In that point of peaceful light?

Life on Mars might be likely, it might be inevitable, it might even be intelligent, but the possibility of people ever actually visiting Mars – or Martians visiting earth – was more or less pure fancy. This made Martians fascinating but not important, rather in the way of dinosaurs – another turn-of-the-century craze. Whatever evidence scientists might find of dinosaurs, or speculations they

might produce about them, without a time machine encounters with dinosaurs were impossible. Similarly, without a space machine, encounters with Martians were impossible.

So while there might be intelligent Martians, there could be no links of history or interest between them and us. This gave the Martians an interesting rhetorical niche that they quickly made their own: 'The man from Mars' became the quintessential intelligent outsider, unswayed by any relevant prior worldliness, unattached to custom. He retains that position to this very day; his natural habitat is the newspaper op-ed page and other didactic or satirical environments, but he turns up elsewhere, too. Temple Grandin, the highly articulate woman with autism in Oliver Sacks's *An Anthropologist on Mars*, applies the titular image to herself as a way of stressing her disassociation from the ways of the world around her; the wonderfully innocent yet artfully contrived metaphors of the poems in Craig Raine's *A Martian Sends a Postcard Home* led to a whole school of poetry (if a small one) being dubbed 'Martianism'. One of the most influential science fiction novels of the twentieth century, Robert Heinlein's *Stranger in a Strange Land*, achieves its impact by showing us the earth through the eyes of a true 'man from Mars' – a human brought up on Mars by Martians.

Rhetorical devices aside, believing in Martians made little difference to the earthly lives of Lowell's readers and this, I suspect, is one of the things that made them easy to believe in. Another spur to belief was the difference that the existence of Martian minds made to the way earthly imaginations saw Mars. One of the Copernican ways in which Martians made the planet Mars a world like the earth was that they made it a place experienced from the inside, a site for subjectivity. Without minds, Lowell argued, Mars and the other planets were 'mere masses of matter' – places without purpose, frightening voids. With minds, they were worlds.

To Lowell, there was no really useful or involving way to think about a planet except as a world inhabited and experienced by mind. The space age, though, has brought us new ways of seeing beyond the earth and changed our way of thinking about what we see. Our spacecraft, tools of observation but hardly observers in themselves, have shown us things we know cannot be witnessed directly or experienced subjectively, but which can still fascinate. The post-Copernican elision between worlds (structures of shared experience and history) and planets (vast lumps of rock and metal and gas that orbit a fire yet vaster) has been rewritten. Yes, the earth that is our world is also a planet. But not all planets are worlds. We no longer need the point of view of a mythical Martian to imagine Mars, or to convince us that Mars might be worth imagining. Now that our spacecraft have been there we can know it intimately from the outside, know it as an objective body rather than a subjective experience. We can measure and map its elemental composition and its wind patterns and its topography and its atmospheric chemistry and its surface mineralogy. The planet Mars can fascinate us just for what it is.

If the space age has opened new ways of seeing mere matter, though, it has also fostered a strange return to something reminiscent of the pre-Copernican universe. The life that Lowell and his like expected elsewhere has not appeared, and so the earth has become unique again. The now-iconic image of a blue-white planet floating in space, or hanging over the deadly deserts of the moon, reinforces the earth's isolation and specialness. And it is this exceptionalism that drives the current scientific thirst for finding life elsewhere, for finding a cosmic mainstream of animation, even civilisation, in which the earth can take its place. It is both wonderful and unsettling to live on a planet that is unique.

Yet if the earth is a single isolated planet, the human world is less constrained. The breakdown of the equation between planets and worlds works both ways. If there can now be planets which are not worlds, then there can be worlds that spread beyond planets – and ours is doing so. Our spacecraft and our imaginations are expanding our world. This projection of our world beyond the earth is for the most part a very tenuous sort of affair. It is mostly a matter of imagery and fantasy. Mars, though, might make it real – which is why Mars matters.

Mars is not an independent world, held together by the memories and meanings of its own inhabitants. But nor is it no world at all. More than any other planet we have seen, Mars is like the

earth. It's not very like the earth. Its gravity is weak, its atmosphere thin, its surface sealess, its soil poisonous, its sunlight deadly in its levels of ultraviolet, its climate beyond frigid. It would kill you in an instant. But it is earthlike enough that it is possible to imagine some of us going there and experiencing this new part of our human world in the way we've always experienced the old part – from the inside. The fact that humans could feasibly become Martians is the strongest of the links between Mars and the earth.

At the beginning of the space age – at the moment when it became clear to all that Mars might indeed one day be experienced subjectively – the International Astronomical Union stepped in to clean up the planet's increasingly baroque nomenclature. Thanks to the efforts of Schiaparelli, Lowell and Eugène Michael Antoniadi, whose beautifully drawn charts had become the standard, the planet had come to boast 558 names for an uncertain number of features. In 1958 the IAU experts settled on 128 named regions and features, with 105 of the names coming from Schiaparelli. Then the first spacecraft images came back and the stalwarts of the IAU needed not only more names but also new rules by which names could be assigned. It was at this point that the convention of naming craters for people with an interest in the planet was laid down. Proctor's astronomical pantheon was reconvened – Dawes, Secchi, Mädler, Beer and the rest of them all got craters, as did Proctor himself.

And in 1972 the International Astronomical Union established for all time the precise location of the Martian meridian. Lacking a transit circle made of good Ipswich steel – or, for that matter, any ancient monuments – the IAU's working group had to use a natural landmark for their zero. They chose the geometrical centre of a small, nicely rounded crater in the middle of a larger crater fifty-six kilometres across. They called that larger crater Airy.

Mert Davies's Net

There is a passage in the oeuvre of William F. Buckley Jr, in which he remarks that no writer in the history of the world has ever successfully made clear to the layman the principles of celestial navigation. Then Buckley announces that celestial navigation is dead simple, and that he will pause in the development of his narrative to redress forever the failure of the literary class to elucidate this abecederian technology. There and then – and with awesome, intrepid courage – he begins his explication: and before he is through, the oceans are in orbit, their barren shoals are bright with shipwrecked stars.

John McPhee, *In Suspect Terrain*

It was Merton Davies who put Airy in his prime position. Mert is a kindly man, tall and thin, dignified but rather jolly. Everyone who knows him speaks fondly of him. You might imagine him embodying decent reliability in a Frank Capra film even before learning that he has worked for the same outfit over more than fifty years. But it's hardly been a small-town life. Mert Davies was one of the pioneers of spy satellites, one of the small cadre of technical experts who changed the facts of geopolitical life by letting cold warriors see the world over which they were at war from a totally new perspective. After that, he became one of only two people to have played an active role in missions to every planet save Pluto.[*] He has reshaped – quite literally – the way that earthlings see their neighbours in space. Davies is the man chiefly responsible for the 'control nets' of most of the solar system's planets and moons – complex mathematical corsets that hold the scientific representations of those planetary surfaces together.

The first control net that he created served as the basis for the first maps of Mars made using data from spacecraft, rather than observations from earth. Compiled from fifty-seven pictures sent back when Mariner 6 and Mariner 7 flew past the planet in 1969, that first net tied together 115 points. When I met Davies in his office in Santa Monica thirty years later, his latest Martian control net held 36,397 points from 6320 images. Well into his eighties, Davies was still hard at work augmenting it further.

Davies had been interested in astronomy since boyhood, an interest he had shared with those close to him. In 1942, when he was working for the Douglas Aircraft corporation in El Segundo, California, he started courting a girl named Louise Darling. His interests made their dates a little unusual. Davies had started making a twelve-inch telescope, a demanding project. 'I had a hard time finishing it,' he recalls. 'The amount of grinding it took and the difficulty of polishing that big a surface was a little bit over my head. I would take her with me to polish.' And so she entered the world of grinding powder and the Foucault test, a simple but wonderfully precise way of gauging a mirror's shape, which allows an amateur with simple equipment to detect imperfections as small as 50 billionths of a metre. Unorthodox courtship, but it worked. When I met Mert in 1999 he and Louise had been married for more than fifty years.

Just after the war, Davies heard that a think tank within Douglas was working on a paper for the Air Force about the possible uses of an artificial satellite. He applied to join the team more or less on the spot. The think tank soon became independent from Douglas and, as the RAND Corporation, it went on to play a major role in defining America's national-security technologies and strategies throughout the Cold War. In the early 1950s Davies and his colleagues looked at ways to use television cameras in space in order to send back images of the Soviet Union. Then they developed the idea of using film instead of television – experience with spy cameras on balloons showed that the picture quality could be phenomenal – and returning the exposed frames to earth in little canisters. The idea grew into the Corona project, which after a seemingly endless run of technical glitches and launch failures at the end of the 1950s became a spectacularly successful spy-satellite programme.

While Corona was in its infancy, Davies was seconded to Air Force intelligence at the Pentagon, where he used the new American space technology to try to figure out what Russian space technology might be capable of. When he returned to Santa Monica in 1962, he was ready for a change. Spy satellites were no longer exciting future possibilities for think-tank dreamers, but practical programmes controlled by staff officers and their industry contractors. And there was another problem. 'A lot of the work at RAND was going into Vietnam – my colleagues were working on reconnaissance issues there – and I wanted no part of that.'

Happily, an alternative offered itself in the form of Bruce Murray, an energetic young professor from the California Institute of Technology in Pasadena, on the other side of Los Angeles. Murray was an earth scientist, not an astronomer. His first glimpse of Mars through a telescope wasn't a childhood epiphany in the backyard. It was a piece of professional work from the Mount Wilson Observatory. Late as it was, though, that first sight provided emotional confirmation for Murray's earlier intellectual decision that the other planets were something worth devoting a lifetime's study to. When Murray looked at Mars through the world-famous sixty-inch telescope, he was not just seeing an evocative light in the sky; he was seeing a world's worth of new geology, a planet-sized puzzle that he and his Caltech colleagues were determined to crack. Their tool was to be the Jet Propulsion Laboratory, a facility that Caltech managed on behalf of the federal government. JPL, in the foothills of the San Gabriel mountains, had been a centre for military aerospace research since the war. In 1958 the Army ceded it to the newly founded National Aeronautics and Space Administration, as part of which it would become America's main centre for planetary exploration. By 1961, JPL was planning NASA's first Mars mission, Mariner 4. The man in charge of building a camera for it was Robert Leighton, a Caltech physics professor. He asked a geologist he knew on the faculty, Bob Sharp, to help him figure out what the camera might be looking at. Sharp asked his eager young colleague Murray to join the team.

Murray and Davies met in 1963; with three young children to support, Murray was keen for some extra income and so found consulting for RAND congenial. He and Davies quite quickly became close friends and Mert started to think he might want to get involved in Murray's end of the space programme. After all, he had the right credentials: he had been in the space business since the days of the V2 and he had some experience in interpreting images of both the earth and moon as seen from orbit. (At the Pentagon he had analysed Russian pictures of the far side of the moon to see whether they might be fakes.) When Mariner 4's television camera sent back its image-data – a string of twenty-one grainy pictures covering just 1 per cent of the planet's surface – Davies was as surprised as almost everybody else to see that it looked not like an earthly desert but like the pock-marked face of the moon, or the aftermath of a terrible war. The space programme was important (Murray and his colleagues would brief the president) but it was also open (they briefed him in front of the cameras). Out among the planets there was no risk of finding yourself in a conflict you wanted no part of, or of having to keep work secret from all but your closest colleagues.

By the time Mariner 6 and Mariner 7 were sent to Mars four years later, in 1969, Davies was a key part of the team dealing with the images they sent back. His particular contribution was to work on the mathematical techniques needed to turn the disparate images into the most reliable possible representation of the planet.

Since the seventeenth century, when Willebrord Snell of Leiden first refined the procedure into something like its modern form, earthbound map makers have turned what can be seen into what can be precisely represented through surveying. Decide on a set of landmarks – Snell and his countrymen liked churches – and then, from each of these landmarks, take the bearings of the other landmarks nearby. From this survey data you can build up a network of fixed points all across the landscape. Plot every point on your map according to measurements made with respect to things in this well-defined network and it will be highly accurate. If, unlike Holland, your country is large, mountainous and only sparsely supplied with steeples, setting up a reliable network in the first place can be hard

work – the United States wasn't properly covered by a single mapping network until the 1930s, when abundant Works Progress Administration labour was available to help with the surveying. But the principle of measuring the angles between lines joining landmarks has been used in basically the same way all over the earth.

Two problems make the mapping of other planets different, one conceptual, one practical. On earth, experience allows you to know what the features you are mapping are: hills, valleys, forests and so on are easily recognised for what they are. While the pictures a spacecraft's cameras send back may be very good, this level of understanding is just not immediately available. When the first images of Mars were sent back by Mariner 4 they were initially unintelligible to Murray and the rest of the imaging team. Before the researchers even started on a physical map, they needed a conceptual one, a way of categorising what was before their eyes. How to do this – how to see what had never been seen before – was the besetting problem of early planetary exploration.

The practical problem is that unlike an earthly surveyor, you can't wander around the surface of an alien planet making measurements at leisure. Your only viewpoint is that of a spacecraft flying past the surface at considerable distance and speed. So you not only don't know what you're looking at; you're also none too sure of where you're looking from. A spacecraft's position is not a given, like that of a church. It is something that its controllers have to continuously work out. What they know for sure is how fast it is receding from the earth, because that causes frequency changes in its radio signals. To find out where the spacecraft actually is, this information is compared with estimates of where the spacecraft thinks it is – the primary tools here are small on-board cameras called star trackers – and calculations of where it ought to be, derived from measurements and models of all the forces – the gravity of the sun and the planets, the gentle nudges from on-board thrusters – that are shaping its trajectory. If all is going well, the calculations based on all these observations fall into line to produce a consistent picture.[*] But though this may be accurate enough for navigation, it is not accurate enough for map making. You don't know precisely where the spacecraft is, or precisely which way its camera is pointing, or, for that matter, precisely where the surface of the planet is. So you can't say exactly what bit of the planet you're looking at in any given picture.

Working round these problems involved Davies in a huge amount of laborious cross-checking and number crunching (Airy himself would have loved it, I suspect). First he had to put together a set of clearly distinguishable features that appeared in more than one of the pictures – the centres of craters, for the most part. The precise locations of these features within the individual frames in the data sent back by the spacecraft then had to be put into a set of mathematical equations along with the best available figures for the spacecraft's position when each picture was taken, and the direction in which the camera was pointing at the time. Then he had to add in factors describing the distortions the cameras were known to inflict on the pictures they took. Once all this was done, the whole calculation had to be fed into a computer on punch cards; the computer then ground through possible solutions until it came to one that made the values of all the variables in the equations consistent. Those values defined a specific way of arranging the set of surface features in three dimensions – imagine it as a framework of dots linked by straight lines – which came as close as possible to satisfying all the data. Effectively, the final answer said 'if the reference points you've specified are arranged in just this way with respect to one another, and if the spacecraft was at these particular points at these particular times, then that would explain why the reference points appear in the positions that they do in these pictures'. That optimal arrangement of reference points was the control net.

Once Davies and his colleagues provided the control net, it could be used to position all the rest of the data. It became possible to say quite accurately where things were with respect to the planet's poles and its prime meridian. Indeed, one of the primary functions of the control net was to define the planet's latitude and longitude system – which is why Davies, as both maker of the control net and a member of the International Astronomical Union committee responsible for giving names to

features on other planets, was able to put Mars's Greenwich in a little round crater within the larger crater that was being named after Airy.

Since his first work on Mars, Davies has done his bit in the mapping of more or less every solid body any American spacecraft has visited. By the 1970s he had completely forsaken the black world of spy satellites for the scientific delights of other planets and the personal pleasure of exploring this one: once unencumbered by security clearances and the knowledge they bring, he was free to travel to meetings all around the world, and did so with Louise and alacrity. He's never made headlines – I doubt he'd want to – but his contributions have been vital prerequisites for much of the work that has.

But there's still more that Mert would like to do. The mathematics of the control net maximise its self-consistency, not its accuracy. This makes it likely that it contains errors. If you had some independent way of checking it – if you had a point in the control net the location of which you knew independently – you might be able to do something about that.

In principle, such independent measurements are possible. When I interviewed Davies in his office at RAND in December 1999, America had landed three spacecraft on the surface of Mars – the two Viking landers in 1976, and Pathfinder in 1997. The radio signals sent back from those spacecraft revealed their positions very accurately with respect to the fixed-star reference system used by astronomers. If you could find the spacecraft in images of the Martian surface that also contained features tied into the control net, you could check the position of the spacecraft with respect to the net against its absolute position as revealed by the radio signals. That would allow you to calibrate the net with new precision. Do the same for a few spacecraft and you could tie the thing down to within a few hundred metres, as opposed to a few kilometres.

The frustration is that you can't see the spacecraft. About the size of small cars, from orbital distances – hundreds of kilometres – they are lost in the Martian deserts. The Mars Observer Camera, part of the Mars Global Surveyor spacecraft, has been trying to pick out some sign of the three spacecraft since 1997. It is by far the most acute camera ever sent to Mars. But even MOC can't pick out the landers. Mankind has made its mark on Mars – but that mark has yet to be seen.

Lacking any proper sightings, checks on the control net using the landers' locations have had to be indirect. From matching the features that the landers see on the horizon around them with features visible in pictures taken from orbit, it's possible to make estimates of where the landers are, estimates that are potentially very accurate. Unfortunately, the different experts who try this sort of triangulation get different answers. When Mert and I met in 1999, various inconsistencies had convinced him that one bit of data which he had thought pretty good, and which he had used to calibrate the control net – a two-decade-old estimate of where exactly in the rubble-strewn plains of Chryse Viking 1 had landed – was, in fact, wrong. In a week's time he was going to go and tell the American Geophysical Union's fall meeting about the mistake and the fact that it had introduced an error of a fraction of a degree into the control net's definition of the prime meridian. But if that was an irritation, there was also a new hope. The very next day, a new lander would be setting itself down on the Martian surface, giving MOC another man-made landmark to try to pick out. A steeple to navigate by.

[*] The other, according to Caltech professor Bruce Murray, is Murray's Caltech colleague Ed Danielsen.

[*] In 1999, NASA's Mars Climate Orbiter demonstrated what happens when things don't go well. When reporting its thruster firings the spacecraft's software used metric measurements (Newton seconds). The software on earth thought that these reports were in pound (thrust) seconds, a smaller unit, and thus underestimated the effects of the thruster firings. This meant that JPL's model of the Climate Orbiter's position became increasingly inaccurate and, when its controllers tried to insert the spacecraft into orbit round Mars, it was plunged deep into the atmosphere and burned up.

The Polar Lander

I can think of nothing left undone to deserve success.
Robert Falcon Scott, diary entry, November 1, 1911

On the morning of that next day, Friday, 3 December 1999, JPL in Pasadena is awash with visitors, just as it always is when one of its spacecraft is about to do something exciting. The road leading past the local high school and up to the lab is lined with outside-broadcast vans. Inside, the tree-lined plaza at the lab's centre – the place where, at the celebration to mark Voyager 2's successful passage past Neptune, Carl Sagan danced with Chuck Berry – is filled with temporary trailers in which the working press will work, when there is work for them to do. It's not just journalists who are wandering around looking for gossip, coffee and companions unseen since the last such event. There are VIPs from the upper echelons of NASA and beyond, distinguished visitors from other research centres, the families and friends of people involved in the mission. And back down the freeway at the convention centre in downtown Pasadena there are hundreds of paying customers turning up for a parallel popular event held by a group called the Planetary Society, a planetary-science fan club and lobbying organisation created by Bruce Murray, Carl Sagan and a one-time JPL mission planner named Lou Friedman. The Planetfest gives the public a chance to watch the events on Mars played out on vast TV screens, to hear the findings analysed by experts, to meet their favourite science fiction authors, to admire and buy art inspired by planetary exploration, to collect toys and gaudy knick-knacks and to party the weekend away. No other scientific event – not even the sequencing of a particularly juicy microbe or chromosome – gets attention like this. But then no other science stirs the emotions like planetary science.

The absent star of the show is the Mars Polar Lander. A life-sized stand-in sits in a sandbox in the middle of the plaza at JPL, a backdrop for TV reporters from around the world. Like most spacecraft, it looks a little ungainly: three widely spaced round feet, each of them braced by a set of three legs; segmented solar panels to either side, partly folded out flat, partly flush to the spacecraft's sloping shoulders, tilted to catch the beams of a sun low on the Martian horizon; spherical propellant tanks and rocket nozzles sit in its belly, antennae, masts and a sort of binocular periscope perch on its back. A scoop on the end of a robot arm scratches the pseudo-Martian sand.

The real Polar Lander, cameras and legs and solar panels tucked into an aeroshell that will protect them from the atmosphere, is falling towards Mars at about 22,500 kilometres an hour. The last course corrections were made early in the morning, fine-tuning the trajectory to maximise the chances of hitting the chosen landing site a bit less than 1000 kilometres from the south pole of Mars. They seem to have worked; the trajectory appears as true as if the spacecraft were running on tracks. Anyway, nothing more can be done – as Apollo astronaut Bill Anders remarked when the third stage of his Saturn V put him and his crewmates on course for the moon, 'Mr Newton is doing the driving now.' The spacecraft has nothing to do but obey the law of gravity. Oh, and to fire the occasional rocket, discard its heat shield at the appropriate time, deploy a parachute or two, all things that have to happen precisely at the right time and can't be controlled from earth because it would take the commands fourteen minutes to get to Mars. Standard spacecraft stuff – only nothing on interplanetary spacecraft is standard. You can never be sure you've checked out all the systems and you never fly exactly the same model twice. Every mission is a sequence of hundreds of events controlled by thousands of mechanisms and circuits, any one of which could go wrong.

Because of all this – and especially because the lab's previous Mars mission, Mars Climate Orbiter, ended in ignominious failure just a few months ago – the tension back at JPL is tangible. But it is also unfocused. There is no more to see than there is to do. An oddity of space exploration is that only very rarely do you get to see the process in action. You see the results, which are often spectacular in and of themselves, but there's never a cut-away camera angle to let you see the spacecraft through

which these wonders of the universe are being revealed. And while it's hardly surprising that we can't see the means by which – through which – we're witnessing these wonders, it's also a great pity. You don't have to be Mert Davies, intent on refining his control net, to want to see a picture of a spacecraft on the rubble-strewn plains of Mars. You just have to be human and to want to see something human in that great emptiness where nothing human has been seen before. Such a sight would close some sort of cognitive circuit; it would make Mars a distant mirror in which we could see something of ourselves reflected. It would thicken the connections between our planets and draw Mars further into our world.

This need to close the loop explains why the most popular unmanned space mission ever was the 1997 Mars Pathfinder. Anyone with a web browser could watch as its limited little rover, Sojourner, fitfully explored the rock garden it had been landed in. It explains why the artists displaying their wares to the faithful down at Planetfest in Pasadena do not, for the most part, just paint spectacular landscapes when they paint Mars – they paint landscapes with human participation inside them: an astronaut, a rover, even an unmanned craft. One of the most popular pictures of Mars ever painted is *Return to utopia* by Pat Rawlings, which shows a future astronaut planting a flag – whose? we can't see – next to the second Viking lander, simultaneously celebrating its far-flung location and pulling it back from nature into the human world.

Here's what we're not seeing by around lunchtime on 3 December: about ten minutes before it hits the atmosphere, Mars Polar Lander begins making its final preparations, resetting its guidance systems, prepping one of its cameras. Mars is vast in its sky, only a few thousand kilometres away, half in shadow, half in sunlight, its surface a range of browns and yellows, the red of its earthly appearance revealed from space as an atmospheric illusion. At this range you can see the craters, the streaks of dust blown by the winds, the strange changing textures of the surface, the largest of the ancient, dried-out valleys, perhaps the wispy whiteness of high dry-ice clouds. New features stream around the curve of the planet as the spacecraft catches up with its target, its trajectory taking it south and east at seven kilometres a second towards the harsh brightness of the southern polar cap. Six minutes before atmospheric entry, the spacecraft twists round so that its aeroshell heat shield is pointed forwards. A minute later a set of six explosive bolts is detonated and the lander slips away from the cruise stage that has been providing it with power and communications on the eleven-month journey from earth. From now on all the power comes from the batteries and no communication is possible until the lander's own antennae are deployed on the ground. Once the cruise stage and the lander are safely separated, the cruise stage goes on to release two microprobes called Scott and Amundsen, spacecraft designed to survive smashing into the planet's crust at high speed and then measure the moisture of its soil. They are so tiny that you could cup one in your hands like a grapefruit.

As lander, cruise stage and probes drift away from each other, perspectives alter. Mars stops being a vast wall in front of the spacecraft and becomes a strange new land below them; the ice-white limb of the planet barring the sky becomes a curved horizon. The outer reaches of the atmosphere begin to stroke the lander's protective aeroshell, too thin at first to have much effect, but getting thicker by the second. Soon on-board accelerometers decide the breaking force is getting strong enough to be worth bothering about and tiny thrusters start firing to keep the aeroshell's blunt nose cone pointed the right way. The atmosphere's grip tightens further. Within a minute or so, the deceleration is up to 12g – the sort of force you'd feel if a cruising airliner came to a full halt in a couple of seconds. The nose cone is at 1650°C and the air around it is incandescent. The Polar Lander is a minute-long meteor in the Martian sky.

Three minutes after atmospheric entry begins, the worst is over, though the lander is still moving at 1500 kilometres an hour. A gun at the back of the aeroshell fires out a parachute and the thin air rips it open seven kilometres above the surface. Ten seconds later the charred front of the aeroshell is jettisoned and a camera pointing downwards starts to take pictures of the landscape below as it rushes upwards. If they make it back to earth, these descent images will make quite a movie.

While all this is happening I'm picking at a tuna sandwich in the JPL cafeteria. I chat to some of the scientists from other projects who are gathering round the television monitors that show what's happening in mission control, then wander back across the plaza, past the model in the sandbox, to the press room. There's no hurry – the probe is silent during the landing sequence and is only due to pipe up twenty-three minutes after touchdown. Even then there will be a fourteen-minute delay as the radio waves creep across the solar system at the speed of light. Plenty of time.

A quarter of a billion kilometres away, Mars Polar Lander's legs snap out from their stowed position, ready for the ground below.

Four months later a board of enquiry decided that this was the crucial moment. When the legs snapped into position, they apparently did so with a touch more vigour than was necessary, flexing a little against the restraints meant to hold them in position. Little magnetic sensors in the spacecraft's body seem almost certain to have interpreted this flexing as meaning that the legs had encountered resistance and were bending under the weight of the spacecraft – just as they would at the moment of touchdown. The state of these sensors was being monitored a hundred times a second by the part of the spacecraft's software that was in charge of turning off the engines straight after landing and, since the legs took more than a hundredth of a second to reach their proper position, the sensors reported that the spacecraft seemed to have touched down on two successive checks. If it had heard this report only once, the software in charge of turning off the engines would have ignored the reading as a transient glitch. Hearing it twice, the software in charge of turning off the engines after touchdown concluded that the spacecraft had indeed touched down. Unfortunately, it was still almost four kilometres up in the air.

A bit more than a minute later, when the spacecraft's radar said that it was only forty metres above the surface, the misinformed software had its virtual hand put on the virtual switch that controlled the engines. It turned them off straight away, unable to know or care that the spacecraft was still moving at almost fifty kilometres an hour. After falling that last forty metres, Mars Polar Lander hit the surface at something like eighty kilometres an hour, a speed it could never survive.

Back in December, no one knows any of this. About an hour after lunch on Friday, we know that the first transmission from the surface hasn't happened, but though that's a little disappointing, no one is really worried. Spacecraft are programmed to be flighty things and at the slightest sign of something out of the ordinary they are apt to go into 'safe modes', which means shutting down all non-vital systems for a set amount of time. The lander's ability to go safe had been turned off during the descent sequence – when wilful inactivity would have been fatal – but once it got down to the ground this override would turn itself off and the spacecraft would be free to go into a silent funk if some subsystem or other had exceeded its safety levels during the landing.

Over the next few days the silence gets worse. Scott and Amundsen, the ground-penetrating microprobes, are never heard from at all. To this day no one knows what happened to them. The team running the polar lander itself methodically lists the things that could be stopping the probe from communicating and tries to work its way around them, using various different types of radio command. Is the main antenna facing the wrong way? Then send the lander instructions to scan its beam across the sky. Did it not hear those instructions? Send them over another frequency. Did it go into a different sort of safe mode, or go safe twice? Listen at the later times when it was meant to transmit. Each possibility is a branch on what the engineers call a fault tree, and every branch has to be checked out.

While all this is going on up at JPL, down at the Pasadena convention centre the Planetfest rolls on. The fact that there are no neat new pictures of the surface to be seen puts a damper on it, to be sure – but not too terrible a one. People still come to hear the assembled luminaries talk about the great future of Mars exploration. They hear from astronauts and scientists and engineers and *Star Trek* actors and Bill Nye me Science Guy, proselytiser by appointment to PBS. And they hear from the science fiction writers. From Larry Niven, who has just written a fantasy in which all humanity's

dreams about Mars come true at the same time; from Greg Bear, whose *Moving Mars* imagined the planet's future as a backwater from which settlers watch the ever more high-tech earth redefine what is human; from Greg Benford, whose *The Martian Race*, published this very weekend, sets a new standard of technical accuracy for first-mission-to-Mars stories. And from Kim Stanley Robinson, whose books *Red Mars, Green Mars*, and *Blue Mars* provide the fullest picture yet attempted of life on that planet. Unlike every previous generation of science fiction writers, these men have had data from Mars orbit and the Martian surface on which to base their visions, and they are scrupulous in their use. In their hands, the physical facts of planetary science and the romance of travel to other worlds are brought as close as they yet can be.

Meanwhile, up at JPL, what seemed so close is slipping away. After each new attempt to make contact an ever more despondent flight team comes out to face an ever smaller press corps and tell us that nothing was heard. They were so excited on Friday morning – by the early hours of Sunday, some are almost in tears. On Monday morning most have had a chance to rest, but though the faces are fresher and the eyes clearer, a certain resignation has settled in. By Monday night, all the one-fault branches on the fault tree have been evaluated; it's clear that at least two separate systems must have failed. The team will keep climbing ever more unlikely limbs of the fault tree for a week or so yet, but for the rest of us that's it. The lander is lost. The last tents in the media caravan are folded up just after midnight; we don't even have the ingenuity, or stamina, to find a bar.

Mariner 9

'I think it's part of the nature of man to start with romance and build to a reality.'
Ray Bradbury, in *Mars and the Mind of Man*

Mars Polar Lander was JPL's thirteenth mission to Mars and its fifth failure. Mariner 3 died with its solar panels pinned to its side by the wrapping in which it had been launched in 1964; Mariner 8 fell into the Atlantic in 1971; Mars Observer exploded as it was trying to go into orbit round Mars in 1993; Mars Climate Orbiter burned up in the atmosphere in 1999; Mars Polar Lander made its mistake just forty metres up a few months later. An optimist might point out that each got closer to the target than the previous failure. A pessimist might point out that the frequency of failure seems to be on the increase.

It's hardly surprising that, with so few missions, everything that has not been a failure has been counted a terrific success. Mars exploration is still too new for there to have been any hey-ho, business-as-usual missions. But among all these successes one stands out: Mariner 9. Mariner 9 was the first American spacecraft to go into orbit round another planet. It was the first interplanetary probe to send back data in a flood, rather than a trickle. It was the first mission to Mars to provide images of the entire surface and record the full diversity of its landscapes. It was the first spacecraft to see a planet change dramatically beneath its eyes, to watch weather on another world. Mariner 9 revealed a Mars that was fascinating in its own right, rather that disappointing in the light of previous earthly expectations. And Mariner 9 allowed a small team of artists and artisans to make the first detailed, reliable maps of another planet.

There were two big differences between Mariner 9 and its earlier siblings (two of which, Mariner 2 and Mariner 5, went to Venus, not Mars). One was that Mariner 9 had a largish rocket system on board, its cluster of spherical fuel tanks hiding the distinctive octagonal magnesium body that all the Mariner family shared. This engine was needed to slow the spacecraft down when it got to Mars, thus allowing it to go into orbit round its target rather than flying past it at breakneck speed, as the previous probes had. The other, less visible, difference was that Mariner 9 would have the opportunity to send back serious amounts of data.

When Mariner 4 flew past Mars in 1965, it seemed extraordinary that the signal it sent back could be heard at all. Mariner 4's radio transmitter had a power of ten watts; it had to send data back to a target – the earth – much less than an arc minute across (an arc minute is a sixtieth of a degree). Only a small fraction of the spacecraft's ten-watt beam actually hit the earth, and only one ten-billionth of that fraction hit the actual receiver – a steerable radio telescope sixty-eight metres in diameter built specifically for the Mars missions at a site a couple of hours' drive into the Mojave Desert from JPL. But the power of electronic engineers to decode such staggeringly faint signals has been one of the least celebrated wonders of the space age.[*] It's an ability at least as wonderful as that of actually launching things into space, and compared with rocketry it's both grown in capability far faster and been a good sight more dependable. That sixty-eight-metre Goldstone dish in the Mojave, along with companions near Madrid and Canberra, now brings data back from the edges of the solar system, a hundred times further away than Mars, and handles data rates as high as 110,000 bits per second. Even in the early days of Mariner 4 the limiting constraint on the rate at which data could be sent back was not the radio link, but the speed at which the tape recorder which stored the data on board the spacecraft could play it back. And that was staggeringly slow: eight bits per second. It took weeks to send back data recorded in minutes.

Mariner 4's pictures each contained less than a thousandth of the data in a nine-inch aerial photograph. The frames were just 200 pixels wide by 200 pixels deep; the brightness of each pixel was recorded as six bits of data, providing sixty-four gradations of tone between black and white. The total amount of data in every frame (thirty kilobytes) was just a little bit more than the amount

of disk-space taken up by an utterly empty document in the version of Word with which I am writing this book. In principle I could download the equivalent of Mariner 4's entire twenty-two-image data-set from the Internet in a matter of seconds using my utterly unexceptional modem. In 1964, though, it took eight hours to get each picture back to JPL. The process was so slow that the waiting scientists printed out the numerical value for each pixel on a long ribbon of ticker tape, cut the ribbon into 200-number-long strips and then coloured each pixel in with chalk according to its numerical value. Every two and a half minutes another strip could be added to the picture. The first space-age image of Mars, taken by the first entirely digital camera ever built and transmitted over 170 million kilometres of empty space, was put together like an infant school painting-by-numbers project.

By the time Mariner 6 and Mariner 7 flew past Mars in 1969, communications were far faster (though the on board tape recorders, which outweighed the cameras whose data they stored, were still a problem). Each of the 1969 Mariners returned a hundred times more data to earth than Mariner 4 had four years earlier. In 1971 Mariner 9 – with a data rate 2000 times that of Mariner 4 and a year in which to transmit, rather than a week – did 100 times better still. And this meant that the whole scale of the operation was different. The 'television teams' – so called because their instrument was basically a TV camera – on Mariners 4, 6 and 7 had been small: Leighton, who masterminded the camera design; a few other Caltech faculty members; some JPL people; and a few select outsiders, such as Mert Davies. But Mariner 9 was going to provide far more data than such a team could digest and the data were to be used not just for analytical science but for the practical business of mapping. Among other things, America was committed to landing robot probes on Mars to look for life in 1976. Those probes – the Vikings – needed landing sites, and choosing landing sites required maps.

NASA would have been happy to make the maps itself. But in the mid-1960s Congress noticed that almost every government agency had its own map makers and decided that the money-hungry, fast-growing space agency would be an exception to this rule. So the mapping of the planets was instead made the duty of the United States Geological Survey. This was not entirely arbitrary; the USGS already had an astrogeology branch, headquartered in Flagstaff, Arizona, which was deeply involved in the study of the moon and was helping to train the Apollo astronauts. The USGS gave primary responsibility for its study of Mars to a team of five geologists, three from Flagstaff, two from the survey's California centre in Menlo Park, south of San Francisco. The senior member of the USGS team was a man called Hal Masursky: in part because Murray was at the same time working on a mission to Venus and Mercury, Masursky became one of the television team's two principal investigators. The other PI was a young man called Brad Smith, a highly rated expert on Mars as observed through telescopes who had yet to complete his PhD.

Up to the point when he joined the astrogeology branch in the early 1960s, Hal Masursky's career had not been stellar. He had never completed his Ph.D.; his terrestrial work had been uneventful. But Masursky became fascinated by the possibilities of geology on other worlds, and turned out to be a great success at it. The success lay not in his own scientific work – though he was a perceptive observer, his complete inability actually to write things up was something of a limitation – but in his ability to get things done within the sometimes bureaucratic world of space exploration and to explain these achievements to the world at large. Some of his colleagues considered him as vivid an off-the-cuff communicator as Carl Sagan.

Hal was at the same time a bright spark and a consummate committee man. He was charming but dogged, willing to get down into the details of sequencing spacecraft manoeuvres and download times whenever necessary, but also keeping a clear eye on the overall objectives. His astrogeological life became in large part devoted to the teamwork necessary for planning and running space missions, and he played a role in almost every major mission of the 1970s and 1980s, making sure they would send back pictures geologists could make use of. If Hal was on a committee, a planetary scientist who learned the political ropes back then once told me, it would get things done; if he wasn't on a

committee, then you didn't want to be on it either. It was probably not an important one, and it might well not get anywhere.

Masursky was good at getting committees to work; in his personal life his gift for structure was less evident. Committee work meant he was endlessly travelling. (It's said that at times he lived in Flagstaff without a car, preferring simply to rent one when he flew in just as he would anywhere else.) His ability to keep projects he was administering within budgets was famously poor. He was married at least four times, religious and passionate in argument. He was diabetic, but rather than accepting the discipline of managing the condition he let his team do so for him. Jurrie van der Woude, an image-processing specialist then at Caltech and later at JPL, remembers finding Masursky passed out on the floor of his office late one night during the Mariner 9 mission. Jurrie shouted for help and people came running – people already armed with candies and orange juice, because they knew what to expect. 'From that point on I was part of the club. No matter where you went around the lab you'd carry orange juice with you. Nobody talked about it, but in press briefings there'd be four or five of us like secret servicemen, waiting and watching for the right time to bring him orange juice. He had this kind of a smile and every so often you'd realise that behind it he was just gone.' Eventually diabetes took its toll; in the late 1980s Masursky sickened, dying in 1990. During his sad decline, he would occasionally elude his last, devoted wife and wander off to Flagstaff's little airport, sure he should be going somewhere. Now he has a crater on Mars: 12.0°N, 32.5°W, a hole 110 kilometres across in the region called Xanthe Terra.

When Mariner 9 set forth from earth in 1971, no one had seen Xanthe in close-up. No one had seen the crater that would one day be named for the principal investigator on the television team, or the striking channel that runs next to it and quite probably once filled it with water, Tiu Vallis. No one knew that Mars offered such sights. Mariner 4 had seen a moonlike surface covered in craters. It had measured the atmospheric pressure as being much lower than most measurements from earth had suggested – about 1 per cent of the pressure at sea level on earth. The long-held picture of Mars as a basically earthlike if very marginal environment – something like a cold high-altitude desert, except worse – was demolished. The surface had to be very old to have accumulated so many craters; the atmosphere must always have been very thin and free of moisture for the craters not to have eroded away. From the composition of the atmosphere – 95 per cent carbon dioxide – and measurements of its temperature and pressure – both low – Leighton and Murray had been able to predict that the polar caps, which earthbound observers had seen as water ice that might moisten their imagined earthlike desert, were in fact made of frozen carbon dioxide. Mariner 7 seemed to confirm this theory when it passed over the south pole carrying infrared instruments capable of measuring the surface's temperature and composition, and found it to be as Murray and Leighton had predicted.

Admittedly, Mars was not all craters. Mariner 6 had seen that Hellas, known as a large bright region to the earthbound astronomers, was much smoother than the cratered terrain next to it, though no one could say why. The same spacecraft also sent back pictures of an odd terrain quickly termed 'chaotic', a collapsed jumble of a landscape from which a few table-top mesas stood proud. It was as though the land had rotted from within. But though such features might prove interesting, the general impression was of a dull, geologically inactive place, more or less unchanged since the creation of the solar system, a place little more interesting than the earth's moon and far harder to get to. Bruce Murray, who unlike many in the business had never had a boyhood romance with the stars, took a certain delight in debunking the delusions of people who still wanted to think of Mars as at least a little earthlike. Murray has a certain intellectual aggression, as do many Caltechers – the USGS geologists on Mariner 9 used to be amazed by the frequency and ferocity of the arguments that Murray's students on the team, Larry Soderblom and Jim Cutts, would get into. Nostalgic notions of an earthlike Mars gave Murray's belligerence its *casus belli.* Mars was simply not what people had thought it to be. Rather than a world to be experienced in the imagination, it was a planet to be measured, a planet

in the new space-age meaning of the term, something woven from digital data streams and ruled by the hard science of physics and chemistry.

On 12 November 1971, the night before Mariner 9 was to go into orbit, Caltech held a public symposium on 'Mars and the Mind of Man' featuring Murray, Carl Sagan and the science fiction authors Arthur C. Clarke and Ray Bradbury: it was the genteel ancestor of the bigger, brasher Planetfests which accompany today's missions. Murray cast himself in wrestling terms as 'the heavy – the guy with the black trunks'. He acknowledged people's 'deep-seated desire to find another place where we can make another start … that is not just a popular thing [but] affects science deeply'. He then set about using his experience of Mariners 4, 6 and 7 to pour cold water – in fact frozen carbon dioxide – on such fancies. Carl Sagan, a new member of the television team and already a passionate advocate of the search for life in planetary exploration, responded by saying that nothing seen so far had ruled out life on Mars – it had just made it harder to imagine if you were parochial enough to imagine all life must be like earth life. Clarke optimistically suggested that if there wasn't life on Mars in 1971, there certainly would be by the end of the century.

While Clarke and his colleagues spoke in Caltech's auditorium, events up at JPL were turning out quite dramatic enough without any added fiction. One of the reasons that 1971 was a good time to launch the first Mars orbiters was that Mars, which has a markedly eccentric orbit, would be at its closest to the sun at the time when it was most easily reached from the earth. Unfortunately, perihelion warms the Martian atmosphere up quite a lot and the resultant winds can kick up dust storms. This possibility had been discussed earlier in the year by the Mariner mission operations team. Brad Smith, Masursky's partner at the helm of the television team, said it would not be a problem. But Smith was wrong. The great storm started on 22 September. Within a few days almost half the southern hemisphere was obscured by the brilliant cloud and a week later a second storm started further to the north. Soon the storms merged. Telescopes on earth saw a Mars utterly without features – and so did Mariner 9. Its first pictures, sent back on 8 November, revealed no detail whatsoever – wags joked that they had arrived at cloud-covered Venus by mistake. On 10 November, when the pre-orbital images should have been as good as those from Mariners 6 and 7, all that could be seen was the faint outline of the south polar cap and a faint dark spot. It turned out to correspond to the location which Schiaparelli had called 'Nix Olympica' – the Snows of Olympus. Two days later three more dark spots were seen a few thousand kilometres from Nix Olympica, forming a line from south-west to north-east across the region called Tharsis. The rest of the planet was still completely blank.

Two days later, after the spacecraft had gone into orbit, new pictures revealed that each of these spots had a crater at its centre. Carl Sagan took a Polaroid of the computer screen and rushed to the geologists' room. Masursky and his colleagues immediately realised what they were seeing. These were not impact craters like those seen by the previous Mariners, but volcanic calderas. Nix Olympica and the other features – dubbed North Spot, Middle Spot and South Spot – were volcanoes, volcanoes vast enough to stick out of the lower atmosphere into air too thin to carry the fine Martian dust. Within hours, Masursky was telling the waiting press corps all about it. Murray, who as well as sporting the black trunks of the killjoy was taking on a role as the television team's prudent conscience, was aghast. Mars had previously shown no signs of volcanism; it was surely rash to jump to such a dramatic conclusion. But within days more detailed photos showed without doubt that Masursky was right.

It's easy now to scoff at Murray's reluctance to see the truth. Mars's volcanoes have become, along with its vast canyon system, the things for which the planet is best known. Inasmuch as there is a popular picture of Mars today, these features – four big lumps with a long set of deep gashes to one side, rendered in a reasonably garish red – are what make it up. In some ways, though, Murray's reluctance to credit such things seems almost fitting, a greater tribute to their stature than straightforward acceptance. It may sound like a lack of imagination – but if you wanted to, you could read it as the opposite. Maybe Murray had the imagination to look beyond the simple images of

calderas and see quite how dauntingly huge the volcanoes would have to be in order to show up on Mariner 9's pictures of a planet wrapped in dust from pole to pole.

Think of the commute that some of the USGS astrogeologists were making on a weekly basis between San Francisco and Los Angeles; like a few thousand people every day, I made it myself while researching this book. You come off the tarmac at San Francisco airport and wheel round over the South Bay; northern California drops away beneath you, views open up. By the time the plane is at its cruising altitude of 33,000 feet, the view has spread out across the state. The Coast Range beneath you is a set of soft creases in the earth's crust, the Sierra Nevada a white rim on the horizon. After about half an hour's flight at a fair fraction of the speed of sound, you start to drop down and pull out over the Pacific, then come back around into LAX. And if your plane could fly through solid basalt, that entire flight profile would fit easily inside the bulk of the volcano then known as Nix Olympica and now called Olympus Mons.

Olympus Mons is a softly sloping cone sitting on a cylindrical pedestal, a flattened lampshade on a 70mm film canister. The face of the pedestal is a cliff that circles the whole mountain and rises on average four or five kilometres above the surrounding plain. Stick that pedestal on to California and it would cover the centre of the state from Marin County in the north to Orange County in the south. The mountain's peak, more than fifteen kilometres above the top of its surrounding cliff, would be high in the stratosphere, far above the reach of any passenger jet. You would be able to see it halfway to Flagstaff, a gently humped impossibility peering over the western horizon.

Yes, Olympus Mons is a mountain, built up by eruption after eruption of smooth-flowing basaltic lava. Yes, earth's 'shield volcanoes' – like Ararat in Turkey, or Kilimanjaro in Tanzania, or Mauna Kea in Hawaii – were built in a similar way and have much the same profile. But the scale of the thing is incomparably grander. Mauna Kea, earth's biggest volcano, would fit into the huge crater at the summit of Olympus Mons with room to spare. If you strung the arc of Japan's home islands round its base the two ends wouldn't meet; nor would the peak of Fuji clear the top of the great cliff that they were failing to encompass. An Everest on top of Everest would not come to the summit of Olympus Mons.

This single brutish Martian lump is larger than whole earthly mountain ranges. Its bulk – some 3½ million cubic kilometres of rock – is about four times the volume of all the Alps put together. If you wanted to build one on earth, you'd have to excavate all of Texas to a depth of five miles for the raw material – and you'd still be doomed to failure, because the planet's very crust would buckle under the strain.

North Spot, Middle Spot and South Spot, stretched out along the ridge of Tharsis, are smaller than Olympus Mons. But not by much.

The great storm, rather than obscuring Mars completely, had in fact served to highlight its most dramatic features. It also set Sagan – always alert for lessons from other planets with relevance to this one – to wondering whether similar phenomena might have any relevance to the earth. Mariner 9's infrared spectrometers showed that the dust did not just obscure the Martian surface from earthly eyes; it also chilled it by shielding it from the sun. In 1976 Sagan, his student James Pollack and other colleagues produced papers showing how the dust thrown into the earth's stratosphere by large volcanic eruptions could cool the home planet in a similar way. Such cooling was to be put forward in the early 1980s as the mechanism by which a large impact by an asteroid or comet – an event guaranteed to kick up a lot of dust – might have killed off the dinosaurs. This new mechanism for mass extinction led to Pollack and his colleagues being asked to model the sun-obscuring effects of nuclear war, and thus to the idea of 'nuclear winter'. Having gone to Mars to look for signs of life, Sagan found intimations of planetary mortality.

As the cooling planet-wide pall of dust started to ebb down the volcanoes' flanks in late 1971, the television team began to pick out the outlines of other features: depressions, in which there was more airborne dust to reflect sunlight back into space, started to stand out as bright blotches. By the

middle of December a vast bright streak had become visible to the east of the three Tharsis volcanoes. When the dust had settled out further the streak was revealed to be a set of linked canyons thousands of kilometres long and five kilometres deep. It would come to be called Valles Marineris after the spacecraft through which it was discovered. By the time the dust subsided in 1972, large parts of the planet's northern hemisphere had been revealed as plains much more sparsely cratered than those over which the first three Mariners had passed. At the same time, other features known from earthly observation, like bright Argyre and Hellas, turned out to be the remnants of absolutely vast impacts.

Most striking of all, particularly to Masursky, were the erosion features. In some places long, narrow valleys ran for hundreds of kilometres across the plains with few if any tributaries. In other regions there were branching networks of smaller valleys, suggestively similar to those that drain earthly landscapes. And elsewhere mere were vast, sweeping channels that seemed to have torn across the crust with unbelievable force, scouring clean areas the size of whole countries. Had water done this? Masursky seemed sure of it and waxed lyrical on the planet's lost rains to journalists; Murray looked on, grinding his teeth. After all, this was an alien world of new possibilities. Streams of lava might have been responsible – or torrents of liquid carbon dioxide, or gushing hydrocarbons, or slow-grinding ice. Even the thin winds were suggested as possible scouring agents – and though that was a spectacular stretch, it was increasingly clear that wind did indeed play a large role in the way the planet looked. Everywhere there were streaks where dust had revealed or hidden the surface beneath; in some places there were full-blown dune fields. The seasonal changes observed from the earth and held by some to mark the spread of primitive vegetation – changes that would have been Mariner 9's primary focus, had its sister ship, Mariner 8, not fallen into the Atlantic just after launch and thus bequeathed the main mapping mission to its sibling – were now explained by the wind, at least in principle.

And there was yet more for Masursky and Murray and their colleagues to wonder at and argue over. Strange parallel ridges and lineations running in step for hundreds of kilometres. The collapsed chaos features seen by Mariner 6, which now appeared to be sources for some of the great channels. Rippling bright clouds of solid carbon dioxide (such clouds, streaming off the heights of Olympus Mons, provided the intermittent bright white expanses that made Schiaparelli think of snow and call the area Nix Olympica). Most strikingly, there were regions at the poles where the interaction of wind-borne dust and expanding and contracting polar caps had built up a weird, laminated terrain. Each layer must correspond to a different set of conditions – different wind patterns, different climates. Millions, maybe billions of years of history were there in those layers, just waiting to be read if only you could get to them and figure out what made them. Murray, in particular, found these polar layered terrains fascinating. Thirty years on he still does. He was to be part of the science team on the ill-fated Scott and Amundsen microprobes that accompanied Mars Polar Lander.

The twenty-four people working shifts on the television team had more than enough data to keep them happy. Every twelve hours a new swathe of pictures would come back, covering the planet in seventeen days. There were always new things to see, new things to think about, new things to ask for close-ups of at the next opportunity. And in the end Mars's rocky surface was stored in their computers and tacked up on their walls, almost seven gigabytes of data, 7329 images. Mars was now much more than one of Tennyson's points of peaceful light – it was taking on, in Auden's words, 'the certainty that constitutes a thing'. It could be measured in detail, and properly mapped.

[*] The excellent Australian film *The Dish* goes some way to redressing this oversight.

The Art of Drawing

How wonderful a good map is, in which one views the world as from another world thanks to the art of drawing.

Samuel van Hoogstraten, *Inleyding tot de Hooge Schoole der Schilderkonst*
(translated in Svetlana Alpers, *The Art of Describing)*

In 1959 Patricia Bridges, a gifted illustrator with a degree in fine arts, started making maps of the moon for me Air Force Chart and Information Center in St Louis. Her technique soon established ACIC as a better moon-mapping outfit than its great rival, the Army Map Service. But St Louis was not a particularly good place from which to see the moon and, though mapping from photographs was possible, direct observation was better. The ever-changing smearing of the atmosphere made it almost impossible for 1960s cameras to capture the moments of clarity in which the moon's features are best seen – but the well-trained human eye could seize such brief impressions, understand what was seen in them and remember it. Through a good telescope eyes as keen as Bridges's could gauge lunar details as little as 200 metres across, more than twice as acute as the resolution in photographs.

The mappers wanted that clarity and so they needed regular access to a good telescope. The twenty-four-inch telescope that Percival Lowell had built in Flagstaff with which to look at Mars was one of the best available, benefiting from high altitude, clean skies and clear nights. So the Air Force moon mappers moved to the Lowell Observatory, settling in permanently in 1961. They were based in a small cabin – previously a machine shop and lumber store – just a hundred metres or so from the observatory's dome. By observing the same features lit from different angles on the waxing and waning moon, Bridges was able to get a sense of the features' forms that a single photograph could never give. Sometimes she would sit there working on her maps night after night until the seeing was just so, at which point a colleague inside the dome would call her on the telephone and she would bundle up in her coat and run over to the telescope to capture some new detail of her subject.

In the mid-1960s, with the Apollo programme a national priority, the Flagstaff operation blossomed. More than half a dozen cartographers were trained in Bridges's technique for lunar shaded-relief mapping. Shaded relief is a way of using heavier tones to suggest the shadows of hills and ridges on a map, giving the eye a sense of the third dimension. There are plenty of ways of doing the shading – with pencils, with paint, with chalks, even through a rather cumbersome system of embossing the relief on to plastic sheets and then photographing them lit from the side. But for the most part these are used to add shading to maps in which the relief is already clearly known through surveying, maps on which the topography is already defined by contours.

For the moon mappers the shadows with which they defined the landscape's features were not an evocative extra to ease interpretation or please the eye. They were the essence of the map, the ultimate expression of the surface's form. As such they needed to be rendered with minute fidelity, and the tool of choice was the airbrush, capable of capturing both the finest details – which is why people who retouched photographs relied on it in the days before Photoshop and similar software – and producing precisely graded washes, which was what commercial artists liked about it. There are other ways of producing maps of the planets: using Mariner 9 pictures and Mert Davies's control net, a British astronomical artist called Charles Cross did a very pretty and accurate set of maps using pencil and charcoal. These were used to make the first ever comprehensive atlas of Mars, with text by Britain's leading populariser of astronomy, Patrick Moore. Cross's work was fine; but compare it with the far greater precision of Bridges's moon work and you see immediately why, when the USGS started planning the production of official maps of Mars, the airbrush technique would have been the obvious one to use even if its leading proponents had not been located in the same town as the USGS astrogeology branch. Ray Batson, the USGS cartographer whom Masursky had chosen to run

the map-making team, made recruiting Bridges, who had left the Air Force mappers in 1968 but still lived in Flagstaff, one of his first priorities.

Another recruit from the Lowell team was Jay Inge. Inge had been a keen stargazer from boyhood on, but bit off more than he could chew, mathematically, when he enrolled for physics and astronomy at the University of California, Los Angeles in the 1960s. After the first semester he was 'casting around for things to do' and ended up taking a degree in bio-medical illustration. Then he heard from a friend – one of his childhood telescope buddies – about what was going on at the Lowell Observatory. The moon mappers needed his illustrating skills and they offered a way back into stargazing. So Inge joined the team at Lowell.

Inge augmented the techniques Bridges had developed in various subtle ways. One particular gift he brought was a dexterous use of the powered eraser, not to get rid of errors – 'an eraser is never used to rescue a poor drawing,' he wrote sternly in a manual on shaded relief mapping – but as a technique for highlighting things. This was, in a way, an adaptation to the airbrush of the 'dark plate' map-making technique that was then sometimes used for charts of the ocean floor; dark plates double illustrators' options by allowing them to both add and subtract from what was on the page to begin with. By taking ink away from the airbrushed original with a trusty K&E Motoraser, the illustrator could clarify and accentuate fine details, especially in the more deeply shaded parts of the maps.

By the time they made a start on the Mariner 9 images Bridges and Inge were highly accomplished, and the techniques they had developed for the moon were being taken up elsewhere. Inge had a fair amount of experience with Mars, too; while at Lowell he compiled telescope observations into a number of 'albedo' maps that showed the light and dark markings familiar for centuries (albedo is an astronomical term for the brightness with which an object reflects sunlight). But the spacecraft data offered new challenges. The television images from Mariner 9 were far better than any previous pictures of Mars, but they were very poor compared with the best images of the moon seen from the earth. (Even those observations were not as good as the pictures taken by the high-resolution camera designed for national security work that flew on board the Lunar Orbiter missions, which in the late 1960s overtook airbrush work as the state of the art for lunar mapping.) And with Mars there was no running up to the telescope in the middle of the night to get a better look. It wasn't all the spacecraft's fault: Mars was not a terribly good photographic subject. Its surface was pretty uniformly dark, and even after the great storm of 1971 had died down the atmosphere carried a residual obscuring burden of dust, not to mention occasional clouds.

The pictures were a lot less than ideal. Their saving grace, though, was that they were stored in a digital format. And even in the 1970s, there was a lot you could do with digital data to make it look better. The distortions in shape and brightness due to the design of the TV tubes could be dealt with. So could the after-image effect caused by the fact that vestiges of the previous picture would be mixed in with the current one. (If all this makes the cameras sound bad, well, they were: but they were also the best that could be sent to Mars.) Contrast could be increased spectacularly with new image-processing algorithms which massaged the data so that small variations in brightness were exaggerated into large ones. The computers could also 'rectify' images in which the camera had been pointed off at an angle, rather than straight down, putting them into a form suitable for mapping. Points from Merton Davies's control net would be identified in a set of pictures and a graph would be created that showed how those points would be arranged in a given map projection. Then the image files would be stretched and squashed until the control points in the images matched the pattern prescribed in the idealised graph. An easy way to check that the system was working correctly was to look at the shapes of craters before and after. In pictures the spacecraft had taken at an angle, perspective made the craters on the surface look elliptical; in pictures the computers had given a correct projection, they were circular.

This time-consuming process produced 'photomosaics' with their proportions corrected and their features enhanced. But these mosaics still had their shortcomings. Some of the individual images

that made them up would be darker than others, giving a sort of fish-scale effect to the assemblage. The images would also have been taken at different times of day and thus different pieces of the landscape would be lit from different directions – confusing to the inexpert eye and irritating to the expert one. Imperfections in the control net squashed and stretched some areas (in the case of the north polar region the small number of distinctive landmarks was particularly problematic, and would cause Inge no end of grief). And many useful images were simply excluded. Much of the Martian surface had been visited repeatedly by Mariner 9's cameras, but only one image of any given feature could make it into any given photomosaic. The others had to be left out, even if they offered extra information. In short, even when rectified, the primary Mariner 9 mosaics were ugly, confusing and less detailed than they could have been.

This was where the airbrush mappers came in: Bridges, Inge and their junior colleagues Susan Davis, Barbara Hall and Anthony Sanchez. They overlaid the photomosaics with Cronaflex, a Mylar film covered in a translucent gel on to which they would apply their ink. For the most part – different mappers had different styles – they would first trace the obvious features, such as rims of craters and edges of valleys, then start to work in the detail. As well as looking through their working surface at the mosaic beneath, they would also look at any other pictures they had that showed the same features. They built up a mental image of the forms they were trying to portray, their imaginations reaching into the images for detail, their discipline pulling them back from self-delusion.[*] They made their Mars in their minds and their airbrushes whispered it on to the Cronaflex. The concentration required was phenomenal. Ralph Aeschliman, the only airbrush artist still working at Flagstaff in 2000, likened it to being a bathroom plunger stuck to a television screen: 'If you got interrupted there was this *schwooup* noise as you tore yourself away.'

Making the maps was a way of working through the data, one that did so in images rather than words. Inge talks of it as an act of interpretation, a way of precisely describing the television team's data. But these were not just descriptions; they were pictures. Indeed, to some they were art. Aeschliman was scraping a living as a landscape artist in the Pacific north-west – he had an intriguing style that drew on Chinese influences – when a reawakened interest in astronomy led him to buy some of the USGS maps in the mid-1980s.[*] 'I'd always hated airbrush art – it was always so slick – but in those maps it was like dancing. It's hard to describe – very disciplined but very free too, the representing of a mental landscape built up from source material that's very scattered and different.' When his rent increased three times in a year, he decided it was time to head for warmer climes and clearer skies in the south-west. When he got to Flagstaff, he came to the USGS and asked for a job.

Aeschliman was instructed in the planetary mappers' technique by Bridges – 'There were times when I thought I'd just never be able to do it' – but his greatest respect was reserved for Inge. 'He was very spontaneous. He worked very rapidly and his work sort of sparkles. It has a presence.' Inge, now confined to a wheelchair by multiple sclerosis and myasthenia gravis, is flattered when I remind him that Aeschliman thinks of him as an artist. Though his living room walls are decorated with expressive abstracts he's painted, Inge claims to set little store by them. 'I'm a dabbler; I don't think I qualify as anything better than a good motel artist.' But then Inge didn't set out to be an artist; he was always set on being part of the research programme itself. So while he plays down any pride that he takes in the obvious artistry of his maps, he is happy to boast about the projects they have made him part of. 'Of the twenty-five mappable surfaces in the solar system – the solid planets and moons we've visited – I've worked on eighteen of them.'

Of all those surfaces, Mars had the most time and ink devoted to it. In 1971 Batson and Masursky decided that they would cover the whole planet at a scale of one to 5 million – fifty kilometres to the centimetre, a scale at which the smallest features identifiable in the Mariner 9 data would be just discernible. To make the work manageable, the surface was cut into thirty pieces, known as quadrangles. Pat Bridges mapped an astonishing eleven of them; Hall, Davis and Sanchez between them did another twelve; Inge did seven as well as maps and globes of the whole planet. He also

oversaw the production process, imposing rigorous quality control, doing the half-tone separations personally, flying to the survey's presses in Reston, Virginia to supervise the printing and making 'an obnoxious little shit' of himself. The series was not finished until 1979, eight years after Mariner 9 arrived at its destination. But the final result is magical. These are maps to lose yourself in, like windows in a spaceship's floor. They seem at the same time transparent to the truth and dense in artistry. They combine the presence of that which is real with the power of that which is inscribed.

The 1960s and 1970s were a great time for mapping. The space age was coming home to roost: the earth, that always-inhabited, always-experienced world, was being made over into an objectivised planet just like its neighbours, a minutely measured ball of rock and water. In the 1960s Argon spy satellites, offshoots of the Corona programme with cameras optimised for map making, were used to produce vast mosaic maps of poorly surveyed Africa and Antarctica. Other satellites were busily tightening up a global control net far more sophisticated than the Martian one, refining humanity's knowledge of the shape of its world so that missiles would more easily be able to find their targets. The needs of the nuclear submarines from which those missiles would be launched, along with the interests of a new generation of earth scientists, were driving new studies of the earth's ocean floors; while detailed data on the ocean depths were highly classified, beautifully drawn maps based on those data allowed earth scientists to see the spreading ridges and transverse faults central to new ideas about plate tectonics.

But the earth, partly because of those submarine-hiding oceans, could never be mapped in its entirety in the way that Mars was. Nor could it be mapped with such supreme disinterest. Earthly maps are heavy with duties to property and strategy, duties which can warp and distort them. On Mars everywhere was alike; nowhere was rich, or strategic, or owned, and so a pure disinterest reigned. There was a political point in their publication – these were American products, based on American ingenuity, printed by the American government – but in the images themselves there was nothing but the data, the interpretation and the artist's style.

Though they were in some sense less faithful to the truth of the planet than the television images they were based on, the maps were far more approachable, especially for the layperson.[*] They had a feeling of naturalism that the other forms the data were presented in lacked. Like most naturalism, this was highly contrived, depending on a number of strict conventions. Tricks of shading were used to make sure the users' eyes saw craters as dimples, not domes (an inside-out illusion endemic in photographs of planetary surfaces). The regional differences in the surface's albedo – the curves and blotches which are all that you can ever see of Mars through any earthly telescope – were suppressed. Mars's albedo was controlled not by the nature of its surface features but by the way the wind blew dust around and over them (the dusty bits were bright – the bits swept clear were darker), and winds were not something the mapping project was interested in. Inge developed a clever way of making separate albedo plates so that the maps could be printed with regional patterns or without, but after a few quadrangles the effort was given up. Nor was the colour on the final prints – a soft, light-brownish pink – the real colour of Mars. It was a colour chosen by Inge just to give a feeling of Mars. And somehow it did. The maps are indeed, as Inge always insists, technical documents that happen to have been drawn up in pictures, not words. But they were something more, too. After the maps were made, the real Mars was not only a surface under the spacecraft's circling cameras. It was also something directly available to, and through, human minds and eyes and hands.

Sadly, mapping Mars descended from being a delight to being a chore. Almost as soon as the first series of one to 5 million maps was finished, it was decided to revise them using new pictures taken by the Viking orbiters which had reached the planet in 1976. The original artwork was pulled out of storage and reworked on the basis of the new data. Because the control net had evolved, features had moved a bit and fudges had to be made. New detail was added, but in some cases the resulting maps looked cluttered and confusing. Inge was no longer checking the presses and the colours became less subtle. Frictions between Inge and Batson took their toll. Bridges retired in 1990; Inge left in

1994 and became embroiled in litigation with the Survey on the basis that his medical condition was unreasonably used to prevent his re-employment in 1997.

The airbrush artists were not replaced. Batson saw that new computer systems could make photomosaics ever more maplike – the Mars Digital Image Mosaic 1:2 million series he oversaw the creation of is now the basic reference for almost everyone who studies the Martian surface. The topographic mapping of the planets is now almost entirely a matter of image processing. This has not banished beauty. In the late 1980s a geologist named Alfred McEwen produced some magnificent views of large reaches of the planet on the computer while at Flagstaff. An image he made of the western hemisphere – the ridge of Tharsis volcanoes close to the limb, the gash of Valles Marineris across the centre, the thin trace of Echus Chasma running thousands of kilometres towards the north like a gold highlight – may be more widely circulated than any other picture of the planet. It is to Mars what Harrison Schmitt's endlessly reproduced picture of east Africa, the Indian Ocean and Antarctica, taken during the Apollo 17 mission, is to the earth. But though they can be beautiful and highly accurate – on such work you can improve things pixel by pixel if need be – the computer images lack the intimacy of the airbrush. By 2000 the late-comer Aeschliman was the only old airbrush hand remaining at the Survey's Flagstaff branch and he was doing his work entirely on screen. There is still an airbrush on the premises somewhere, but there is no longer any compressed nitrogen to bring it to life.

The maps themselves, scarred by revisions, sit in storage. All, that is, except one. Late in 1972, according to Jurrie van der Woude, who looked after some of the logistics of the Mariner 9 pictures and has been doing similar things at JPL ever since, Bruce Murray pleaded for a copy of the one-sheet shaded relief map of the whole planet that Batson's team was making based on the Mariner data. Van der Woude called Batson in Flagstaff, who admitted that Inge and Bridges had finished the map. Plates of it were being made for reproduction. When it was released it would turn out to be big news – a page of its own in the *New York Times*, a British tabloid headline screaming 'American Miracle – Map of Mars!'. But it was not yet released. Indeed, there were not yet any printed copies.

Van der Woude persisted; eventually Batson agreed to send the original over to Pasadena, as long as it came back swiftly. Van der Woude gave it to Murray with dire imprecations that it must, but must, be returned in two days. Three days later van der Woude started to think that the normally friendly Murray was avoiding him.

It took a week or so for van der Woude to corner Murray and find out what had happened. Murray was an ambitious man; within a few years he would be the director of JPL. He had wanted the map to impress Harold Brown – then president of Caltech, later secretary of Defense. Brown had thought the map wonderful and asked to show it to a guest, Henry Kissinger. Kissinger, too, was impressed and commandeered the map in order to offer it as a gift to Leonid Brezhnev; in part, we can be sure, because the Soviet Union's two missions to Mars in 1971 had failed, their pre-programming too rigid to allow diem to sit out the dust storm in orbit before getting to work, as Mariner 9 had done. And so the map had gone to the Kremlin.[*]

At least that's Jurrie van der Woude's story. Inge remembers that the map was lost, but not how. Murray says he remembers nothing of it – as does Harold Brown. Kissinger has proved elusive on the matter. So I have to doubt it. But I want it to be true. I want the first modern map of that planet to have played a role, even just a small one, in the history of this one. I want it to have reached the top. And I want it to have ended up where Jurrie says he last saw it, glimpsed in the background during a televised interview with a Russian space scientist, apparently taking pride of place on his office wall. I want it to be somewhere where it gets treated as an icon.

[*] There were exceptions. Experience on the moon had led the mappers to treat odd features as craters until proved otherwise, so some Martian oddities ended up drawn as craters even when they weren't. One of these non-crater craters went on to feature as a landmark in a rather good science fiction novel, Paul McAuley's *The Secret of Life.*

[*] It's a nice coincidence that the father of astronomical art, Chesley Bonestell, was also much drawn to Chinese landscapes and delighted in being able to produce good enough examples of the genre to fool his friend Ansel Adams into accepting them as genuine.

[*] The other great cartographic products of the Mariner 9 mission, a set of ten-foot globes made at JPL through the painstaking hand-positioning of fragments of images on spherical surfaces, have a strange patchwork texture that makes them almost impossible for anyone but an expert to interpret.

[*] They were not the first planetary maps to get to the highest offices. Maps of the moon by the engineer James Nasmyth – better known for his steam hammer – so fascinated Prince Albert that he had Nasmyth present them to Queen Victoria, who was duly impressed.

The Laser Altimeter

Then felt I like some watcher of the skies
When a new planet swims into his ken;
Or like stout Cortez when with eagle eyes
He stared at the Pacific – and all his men
Looked at each other with a wild surmise –
Silent, upon a peak in Darien.
John Keats, 'On First Looking into Chapman's Homer'

On 13 February 1969, nine days before Mariner 6 set off for Mars and five months before Neil Armstrong was to step on to the dust of the Sea of Tranquillity, the newly inaugurated president, Richard Nixon, asked his vice-president, Spiro Agnew, to explore the options for a post-Apollo space programme. Agnew became enthused. When Apollo 11 made its historic landing that July, he talked of committing the nation to the goal of sending people to Mars. The report of Agnew's Space Task Group, offered to the president in September 1969, discussed this possibility and many others – but more or less ignored the question of how much it was going to cost. Nixon could not allow himself that privilege.

In May 1971, the month Mariner 9 was launched, the Office of Management and Budget (OMB) informed NASA that its budget, already significantly cut back from its mid-1960s heights, would be frozen for five years. On 5 January 1972, two months after Mariner 9 reached Mars, President Nixon authorised NASA to start work on a reusable Space Transportation System – the space shuttle. There was severe doubt – at OMB and elsewhere – as to whether this was wise; NASA's claims that it would make space travel far cheaper were highly dubious. But it was the least ambitious thing on offer that would keep people flying into space. And people in space, even if they had nowhere particular to go once they got there, was an idea that meant something to Nixon and to many of the men around him.

From 1972 onwards the space shuttle was central to NASA's institutional survival. A national means became the agency's end. Almost everything else was either a distraction or, if it looked expensive, a threat. The planetary missions already approved – the Pioneer 10 and 11 missions to Jupiter and Saturn, and the Viking missions to Mars – were not in too much trouble. But missions not already accepted were delayed and scaled back. The ambitious TOPS probes to the outer solar system that JPL had been planning were replaced with enhanced, enlarged versions of the now ageing Mariner spacecraft design. In the end that did little harm – launched in 1977, the Voyagers were a spectacular success. But they were the last hurrah of the '60s horde. Between 1979 and 1991 JPL launched only two more planetary spacecraft.[*]

It was in this climate of cutbacks that the Viking landers lowered themselves to the surface of Mars in 1976. For years they sampled dead soil, analysed dry winds and photographed barren landscapes at two unprepossessing sites in the planet's northern hemisphere. In engineering terms they were a spectacular triumph. Their accompanying orbiters, meanwhile, added huge numbers of new pictures to the Mariner archive. And that was just as well, since the Viking treasury was to be the raw material for most of the next two decades of Mars research. The Viking missions were the most expensive effort in the history of planetary exploration and their single take-home message, according to most of the scientists involved, was that Mars was as lifeless seen from the surface as it had appeared to be from orbit. Expensive, dead and already the subject of overflowing data archives; to NASA budget-setters Mars looked like a pretty good place not to return to.

Which didn't mean that scientists stopped talk about new missions to Mars. At any given time there will always be lots of ideas for missions that someone or other dearly wants to see fly. Some are little more than water-cooler chatter. Some are studied but never approved. Some are approved

but then dropped. Each one that flies leaves the ashes of a dozen other dreams in its wake. The field of planetary science is full of brilliant people in their forties who have still never managed to get an instrument they defined or built on to a spacecraft, never gaining the status of a principal investigator.

In the early 1980s one of the competing dreams was a spacecraft called Mars Geoscience/ Climatology Orbiter. Its proponents admitted that, yes, it did seem that Mars was a dead planet, both biologically and geologically. Although there were arguments about how to date features on the surface – arguments which will be discussed later, along with many other scientific issues some readers probably think I'm passing over too quickly at the moment – most of the interesting events in Martian history were thought to have happened billions of years ago. But dead could be interesting and besides, Mars had only been studied from a fairly narrow point of view. Most of the data were in the form of pictures. To geologists like Hal Masursky and his crew, these pictures were great. Geologists are interested in stories about which rocks are where and how they got there. While pictures taken from orbit were not terribly good guides to the nature of the rocks, their form and arrangement – the morphology of the surface – were well captured, and that provided a lot of grist to the geological mill.

Geology, though, is not the only way to study a planet. Geophysicists are interested in understanding physical forces and processes, something they seek to do in large measure by building mathematical models. From this point of view pictures, while pretty, are no substitute for numbers. Geochemists are interested in the chemical elements from which planets are made up. Climatologists want to know whether they can understand the atmosphere's behaviour. All these disciplines had an interest in Mars that the Viking data-set couldn't satisfy. A modest orbiter dedicated to geophysics, geochemistry and climatology might be able to fill in the gaps in humanity's knowledge of Mars – the mineral composition of its surface, its precise shape, the strength of any magnetic field, the structure of its atmosphere – with model-friendly numerical data.

The argument was pretty good, the prospective investigators were widely respected and the idea that the spacecraft could be a cheap modification of a design already used for satellites orbiting the earth was a plausible and appealing selling point. Indeed, the idea was intriguing enough that it started to grow. If a small geosciences spacecraft could be sent to Mars, why not send a similar one back to the moon? Or to orbit an asteroid? Buying the same design and components in bulk would keep the prices down, after all. And so the geoscientists' Mars mission became Mars Observer, first in a new line of Observer spacecraft. Under pressure from geologists like Masursky – and with an eye to public relations – NASA added a small, comparatively cheap camera to the design; left to the geophysicists, Mars Observer would have no ability to take pictures in any usual sense of the word.

One of Mars Observer's objectives was to get a detailed picture of the planet's relief. The Mariner and Viking scientists had used a wide number of different techniques to try to calculate how high features on the Martian surface were. They used triangulations based on the visual images. They used the precise instants at which radio signals from orbiters were cut off as they passed behind the planet. They used subtle differences in the amount of infrared and ultraviolet light reflected from different parts of the planet through different depths of atmosphere. They used narrow beams of radio waves bounced off the surface by earth-based radio telescopes. All these different measurements were synthesised by Sherman Wu, in Flagstaff, to provide contours for the Survey's maps. But even Wu did not think the elevations he painstakingly arrived at were accurate to more than about a kilometre.

Mars Observer was to sort all this out with an on-board radar system developed by a team at NASA's Goddard Space Flight Center led by David Smith, a British geophysicist. Smith is a warm, affably excited man who, had he stayed in his native country, would be endlessly returning the smiles of women struck by his resemblance to the widely adored sportscaster Des Lynam. He had spent the 1970s applying the geophysical ideas attendant upon plate tectonics to studies of the shape of the earth, and he was excited about moving on to other planets shaped by other processes. Then, in late 1986, the shuttle struck again. Mars Observer had been scheduled for launch in 1990, but after the Challenger disaster the risk of the shuttle's schedule slipping convinced NASA officials to delay

the launch until the next time the planets were correctly aligned, two years later. Delaying by two years meant that the spacecraft's costs went up, because it was not feasible simply to disband the teams already at work. Savings had to be made and so the two heaviest instruments were dropped. One was the radar.

David Smith was not going to give up. He convinced NASA to put $10 million on the table to produce a replacement instrument and, having looked at a couple of radars, decided to use a new, much less tested technology, one that bounced laser light off the surface instead of radio waves. People in Smith's group at Goddard were already working on such an altimeter for the proposed Lunar Observer; a modified version became a relatively cheap altimeter for the Mars Observer. There were risks involved – no laser system had ever survived in space remotely as long as this one would have to – and the development was a little hairy in places. But they got the instrument finished on time and in budget. That was more than could be said for the rest of the mission. Partly due to the delays, Mars Observer's costs rocketed – the notional later Observers were cancelled as a result. Then it was decided to launch on an expendable rocket rather than a shuttle, adding yet more to the expense.[*] Then a hurricane hit the rocket while it was on the pad at Canaveral. Finally, on 25 September 1992, with the Mars Observer Laser Altimeter (MOLA) safely on board, Mars Observer got off the ground. And eleven months later, having been told to pressurise its fuel tanks in preparation for going into orbit around Mars, the spacecraft fell silent, never to be heard from again. It is more or less universally assumed to have exploded.

It was a terrible blow. Back when Mars missions were sent out two at a time, losing one was OK; Mariner 3 was lost, part of Mariner 7 exploded, Mariner 8 was lost, but Mariners 4, 6 and 9 did just fine. Mars Observer, though, was a singleton and the designers of its nine scientific instruments were bereft. Smith told me that while imagining ways in which the MOLA instrument itself might fail had come all too easily to him, he'd never imagined the whole spacecraft being lost. NASA's administrator, though – a bullying, obstreperous but undeniably dynamic and often perceptive man named Dan Goldin – decided the loss was an opportunity. Goldin was sick of being responsible for the sort of space programme that launched only a couple of planetary spacecraft every decade and was determined to find ways of sending out more missions – 'faster, better, cheaper' missions, as he delighted in calling them. The first faster, better, cheaper programme, called Discovery, was to send spacecraft all over the solar system. Indeed, the second Discovery mission, due to take off in late 1996, was a Mars lander – Mars Pathfinder. (Mars Pathfinder was actually conceived before the Discovery programme; as its name implies, it was meant to be the first in a series of simple landers. The series of simple landers was cancelled and Pathfinder, like Mars Observer, became a one-off,[*] slotted into the Discovery programme for more or less purely political reasons.) Goldin and his advisers at NASA headquarters decided that a second line of faster-better-cheaper spacecraft should be devoted to Mars. In order to spur new thinking and greater efficiency, the size of the spacecraft and the budgets in this Mars Surveyor programme were to be tightly constrained.

The first of the missions was Mars Global Surveyor (MGS) and it has proved massively successful. Launched in November 1996, it arrived at Mars a few months after Mars Pathfinder's landing on 4 July 1997. MGS carried copies of five of Mars Observer's instruments, for the most part cobbled together out of spare parts. Soon after arriving it started a long series of passes through the thin upper atmosphere, a way of losing energy to make its orbit shorter and more circular. This technique, 'aerobraking', was new and somewhat risky. In the old days before faster-better-cheaper, changing orbits was something you did with engines, not drag. But drag is free and engines cost money.

In the end this aerobraking took a lot longer than anticipated: most of the atmospheric drag was felt by MGS's solar panels and the arm holding one of these panels turned out to have a flaw in it. The aerobraking sequence was modified so that the spacecraft dipped into the atmosphere even less than had been planned, the force exerted on it ending up as less than three newtons – about the force

it takes to lift a Big Mac. This slowed things down and it was not until early 1999 that MGS reached its final orbit, circling the planet every two hours or so, about 400 kilometres above the surface. The instruments now got down to business. The infrared spectrometer scanned the surface to see what minerals were present, and where. The camera, capable of picking out features just a couple of metres across, started adding long, thin tracks of extraordinary and frequently confusing new details to the coarser pictures of the Mariners and Vikings. And MOLA's laser gently zapped the surface beneath the spacecraft ten times a second. The laser beam would illuminate a patch of Mars about 160 metres across and the altimeter's clock would measure the time it took the light to get mere and bounce back (less than three thousandths of a second). The exact length of time revealed how high up the spacecraft was. Combine that altitude with tracking data showing where the spacecraft was – the tracking on MGS was exquisite – and you get a point in a global altimetry database. By the middle of April MOLA had produced almost 27 million such altitude measurements. For the most part they were precise to within less than a metre, which means that two nearby spots which seemed to have the same altitude would in reality be no more than a metre different in elevation. The overall accuracy with which the MOLA measurements determined the global shape of Mars was about eight metres.

A year after MGS reached its final orbit, in March 2000, planetary scientists from all over America and much of the rest of the world gathered in Houston for the Lunar and Planetary Science Conference, just as they have done every year since 1970, when the first such conference pored over studies of the first samples returned from the moon. For a week, the Johnson Space Center's recreation building was turned over to them, and its basketball courts rang to the announcement of more and more news from Mars. At least a hundred papers on Mars were presented, most of them informed by MGS data in one way or another. To many of those attending, Mars seemed to be changing before their eyes. MGS measurements were discovering new features and forcing the reinterpretation of old ones. The idea that there had once been an ocean on Mars was starting to gain serious respectability. So was the idea that, far from having been geologically dead for billions of years, Mars was in fact still active. The old familiar face of the planet was taking on a youthful cast in the new light. The scientists were as reinvigorated as their planet.

But if the Houston meeting was full of scientific promise, there was also a fair share of institutional foreboding. Condolences were offered to the people who would have been presenting the first data from the Mars Surveyor programme's 1999 missions, Mars Polar Lander or Mars Climate Orbiter, had it not been for their accidents. Some of these unfortunates – the ones who had worked on an instrument designed to analyse the way the Martian atmosphere changes with altitude – had watched their instrument burn up not once but twice, first on Mars Observer, then again on Mars Climate Orbiter. The reports of a whole slew of investigative committees on the previous year's disasters were due out in the next few weeks and everyone knew that they would make sad, infuriating reading. While Mars Global Surveyor was a wonder, the programme it had spearheaded was a disaster.

On a phenomenally wet Tuesday evening, on a set of couches in the foyer of a building on the University of Houston's Clear Lake campus, Carl Pilcher, the man responsible for solar system science at NASA headquarters, discussed the situation with various worried and disaffected scientists. He more or less confirmed that the next Mars lander, one that shared the design of Mars Polar Lander and was due to be sent off in 2001, was being cancelled. He accepted that the constraints that had been put on the programme had proved too tough – that in the effort to force JPL to make the Mars Surveyor programme faster-better-cheaper, mistakes had been made both at the lab and at NASA headquarters. He accepted that faster-better-cheaper had meant that the scientists had worked themselves to the bone and encouraged everyone there to help NASA get it right next time round. When he'd finished it was clear that the Surveyor programme as it had been talked about just a few months ago, with plans for missions in 2003 and 2005 that would not just study Mars *in situ* but send samples of its surface back to the earth, was over and that as yet there was nothing to replace it. With

one exception – a small orbiter that would carry the last of the Mars Observer instruments to their objective in 2001 – the future of Mars exploration was, yet again, a blank.

But Mars itself was not. Just across the aisle from Pilcher's attempt to share the pain of his bruised community was a special presentation by the MOLA team. As befits a geophysical instrument, MOLA is in the numbers game. If you put enough numbers together, though, you can get a pretty good picture. The MOLA team had taken their data-set, arranged it on a Mercator projection and printed it out as a map. The first version of this map, published in the journal *Science* the summer before, had been impressive. Garishly colourful, it had shown so much detail in its crater rims and mountain tops that many looking at it had assumed it was a colourful overlay superimposed on some sort of photomosaic or airbrushed map. But every last bit of the picture came from the MOLA data-set, from simple measurements of the time it took for a pulse of laser light to reach the surface of Mars and bounce back to MGS.

By the time of the Houston conference the map had been much improved. MGS had been in its proper orbit for more than an earth year (though only just half of a Mars year, each of which lasts 687 earth days, or 669.6 Mars days). More data had been added and very large printers had been used to blow the image up far beyond the scale of a scientific paper. The version in the University of Houston foyer was about two metres long and a metre and a half high. It would have been eye-catching even if you didn't know what it was. If you did know, it was little short of a miracle. Here were real data, as hard and scientific as you could wish, woven into the image of a planet. It was not a realistic image. The altitude data were colour coded, so that the terrain ranged from blue in the lowlands through green to yellow to red to white. Hellas, the deep basin in the south, looked out like a baleful violet eye; the rise of Tharsis, its three great volcanoes snowy white, was ringed with burning red. Faint features were enhanced by computer filtering, just as they had been in the Mariner 9 photographs, to exaggerate details. Shaded relief had been added, not by skilled artists, but by a computer program first developed for charts of the ocean floor. It did a pretty impressive job – while still suggesting, as all such shading does, that the planet knew no night and that the sun was somewhere over the north pole. No, the map was not realistic. But to the people who walked by, and stopped, and stared, it was very real.

I watched for an hour or so as almost every scientist with any interest in Mars passing by on the way to or from the poster presentations elsewhere in the building stopped to stare at the MOLA map. They talked to each other; they pointed out features. They got close and squinted, then stepped back to take it all in. They enthused and gestured, and then fell silent and just stared. Peter Smith, designer and operator of Mars Pathfinder's camera and, in his youth, a photographer with serious artistic ambitions, said it was the most incredible picture he'd ever seen. Baerbel Lucchitta, a striking, stately geologist who has been at the USGS in Flagstaff since the early 1970s, traced her favourite features with a little girl's grin. When people finally walked away, their eyes and minds full, they couldn't help but look back over their shoulders to get just one more glimpse. Here was a map that was most definitely being treated as an icon.

And David Smith just stood by his team's creation and beamed. Other people on the MOLA team have told me that they always expected to put together such a picture of the planet, but Smith says he had had no idea the endless stream of data points would add up to such a striking visual statement. When I'd visited him in his office me year before, when the largest printed version of the map had been about thirty-five centimetres across, we'd looked at the data laid out numerically in vast spreadsheets. Though Smith had been keen to have the biggest possible version of the map printed for me Houston meeting, he'd not actually seen the resultant poster before that Tuesday evening. He was looking at it – and showing it off – for the first time, the joy of it all over his face. Across the aisle from the MOLA map, Carl Pilcher was explaining that an era of exploration that had seemed to be just beginning was coming to an end. But Smith just kept talking and smiling and looking with pride at his map. From time to time he'd touch it, running his hand lightly across the smooth blue of

the planet's northern lowlands. As though he could feel the onset of the higher plains to the south. As though the craters might scratch his fingertips.

300 million kilometres away, an instrument he had argued for and cajoled into being and thought about every day for more than a decade was illuminating the surface of an alien planet ten times every second. And in the rain-soaked Houston suburbs David Smith was stroking the face of Mars, a picture of delight.

[*] At a conference in Germany in 1990, a frustrated JPL engineer named Donna Shirley told a story about a recently deceased NASA engineer asked by St Peter what he'd achieved with his life, to which the answer was 'First viewgraph, please …' Shirley eventually led the Mars Pathfinder team.

[*] Although a shuttle launch costs a lot of money, those costs are not typically borne by any spacecraft along for the ride, but the cost of a one-off rocket is billed to the mission that it launches.

[*] This sole-survivor-of-an-imagined-series motif is a common one in the history of NASA; as individual missions grow costly, their proposed successors are cancelled. The Planetary Explorer 'programme' of the 1970s ended up being a single mission. So did the Mariner Mark IIs conceived in the 1980s.

Part 2 – Histories

When the investigator, having under consideration a fact or group of facts whose origin or cause is unknown, seeks to discover their origin, his first step is to make a guess.

Grove Karl Gilbert, 'The Origin of Hypotheses'

Meteor Crater

'Craters? Why didn't we think of craters?'
Isaac Asimov to Frederik Pohl, on first seeing the
images of Mars from Mariner 4

If you care for impressive and beguiling landscapes, Flagstaff, Arizona has a lot to recommend it. The San Francisco peaks – remnants of a shattered volcano similar in scale to Mount St Helens – loom over a town scarcely a hundred years old, wrapped in the forests that attracted its founders. To the south the beautiful canyons of Sedona, carved into the rocks of the Colorado Plateau by water draining from beneath the forests; to the east the spectacular Painted Desert; to the north the Grand Canyon itself, more than a billion years deep, more gazed at and photographed than any other hole the world has to offer. Around the San Francisco peaks sit lower cinder cones like giant black molehills, weirdly fresh. Some are intact, some thoroughly quarried: their ash grits the roads in winter. One of them, remarkably, is in the process of being turned into a vast meditation on earth and sky, light and stone, by the artist James Turrell, earth movers his chisels.

If the land is wonderful, so is the sky, which seems to expand in sympathy with the majesty below. The air is dry, clean, a little thin – just the sort of place astronomers like to set up shop. Above the town, amid the ponderosa pines of Mars Hill, sits the telescope through which Percival Lowell imagined the landscapes of Mars. You can go up and have a look through it, if you like; at the right time of year you'll be able to see Mars floating in the eyepiece just as he did, blotchy but beckoning. During my most recent visit it was the wrong time of year, with Mars best seen at about five in the morning, long after Lowell Observatory has closed itself to tourists. But even watched from a motel car park in the pre-dawn glow, Mars seemed closer in Flagstaff than it does in most places, shining clear and bright and true.

To appreciate land and sky together, drive about half an hour east of Flagstaff. A quarter of an hour beyond the line in the landscape where the Coconino forest responds to some subtle cue of altitude or precipitation and gives way to the Painted Desert, you'll find what used to be called Coon Butte. From a distance it looks not unlike the flattened mesas that sit further off behind it, except for the fact that its heights are a little more crenellated. As you come closer, though, you begin to get the feeling that it is something quite different: smaller, lower, subtly different in form and nature. Rather than sitting on top of the desert like the low flat hills to the south, or puncturing it like the cinder cones behind you, Coon Butte seems to be a bending of the plateau itself, a twisting of the land towards the sky. And so it is.

Coon Butte is one of the places where the sciences of astronomy and geology meet. It marks the spot where, 50,000 years ago, a very small asteroid's orbit round the sun was cut short by the surface of the earth. Most asteroids are made of stone friable enough that small ones will explode high above the earth's surface, shattered by the shock of being slowed by the atmosphere. The fifty-metre asteroid that struck the Painted Desert that day was made of sterner stuff: iron. It pierced the atmosphere intact and ploughed on into the planet. Only after it had punched a hole through the surface of the desert did shock waves tear it apart in an underground explosion a thousand times more energetic than that of the Hiroshima bomb, throwing millions of tonnes of the plateau's rocks back into the sky. The strata of rock surrounding the impact were bent upwards, raising the surface of the desert in a ring and forming a sharp upturned rim to the crater. Some boulders were thrown half the distance back to Flagstaff; within four kilometres the desert was covered with a thick blanket of debris. The hole left behind was about 200 metres deep and 1.2 kilometres across, excavated in seconds. The rim of raised rock stood sixty or seventy metres above the surrounding desert. After 50,000 years, erosion has smoothed it down to fifty metres.

Meteor Crater, as it is now called, is an impressive sight. By the time you reach the observation area on the north side of its rim – the only part to which the public normally has access – you have driven at least eight kilometres out of your way, you have paid for a ticket, you have walked past a gift shop and a well thought-out visitor's centre; you know what to expect. Even so, to come across this sudden theatre of steep relief in an otherwise flat desert takes you aback. It is a big, dramatic hole, its base smoothed by the dried-out bed of a little lake, the strata of raw bedrock poking out of its sides like piers in an arena to seat a million.

At the same time, by the standards of truly dramatic valleys, canyons and volcanoes – standards the Arizona landscape requires all its tourist features to measure up to – Meteor Crater is not really so terribly large. Its sides are steep and deep, to be sure: if St Paul's Cathedral were built at the bottom, the great golden cross on top of the dome would be well below your eye level. But the depths are enclosed in a way that almost belittles them. Craters are the most revealing of landscapes; from the rim you can quickly take in all there is to see. And this is not that large a crater. The rim is only four kilometres around. You could walk round it in a couple of hours (the walking is quite hard, for the rim is not regular); your eye runs round it automatically, limiting its scope in the process. Anything you can grasp this easily cannot give a sense of true enormity.

The most striking effect is not to look down from the rim into the crater's depths, but rather to look straight across. To the south, the circle of the crater's rim and that of the further horizon lie one upon the other, tangent arcs. Turn your head slowly – pan like a camera – and they become detached. The rim falls away from the true horizon; it twists into the middle distance, banking towards you as the true horizon keeps its distance, becoming a feature within the landscape rather than a limit at the edge of it. Eventually it ends up under your feet, a rampart of rubble dividing the bowl enclosed within from the great desert plain outside. And yet the rim still feels linked to the horizon itself. The great circle of the planet and the ring of the rim seem aspects of the same thing; the great void below echoes the great vault above. The effect has something in common with the old cliché of a straight road, a flat plain and a vanishing point on the horizon. But here there are no points and lines and directions: just circles turning in on themselves over 360°. This sense of a world arranged in nested circles may be something nothing else can offer as well as a deep astronomical impact with a well-preserved rim. And on the earth, there are no other impact craters with rims as well preserved as Meteor Crater's.

On Mars, by way of contrast, there may be a quarter of a million impact craters the size of Meteor Crater. And there are craters of all other sizes, too. There are great impact basins large enough to put the European Union into; there are craters small enough to use for tennis courts. There are craters that overlap like the circles of an Olympic flag. There are craters on the rims of bigger craters. There are craters within craters within craters. Some are as young as Meteor Crater itself, some even younger. Some are more than 80,000 times older, landscapes more ancient than anything on the earth's shifting surface except a few tiny zircon crystals preserved by chance.

And those are just the ones you can see in the airbrush maps and the Viking pictures; the ones with clear, well defined rims. One of the discoveries made with the data from Mars Global Surveyor's MOLA altimeter was that there are hidden craters, too, craters yet more ancient than the visible ones, if only by a little. The MOLA team has developed all sorts of ways of using brightness and colour cues to bring out different aspects of their vast data-set. One of their best tricks is a way of looking at the planet slice by slice on a computer screen. The spectrum of colours that allows the eye to understand what it is seeing is concentrated into a thin range of altitudes – just a few hundred metres, perhaps – with all lower places darkly blue, all higher grimly purple; the highlighted range can be moved up or down at will. Look at a mountain this way and you will see a circular band of rainbow with a dark centre. Toggle the highlighted range upwards and the noose of light will tighten to a solid disc at the summit; lower it and the ring of colour will expand slowly until it smears itself out across the plains at the mountain's base.

Run this magical palette over the surface of Mars and crater rims will stand proud as thin, hollow crowns. But rimless craters can be found too: solid circles of equal altitude. These are old, eroded craters, craters the unaided eye would never pick up. These shadow craters can be quite big: one of the first to be discovered this way was about 450 kilometres across, giving it an area about the same as Michigan's or England's, and definitely putting it in the first division of Martian craters. And they are quite numerous. In the summer of 1999, seventy flat circles of various sizes that looked like ancient impact scars were discovered by one high school student doing an internship with the MOLA geology team.

Discoveries on such a scale mark a peculiarly auspicious beginning to a scientific career. But if the intern was spectacularly successful in how she did her job, she was not particularly distinctive in the job she was doing. Almost every geologist who looks to the skies as well as the earth starts off counting craters; most will still be doing so, now and then, decades later. They are the way that astrogeologists measure time. On the earth, geological time is measured in layers; layering is history and depth is age, as a drive to any edge of the Colorado Plateau will demonstrate. Stratification, though, like embonpoint, is best seen in profile; on planets looked on only from above the study of strata is geometrically challenging, to put it mildly. But craters, too, are the testaments of time; like sediment on a sea floor, they accumulate over the years. Most planets with rocky surfaces are amply supplied with craters: the earth, endlessly reinventing its surface through erosion and plate tectonics, is the great exception. Reading the record of craters has made sense of the geology of the moon, has revealed global cataclysms responsible for remaking the surface of Venus and has provided, at least in outline, the history of the Martian surface from the most recent sharp-edged scar to the most ancient rimless basin.

It was through Meteor Crater mat people first learned how to read such records. It gave them what geologists most need: an analogue through which to understand processes not yet understood in any other way. Analogy sits at the heart of geology; it has long linked the past to the present, and now serves to tie the earthly to the alien. Meteor Crater allowed geologists to understand impacts, and its nested horizons became the door to other worlds and other times. Its role in understanding was not just theoretical. In the 1960s Meteor Crater was one of the sites chosen to train the only men from earth ever to walk anywhere else; strain your eyes and by the lake bed at the bottom you can see the statue of an Apollo astronaut that commemorates them. From his point of view there is no double horizon; beyond his little bowl of a world there is just the great urgent vault of the sky.

‘A Little Daft on the Subject of the Moon’

We pride ourselves upon being men of the world, forgetting that this is but objectionable singularity unless we are, in some wise, men of more worlds than one.

Percival Lowell, Mars

The story of how Meteor Crater came to be understood as the best-preserved earthly exemplar of the ancient landscapes of Mars comes in two parts. In the first part a great geologist got it wrong, but in doing so showed how geology could, in principle, tackle subjects beyond the earth. In the second part a great geologist got it right and used his insights to turn the geological mapping of other planets, including Mars, into a practical concern. Both men were geologists with the US Geological Survey and both were filled with the romance of the American West – a romance that both science and the popular imagination have projected on to Mars for more than a century.

Grove Karl Gilbert was one of the happy generation of American geologists which, in the second part of the nineteenth century, took its impressive beards and intellects to every corner of the American West. They were part of a worldwide phenomenon that the historian William Goetzmann has called the second age of exploration – the period between Cook’s voyages in the late eighteenth century and Amundsen’s trek to the south pole in the early twentieth during which Europeans moved beyond the coastlines of other continents and across their hearts. The centres of Africa, Asia and Australia were all explored at this time.

In the American West Gilbert and his peers – John Wesley Powell, Clarence King, Clarence Dutton, William Davis – encountered a world that spoke to them of the archaic and at the same time cried out for the modern, an awe-inspiring natural world that could only be opened to civilisation through the technologies of electricity, irrigation and the railroad. Its forbidding landscapes – often wonderfully captured by the artists and photographers who accompanied the various expeditions – were utterly unlike those the scientists were familiar with back east; plateaux dissected by massive erosion, the strangely faulted terrains of the basin and range province, all manner of volcanic dramas. The explorers measured the landscapes, mapped them, developed new language to describe them: ‘laccolith’, ‘isostasy’, ‘gradation’. Dutton, in particular, was a literary gent (as well as a soldier, a chemist and a theology school drop-out) who styled himself ‘omnibiblical’; his writing overflows with energy. His descriptions were evocative, grandiose and sometimes extremely funny, continuously aware of his audience back east and the novelty he was bringing to it. In his memoir of the Grand Canyon, the Survey’s first publication, he wrote in self-justification:

I have in many places departed from the severe ascetic style which has become conventional in scientific monographs. Perhaps an apology is called for. Under ordinary circumstances the ascetic discipline is necessary. Give the imagination an inch and it is apt to take an ell, and the fundamental requirement of the scientific method – accuracy of statement – is imperiled. But in the Grand Cañon district there is no such danger. The stimulants which are demoralizing elsewhere are necessary here to exalt the mind sufficiently to comprehend the sublimity of the subjects. Their sublimity has in fact been hitherto underrated. Great as is the fame of the Grand Cañon of the Colorado, the half remains to be told.

Dutton, Gilbert and their peers did not just find new language with which to express themselves; they came up with new theories about how the earth might work, theories which allowed for far greater violence and more sudden novelty than the sedate forms of geology practised by their European forebears and contemporaries. It was the need to explain the landscapes of the West, and the mineral wealth they might hold, that led to American geology becoming a nationally distinct enterprise quicker than any of the country’s other sciences.

By the time he came to Meteor Crater in 1891 Gilbert had spent twenty years, as he put it, ‘aboard the occidental mule’, trying to understand the processes that had shaped the landscapes around

him. He was a precise man, mathematically orientated, but he also had a zest for the experiences that would help him explain how the landscapes he carefully measured had come to be. It was, he wrote, 'the natural and legitimate ambition of a properly constituted geologist to see a glacier, witness an eruption and feel an earthquake'. When he achieved the last of those ambitions in 1906, it was with 'unalloyed pleasure'; woken by the shocks of the San Francisco earthquake he set to timing them and measuring their direction. He brought the same precision to his other work, closely harnessed to a love of physical and mechanical analogy.

His love for the orderly and mathematically tractable led him to study the stars as well as the earth. Travelling down the Grand Canyon on one of the first expeditions to do so, he had made a point of observing Venus from its depths. He was by his own admission 'a little daft on the subject of the moon', and in Washington DC he made use of the Naval Observatory's telescopes to observe it in detail, prompting ridicule from congressmen who affected to think that if distinguished members of the US Geological Survey had nothing better to do than look at the heavens, the Survey should clearly be disbanded, its earthly work complete. In Gilbert's thought, though, geology and astronomy belonged together; together they could explain not just rocks but entire planets.

In the summer of 1891 a Dr Foote reported to the American Association for the Advancement of Science that he had found significant amounts of meteoritic iron at Canyon Diablo in the Painted Desert, near the crater at Coon Butte. Gilbert was intrigued. He thought matter falling from the sky might shed light on what he saw as one of the great planetary problems: why the earth's crust is systematically denser in ocean basins than under continents. Gilbert thought this heterogeneity might be due to the fact that the earth had been assembled from smaller objects, which later theorists would call planetesimals: dense crust marked the contributions of dense planetesimals. Gilbert wondered whether the large crater in this field of meteoritic iron marked the spot where a 'small star' had been 'added to the earth' relatively recently. Always ready to head west when possible, he arrived at Meteor Crater that October.

Gilbert saw two possible types of explanation for the crater: it could have been formed by something coming in – an impact – or by something coming out – a volcanic explosion. The best argument for a falling star was the meteoritic iron littering the surrounding desert. Gilbert calculated the odds of a crater forming in such a dense meteor field purely by chance as 800 to 1. If the crater had been clearly volcanic, then this might not have mattered. But though there were volcanoes nearby, the crater's walls and floors were sedimentary rock, the same strata of sandstone and limestone from which the rest of the Colorado Plateau is built.

In a typically methodical manner Gilbert set out to test the alternatives through their implications. If there were a 'star' buried beneath the crater somewhere, then like Archimedes in his bath it would have displaced material that was there before. If so, there would be more material in the crater's raised rim and its surrounding blanket of ejecta than was needed to refill the crater itself. But when, through painstaking surveying, Gilbert and his assistants compared the volume of the crater's cavity with the volume of the rock that had been excavated in the catastrophe, they found that if the rim and ejecta were put back into the crater they would almost exactly fill it up; thus there was no evidence for the bulk of an added meteor below the crater floor. What was more, if a large iron meteorite did lie buried there it should have had a quite discernible magnetic field. But no such field was found. So Gilbert decided the crater had been formed by an explosion of steam, set off when deep volcanic activity had penetrated a subterranean aquifer; he placed Coon Butte in the family of anomalous volcanic craters called 'maars' (no relation). This hypothesis sat well with the natural inclination of the area's uneducated shepherds: that the crater looked as though it had been formed by something exploding out of the earth, not by something falling into it.

Disappointed as he may have been – a maar is an interesting thing, but hardly a star – Gilbert still put his observations to good use. In his 1895 address as president of the Geological Society of Washington, published as 'On the Origin of Hypotheses', he presented the story of Coon Butte

as a sort of moral fable on the correct way of approaching geology. To explain a novel feature, the geologist should first reason by analogy: what sort of thing is it like? The analogy might seem a distant one – a gaping crater in a desert is not very like the 'raindrop falling on soft ooze' to which Gilbert compared Coon Butte – but that need not matter. What matters is that there be a number of analogies, that they have different physical implications, and that those implications then be tested. This was Gilbert's highly influential encapsulation of what was becoming the pragmatic cornerstone of geological science in America: a method of 'multiple working hypotheses' in which contradictory explanations were to be entertained simultaneously.

One of the disappointments for Gilbert in finding Meteor Crater to have been produced from within and not without was that he had hoped to use it as an analogy with which to bolster his theories about the moon. Everyone who wrote on the moon explained it by analogy to the earth; the problem lay in choosing the right analogy. In 1874 James Carpenter, a Greenwich astronomer, and James Nasmyth, an engineer whose father had been a landscape artist and whose own pictures of the moon had caught the eye of Prince Albert, published a wonderful illustrated book called *The Moon: Considered as a Planet, a World and a Satellite.*[*] Inside, spectacular photographs and prints of the moon are compared with similarly lit photographs of a range of other objects – an old man's wrinkled hand, a desiccated apple, a cracked sphere of glass. The idea is to teach the reader's eye new ways of seeing the moon and give his mind new analogies by which to understand it. (Their influence was long-lasting. Lowell used the desiccated apple in his books on Mars to demonstrate what happens when a planet dries up; the first post-Mariner textbook on Martian geology has very Nasmyth-like cracked glass spheres in it to demonstrate stress patterns.)

To make their case for the volcanic origin of the moon's craters, Nasmyth and Carpenter created a scale model of what Vesuvius and the bay of Naples must look like from above and compared it with similar models of the lunar surface. Other lunar analogies on offer suggested that the dark expanses of the moon called 'seas' were in fact made of ice, or that they were the dried beds of seas now vanished. Charles Babbage, the pioneer of mechanical computing, elaborated on this idea with the notion that craters in these dried seas were in fact coral atolls like those studied by Darwin.

Gilbert rejected all these analogies, seeing the craters and larger basins and 'seas' as the marks left by planetesimals. His idea was that once the earth had been ringed by planetesimals – much as Saturn is ringed today – and that these had then coalesced into the moon; the last ones in had left the surface scarred. Lacking a natural earthly analogue for such cratering, Gilbert experimented with crater making himself, firing various projectiles into clay: he called the hobby 'his knitting' and found the results satisfactorily lunar. To those who objected to a geologist trespassing in the realms of astronomy, he defended his speculations in terms that could serve as the credo for astrogeology to this day: 'The problem is largely a problem of the interpretation of form, and is therefore not inappropriate to one who has given much thought to the origin of terrestrial topography.'

Gene Shoemaker's thinking on terrestrial topography, which would find application in the interpretation of form on the moon and beyond, took place in large part on the Colorado Plateau which Gilbert had known so well (indeed, he had given it its name). In 1948, twenty years old and with a Caltech degree in geology already behind him, Shoemaker joined the US Geological Survey and found himself working in southern Colorado. He discovered that he loved the landscapes of the south-west. He loved the pines, he loved the open spaces, he loved the great, vaulting skies. He stared up at the desert moon with wonder.

In the field, he did not have much contact with the rest of the world. But he did get the Caltech alumni newspaper, which revealed that experiments with captured V2 rockets elsewhere in New Mexico were reaching the very edge of the atmosphere. It was a revelation. 'Why, we're going to explore space,' he later remembered thinking, 'and I want to be part of it! The moon is made of rock, so geologists are the logical ones to go there – me, for example.'

Shoemaker kept his wild dream to himself – a decade before Sputnik there was little call for space age geology. The atomic age, though, needed geologists badly. Cold War strategy required that America develop reliable domestic sources of uranium, and the Colorado Plateau was thought likely to hold the reserves required. So in his first years with the USGS Shoemaker joined in the last great American mining boom; at the same time he started work on a Ph.D at Princeton and got married. He criss-crossed the Colorado Plateau from site to site, 'half man, half jeep', according to his wife, Carolyn, who often accompanied him. It wasn't normal for geologists' wives to come along on field trips, but the Shoemakers didn't care. When they had children, the children came too.

All the while, Shoemaker kept thinking about the moon. He read everything there was to read on the subject, including Grove Karl Gilbert; he tailored his fieldwork to suit his extraterrestrial interests. It was this which led him to map diatremes in the Painted Desert's Hopi Buttes. Diatremes are volcanic features, chimneys of magma that rise to the surface causing explosions, which throw out a lot of normally well-buried rock and comparatively little lava; they can create the low-lying craters called maars to whose number Gilbert had added Meteor Crater. As a uranium prospector, Shoemaker was interested in diatremes because the rocks they threw out when they cleared their throats might be from uranium-bearing strata. As a would-be lunar geologist, he was interested in them because their associated craters often occur in families laid out along a straight line; many lunar craters show a similar linear tendency. Diatremes might thus be analogies by which to understand some forms of volcanism on the moon.

Shoemaker caught his first fleeting glimpse of Meteor Crater in the late summer of 1952. One afternoon, driving past the town of Winslow, he convinced his wife and a colleague that the site to which the great Grove Karl Gilbert had devoted his time might be worth a look. They didn't have the entrance fee required for the public viewing platform on the north edge of the crater, so they had to take an indirect approach via a dirt track and then scramble up the rim. By the time they got to the top, the sun was setting and most of the great bowl was already in twilight. They stayed only a few minutes and Shoemaker saw nothing to contradict Gilbert's assessment. In a few years, though, he would. A landscape that was only then being brought into existence gave Shoemaker the analogy he needed to understand Meteor Crater.

By the mid-1950s the American uranium rush had uncovered deposits of the stuff large enough to meet any plausible need. Plutonium, though, was another matter. Natural plutonium exists in only the most tiny of quantities, on the order of a kilogram per planet or so. If you want to make bombs of plutonium – which has a number of advantages over the use of uranium – you first have to produce the stuff. This is normally done with the help of a nuclear reactor which breeds plutonium from uranium. However, in the mid-1950s a quicker alternative started to be discussed: simply wrapping nuclear weapons in now plentiful uranium and setting them off somewhere where their blasts would be contained. Neutrons given off in the explosion would turn some of the mantling uranium into plutonium, which could then be scraped up and put into more bombs.

A necessary part of this alarming scheme was finding places where you could set off nuclear bombs without the debris being scattered to kingdom come. One possibility was salt caverns; since Shoemaker's Princeton work dealt with salt structures in southern Utah, he was called on to look into the question. As a result, he saw what few other geologists had had the chance to see; a pair of craters at the Atomic Energy Commission's Nevada test site that had been formed by underground nuclear explosions, craters called Teapot Ess and Jangle U. The shapes of the craters, he learned, were determined by the interplay of various sets of shock waves, some heading out from the bomb, some bouncing back. The nuclear-testing fraternity had a keen understanding of shock waves; a correct calculation of the behaviour of the shock waves inside their bombs was the key to getting them to go off properly in the first place. So Shoemaker learned of the power of shock waves both from the physicists and from the craters themselves, their edges deformed by enormous pressures, the sand around them fused to glass.

When Shoemaker went back to Meteor Crater in 1957 it was not directly because of his new experience in matters nuclear (he advised the bomb makers, incidentally, that keeping explosions contained underground was not going to work). But that new experience changed the way he saw the crater; now it looked like the aftermath of something like a nuclear explosion, something formed by shock waves in a matter of seconds. He set about making a systematic study – a process which required that he make friends with its owners, the Barringer family. In the early decades of the twentieth century Daniel Barringer, a lawyer and mining engineer, spent a lot of time trying to convince people that the crater had been formed by an impact, and a lot of money trying to mine its floor for the huge and valuable lump of pure iron he expected to find there. His failure to convince the world that it was even worth looking for such iron was in part due to the fact that no less an authority than G. K. Gilbert had disagreed with the idea. Barringer's heirs had inherited both a largely useless crater and a dislike of geologists from the Survey. Shoemaker, though, became their friend and ally, in part because he was introduced to them by their old schoolmaster.

Shoemaker's work at the crater in the late 1950s both vindicated Daniel Barringer's insight and revealed his dream to have been illusory. Shoemaker found places where heat had turned sandstones into glass; he mapped inverted strata on the crater's rim where the lip had been folded back on itself just as the rim of Jangle U had. Most crucially, he and a colleague found that the sandstones in the crater contained coesite, a very dense mineral created when quartz is subjected to extreme pressures. Only transient shock waves of immense power could create such pressures on the scale required: coesite was frozen smoke from the impact's gun. Meteor Crater was indeed caused by an impact, as Barringer had thought. But the rebounding shock waves that formed the crater had completely exploded the incoming lump of iron he had hoped to profit from. As Gilbert's volumetric assessments had shown, there was no extraterrestrial motherlode beneath the floor.

While Shoemaker worked to forge this causal link between heavens and earth, a matching connection was being set up in the opposite direction; the first earthly objects were being sent beyond the planet. Exploration of the moon suddenly seemed a practical possibility and Shoemaker was keen that the USGS should grasp it – just as Gilbert would have been. The Survey was keen, too. It had expanded a lot during the search for uranium, and now that that search was over, and the Atomic Energy Commission had withdrawn funding, it was left with more geologists than it had money or jobs for. Shoemaker's astrogeological dreams might take up the slack – if funding could be found.

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