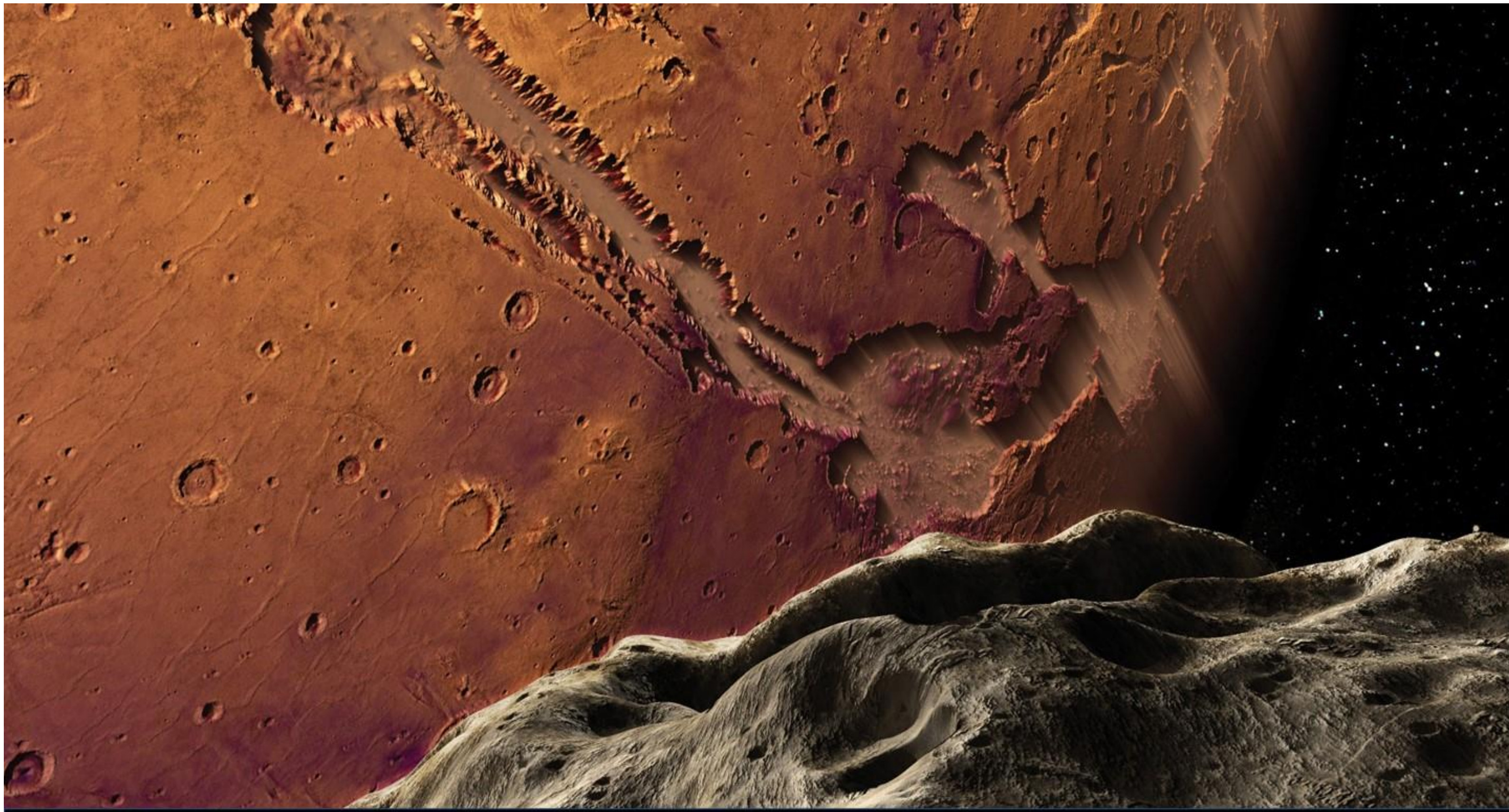

Stories of Mars

Visions of the Red Planet from Mars Society Australia

Stories from Colin Pain, Jon Clarke, Steven Hobbs, Shaun Moss, Trevor Rodwell and Robert Zubrin

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Mars Society Australia

Cover by Steven Hobbs

Front

Upper: Valles Marineris from Phobos (Steven Hobbs)

Lower: Comet with Opportunity looking on (Steven Hobbs)

Back

Upper: Curiosity view of the rim of Gale Crater (part of NASA image PIA22209).

Lower: Mars Globe (NASA image PIA23515)

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The Authors

Jonathan Clarke is a geologist, astrobiologist, and President of Mars Society Australia. He is an associate of the Australian Centre for Astrobiology, an instructor in astrobiology at Swinburne University in Melbourne, and holds an adjunct position at Amity University, Mumbai. Jonathan has published on Mars and Mars analogues in the areas of geology, astrobiology, Mars mission design and site selection. He has spent at total of six months in Mars analogue stations in Utah and the Arctic.

Steven Hobbs is an Adjunct Lecturer at University of New South Wales and actively researches Martian surface processes and deep space robotics.

Shaun Moss is a computer scientist who has contributed to the Mars community for over 20 years. He is the author of *The International Mars Research Station*.

Colin Pain, a retired geomorphologist who previously worked at Geoscience Australia, holds an honorary position at the University of Seville. He has published several papers on the landforms and regolith of Mars, and on Mars analogues.

Trevor Rodwell is an artist and writer. His lifelong interest in space led to his research in cultural cosmology at the University of Canberra. He writes and gives public talks on the subject.

Robert Zubrin, an astronautical engineer, is President of the Mars Society and author of the recently published *The Case for Space: How the Revolution in Spaceflight Opens up a Future of Limitless Possibility*.

Preface

The British political writer Percy Greg in 1880 penned Across the Zodiac , in which the narrator (in 1830 no less!) discovers a form of anti-gravity and builds a ship, the Astronaut, that will take him to Mars. The Mars in this tale is both habitable and inhabited by small humanoid aliens and features canals (Giovanni Schiaparelli had astounded the world with his reports of *canalli* in 1877). There is of course war, interplanetary romance, strange creatures and tragedy.

Since then Mars has focused the human imagination outward past the Moon's orbit to the next world and beyond. There imaginative journeys to (and sometimes from) the Moon, Mars, and beyond spurred many of the spaceflight pioneers who worked to turn romance into reality. Even as first the astronomers and then the mission scientists on actual Mars missions revealed the real Mars as a frozen, dry, windy, hypobaric wasteland, new visionaries worked out the challenges of travel to and living on the planet, progressing from expeditions to scientific outposts, then perhaps as a permanent isolated community, and eventually the possibility of terraforming Mars to be more habitable.

This book explores six separate but linked visions of Mars and humanity's possible future there by members of Mars Society Australia (MSA) and the President of the US Mars Society (USMS).

Steve Hobbs (MSA), planetary scientist, robotics engineer, and space artist, chronicles the exploration of Mars from the earliest observations to the latest missions. His sections closes with a retrospective on one of the strangest, and most frustrating of the early observers of Mars, who, despite being wrong in almost every way, inspired a whole generation of people to imagine, study, and devise means of exploring Mars.

Colin Plain (MSA), geomorphologist, soil scientist, and regolith geologist, describes the real Mars that that has emerged from robotic missions over the last 60 years. He reveals a planet of giant volcanoes and canyons, former river beds, impact craters, and permafrost. Its long and complex history is far stranger than anything we imagined and that we only just beginning to explore.

The next level in exploring Mars is sending people there. Astronaut explorers are more capable that robotic missions by many orders of magnitude, as well as bring capabilities impossible to achieve with robots. Shaun Moss (MSA) has thought extensively about Mars mission design and has published a book on the subject. In his section he reviews the history of crewed Mars mission designs and possibilities for the future.

The US Mars Society in 2001 pioneered the development of Mars analogue research stations and operations two such stations, one in the Canadian Arctic and one in Utah. Since then a number of other stations have been built by various organisations at different locations, more are in the planning stage. They provide locations for the field testing of equipment, human factors research, training, and above all experience in operational conduct and planning. Other lessons can be gained from polar stations, long duration spaceflight, underwater habitats, enclosure experiments (Mars 500), and artificial biospheres. My chapter summarises experience in Mars analogue habitats, drawing especially on my experience at the two Mars Society stations

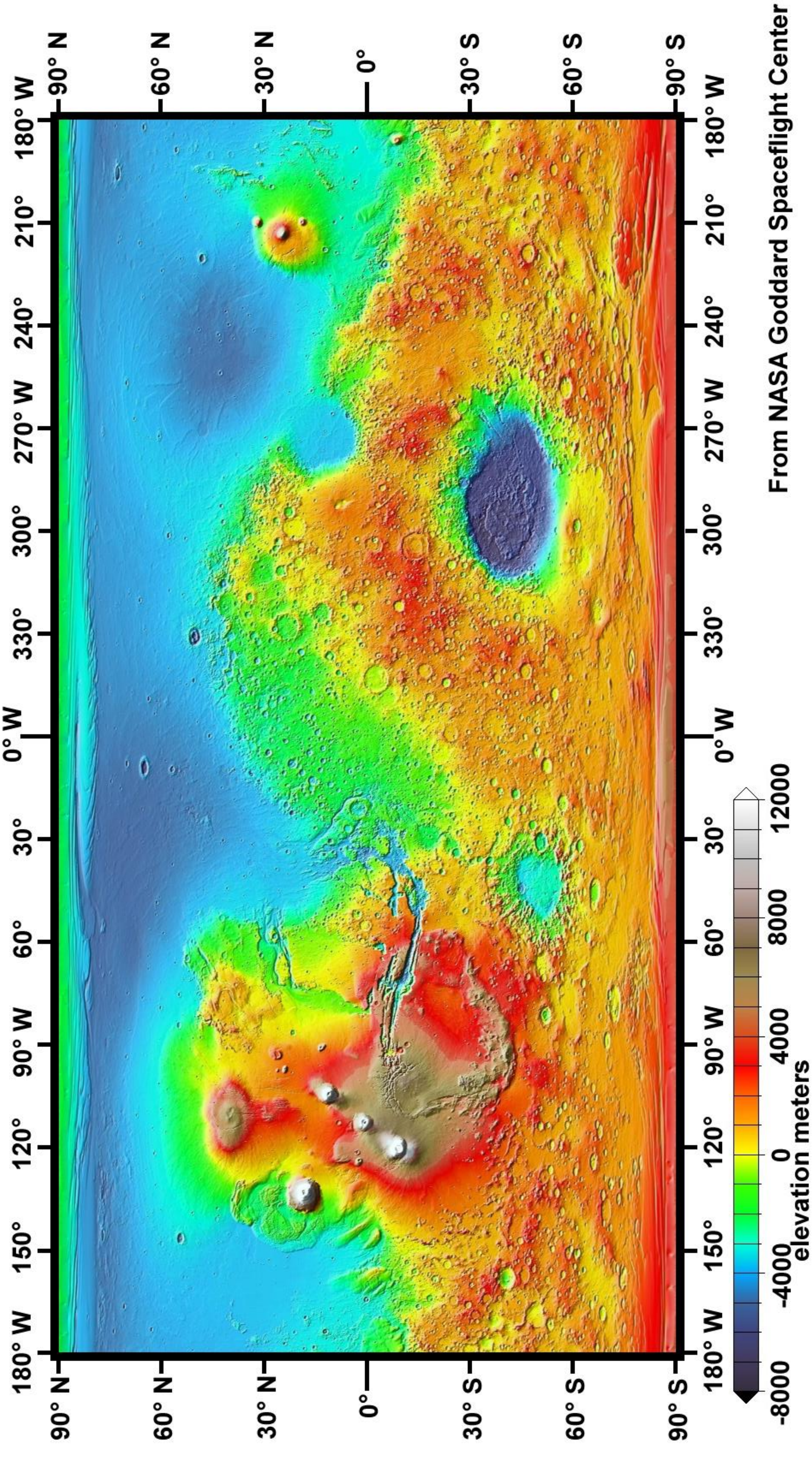
Trevor Rodwell (MSA) has contributed a chapter titled Eye to the Sky: An Overview of Culture and Imagination in the Human Engagement with Space. In it he explores the cultural dimension, seeing Mars exploration as part of the ongoing engagement by humanity with the universe around us.

The final chapter is by Robert Zubrin (USMS). Robert is the founder and president of the US Mars Society. He is perhaps best known for his work on the Mars Direct Mars mission proposal, a revolutionary new approach that transformed Mars mission design concepts for 30 years that still sets the benchmark for efficiency and capability. Robert focuses on the longer term implications of Mars exploration, an appropriate place to conclude this book. He examines how and why Mars should be settled to form a new human civilisation, and why we should.

Jonathan Clarke
President
Mars Society Australia

April 2020

Color-coded Elevations on Mars, MOLA Altimeter, MGS Mission



Mars: God of War and Emissaries from Earth

Steven Hobbs

To the ancients, it was an angry red star that brightened every two years to declare war and conflict on those mortals below. To the modern scientist, it is the most Earth-like planet in the known universe and possible abode for life outside our own world. Of all the planets in the solar system none has captured the human imagination, or as much attention as Mars. For millennia, humanity have been dreaming of fantastic beings on the Red Planet, and travelling there to find out. More spacecraft have been sent to Mars than any other planet, to the point that Mars has been continuously peopled by ground dwelling and orbital robots for over 20 years.

So why has Mars received all of this attention? There are a variety of reasons, many practical, some not so much. On a practical note Mars is one of 50 % of the planets in our solar system with a surface that can actually be landed on. Mars is also the second closest planet to Earth, being a mere 55 million km from Earth at closest approach. This equates to about a six month journey for spacecraft, meaning that researchers don't have to wait very long between launching a Mars mission and receiving results. This is in stark contrast to missions to the outer solar system, where years may pass in waiting for a spacecraft to arrive at its destination.

Another reason is that Mars is currently the most Earth-like planet that we know of in the known universe. Mars shares many features with our world, such as polar caps, volcanoes, sand dunes and a host of features that have been carved by liquid water. These latter features continue to excite planetary scientists and suggest Mars might have been habitable for life at some point in the past.

Mars of old

Even during pre-telescopic times the bright red star that shone in skies every 26 months attracted attention. Mars's blood-red colour was attributed to violence and conflict, and as such the Romans named Mars after their god of war. For thousands of years the presence of Mars was thought to dictate the rise and fall of power, and the fortunes of war. In 1877, England was involved in a bloody conflict with Russia. At this time astronomer Richard A. Proctor, who would later draw one of the first maps of Mars wrote:

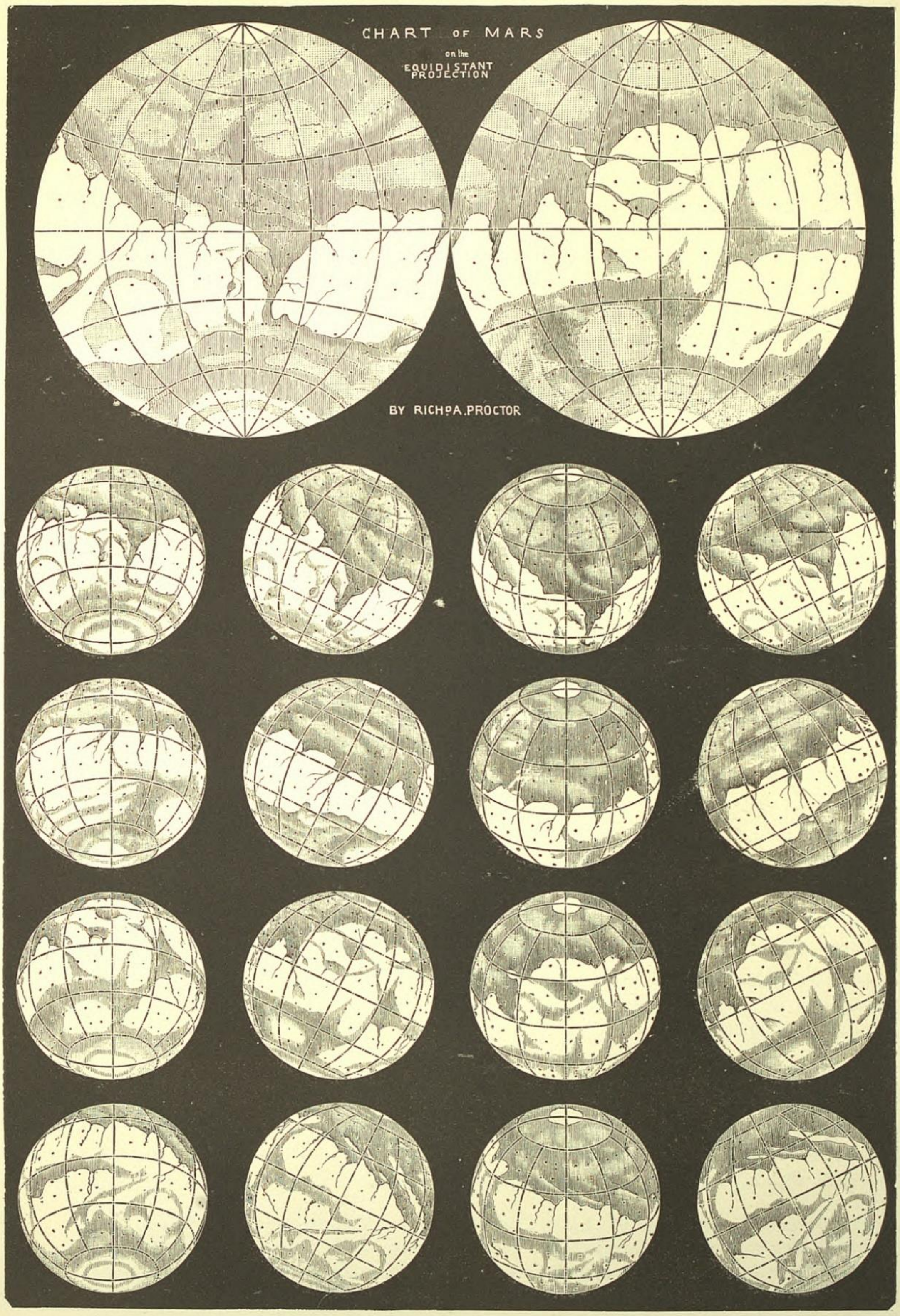
> *In the earlier part of the Crimean War, Mars shone in our midnight skies…if Mars were in truth the planet of war…if his influence poured from near at hand upon the nations of the earth…it might well be feared that the closing months of 1877 would bring desolation on many fair terrestrial fields.*

Conflict an interest over Mars wasn't just limited to war – its occasional backward motion across the night sky caused consternation to early astronomers. This contrary motion went against the classical thinking that Earth was the centre of the universe and all celestial objects, including the sun, Moon and stars, rotated around it on crystalline spheres The Martian motion, and proper functioning of the solar system would later be revolutionised with the discovery that all planets, including Earth, rotated around the Sun in the 16th Century. Mars would appear to move backward as the Earth caught up with it in its faster orbit around the Sun. This motion was also seen by Australian indigenous peoples as spirits going walkabout, stopping and changing direction.

Mars is small, only half the size of Earth, and only appeared as a fuzzy red disk in the great astronomer Galileo's telescope. The ability to resolve actual features on its surface had to wait almost 100 years later when Christian Huygens, with better instruments than Galileo, discovered a dark patch later called Syrtis Major. Later observations by Huygens and others indicated that Mars possessed ice-rich polar caps, and that its period of rotation was around 24 hours, very similar to Earth's. This was a period where society was moving away from the notion that Mars was a mysterious god that governed the lives of people on Earth but was instead being discovered as an equally mysterious world in its own right. During this period, astronomer's questions whether Mars, sharing similar rotation and polar caps to Earth, might also be teeming with life. What form might this life take? There was no way to know for sure but Mars remained a popular target for astronomers.

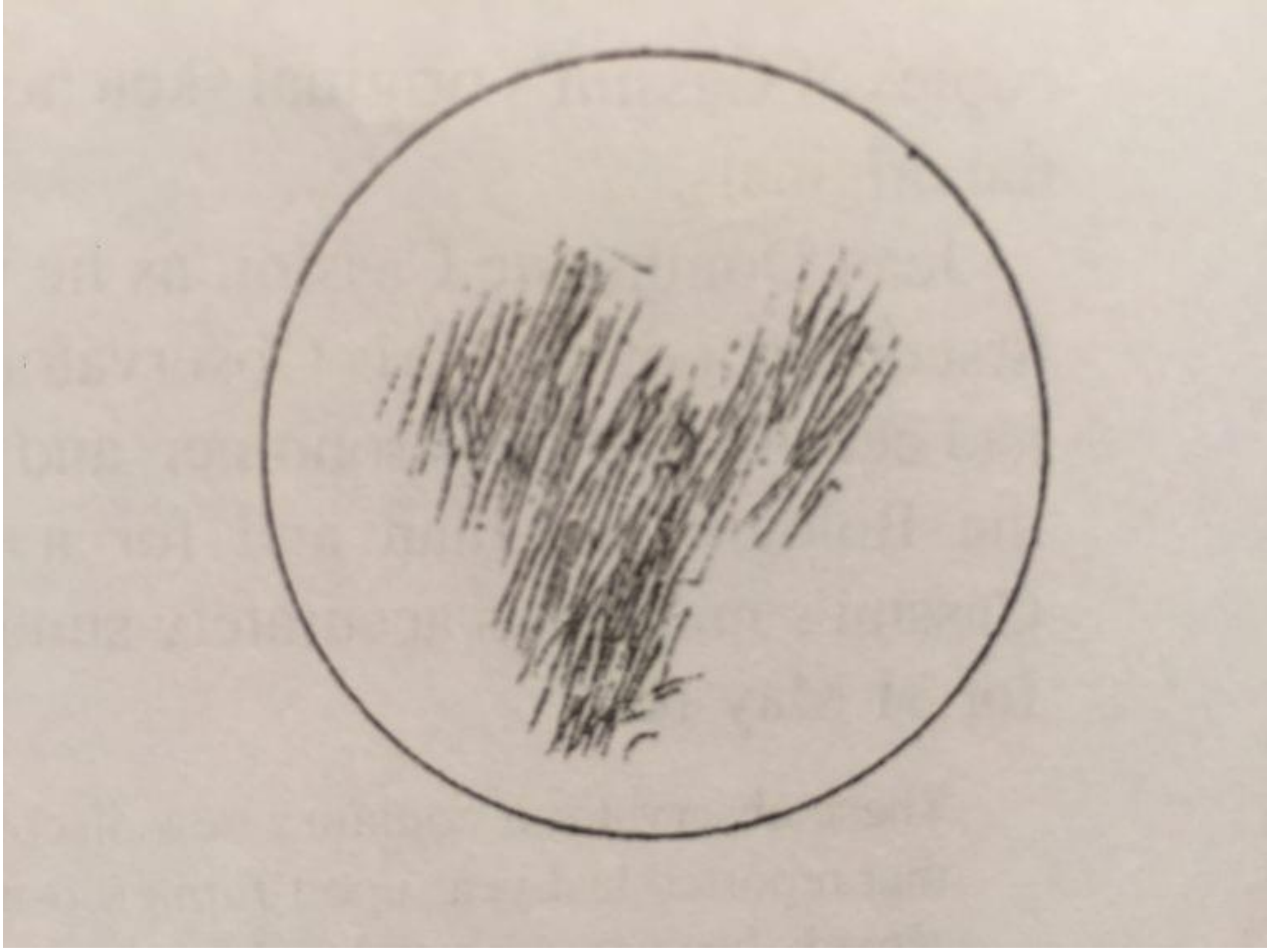
In 1877, an Italian astronomer named Giovalli Schiaparelli thought he saw thin, parallel lines on Mars and named these canali in Italian, translated to canals. This seemingly innocuous naming changed Mars exploration forever as a wealthy Bostonian textile businessman became fed up with the academia of the day and used part of his fortune to build an observatory in Flagstaff, Arizona. Dr Percival Lowell, peering through his own telescope near the turn of last century dubbed these lines 'canals' and suggested they were artificial in origin. He wrote of his conclusions in Mars and its Canals:

PLATE XXIV.



Map and sixteen projections of Mars made by combining drawings of the planet by Dawes, Green, Schiaparelli, and others.

From Richard Proctor 1870. Other Worlds than Ours. London. Public domain, downloaded from https://planetarymapping.wordpress.com/2016/01/29/proctors-mars-maps-1865-1892/



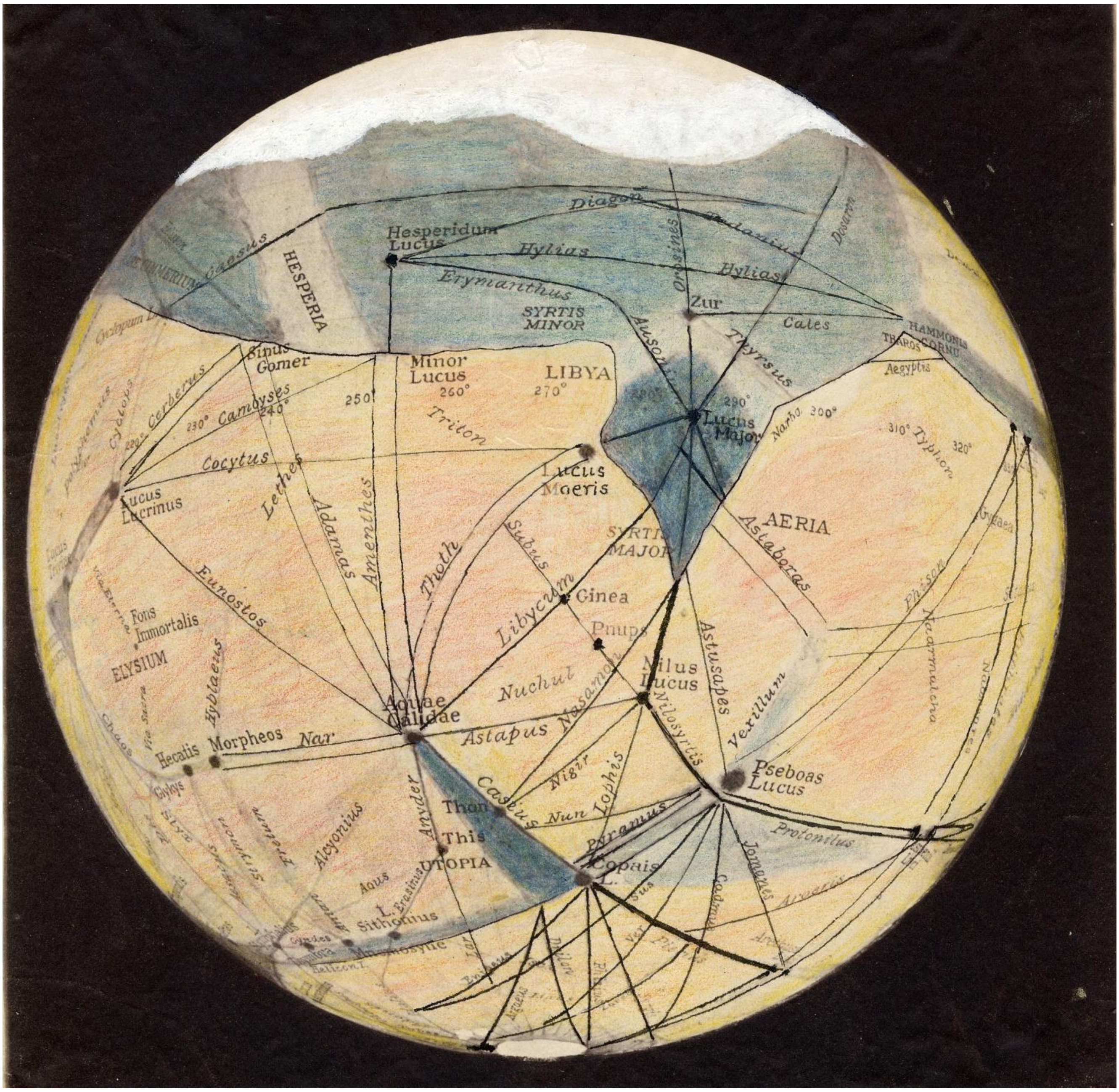
Sketch of Mars made by Christiaan Huygens, made on November 28, 1659. The dark patch in this sketch, first seen by Huygens and one of the most easily identified features on the surface of Mars, is now known as Syrtis Major Planum. In the nineteenth century, it was variously known as the Hourglass Sea (or Mer du Sablier), the Atlantic Canale and the Kaiser Sea. Image source: Flammarion, La Planète Mars, 1892.

That Mars is inhabited by beings of some sort or other we may consider as certain as it is uncertain what those beings may be. The theory of the existence of intelligent life on Mars may be likened to the atomic theory in chemistry in that in both we are led to the belief in units which we are alike unable to define. Both theories explain the facts in their respective fields and are the only theories that do, while as to what an atom may resemble we know as little as what a Martian may be like. But the behaviour of chemic compounds points to the existence of atoms too small for us to see, and in the same way the aspect and behaviour of the Martian markings implies the action of agents too far away to be made out.

> *But though in neither case can we tell anything of the Bodily form of its unit, we can in both predicate a good deal about their workings. Apart from the general fact of intelligence implied by the geometric character of their constructions, is the evidence as to its degree afforded by the cosmopolitan extent of the action. Girdling their globe and stretching from pole, to pole, the Martian canal system not only embraces their whole world, but is an organized entity. Each canal joins another, which in turn connects with a third, and so on over the entire surface of the planet.*

The light and dark patches on the disk of Mars, swimming in the eternal turbulent atmosphere of Earth fuelled speculations of a planet familiar to our own. In the late 1800's Irish astronomer Robert S. Ball, who would deliver over 2500 astronomy lectures to laymen audiences, wrote:

> *It seems hard to decline the suggestion that the marks on the planet may really correspond to the divisions of land and water on that globe. There are circumstances which strongly suggest that water may also be present."*



Colour Drawing of Mars by Percival Lowell, made in 1905. Downloaded from https://azmemory.azlibrary.gov/digital/collection/loaselect/id/7/

Dr Percival Lowell went one step further:

> *"In their color, blue-green, the dark areas exactly typify the distant look of our own forests; whereas we are not at all sure that seas would. From color alone we are more justified in deeming them vegetal than marine… We conclude, therefore, that the blue-green areas of Mars are not seas, but areas of vegetation."*

Dozens of newspaper and magazine articles, as well as science fiction and fantasy writers, populated Mars with fantastic aliens that stretched the limit of human imagination. The Martian civilization struggling to survive against a dying world was thought, through education, to counterbalance the selfish expansionism of humanity. Conversely such an advanced race could look hungrily at the plentiful Earth with eyes of conquest: a story H.G. Wells presented with "War of the Worlds." More than one apprehensive gaze was cast to the red planet to ensure such an old civilisation didn't decide Earth was a better home and come visiting.

Many in Europe took a more conservative view. Just prior to Schiaparelli's "discovery" of the Martian canals Richard A. Proctor had written:

> *...the unchanging colour of the land regions implies they are naked and sterile…we must accept the conclusion that the land surface is arid desert.*

In 1895 Robert S. Ball, lecturing school students about the Martian atmosphere, remarked:

> *As to the composition of this atmosphere we know nothing. For anything we can tell it might be a gas so poisonous that a single inspiration might be fatal to us; or if it contained oxygen in a much larger portion than our air does, it might be fatal from the mere excitement to our circulation which an over-supply of stimulant could produce. I do not think it the least likely that our existence could be supported on Mars, even if we could get there. We also require certain conditions of climate, which would probably be all totally different from those we should find on Mars."*

Alfred Russell Wallace, co-evolutionist with Charles Darwin was more critical of Lowell's theories:

> *Not only is Mars not inhabited by intelligent beings, but it is uninhabitable.*

This was treated with scorn by Lowell, particularly when Wallace had almost certainly never studied Mars through a telescope. For the next twenty years a 'Mars fever' gripped the educated population and the planet was studied as never before. In fact a radio broadcast of H.G. Wells War of the Worlds in 1938 caused panic in some quarters when it was mistaken for a real news bulletin.

Through the 20th Century, as instruments and methods became more sophisticated, the idea of a drier, colder Mars took hold. Attempts to confirm Martian canals seen by Lowell were criticised by, among others, the highly reputed observer of Mars, Eugene Antoniadi in Europe:

> *Nobody has ever seen a true canal on Mars, and thus the more or less rectilinear canals of Schiaparelli, single or double, do not exist either as canals or as geometrical lines; but they have a basis in reality, since all are situated either on a continuously spotted irregular track, a rugged grey border, or an isolated and complex patch. Indeed, the whole of Mars presents this infinitely irregular structure.*

Jon Clarke, president of Mars Society Australia said:

> *Prior to Mariner 4, the first spacecraft sent to Mars, what was correctly known about Mars amounted to a page or two. This would have included basic facts like the planet's diameter, albedo, orbit, rotation, inclination, density, gravity, and little else. Similar basic details about the moons of Mars were also known. We thought we knew a lot more. We thought that we knew of systematic seasonal changes in colour and albedo, things like the "wave of darkening" and "blue clearing" were confidently described, if not understood. The dark areas were thought to represent significant physiographic features, even if their nature was debated. The atmosphere was thought to contain a significant about of inert gas such as nitrogen. The polar caps were thought to be frost. These known "facts" were all wrong. Then there were features such as canals and surface vegetation that many (not all) thought of as real that proved to be non-existent. Furthermore discussion of these ideas actually hampered understanding of Mars.*

The dark patches on Mars, long believed to be evidence of vegetation, came under intense scrutiny. The development of more sensitive equipment enabled scientific analysis of these "green patches". French-American astronomer Gerard de Vaucouleurs used the latest lead fulminate technology and painstakingly studied one of the dark patches:

> *The nature of the dark areas is still unknown. It is only reasonably certain that they cannot contain chlorophyll plants similar to the higher forms of vegetal life on Earth."*

In the US, the legacy of Lowell cast a long shadow, his treatise on Martian canals influencing generations of Mars investigators. Both Goddard, inventor of the liquid fuelled rocket and Dr Verner Von Braun, father of America's space program were inspired by the Red Planet. Lowell's vision also spurred NASA to build Mariner 4, the first spacecraft to successfully visit Mars. Dan McGleese, former JPL chief scientist:

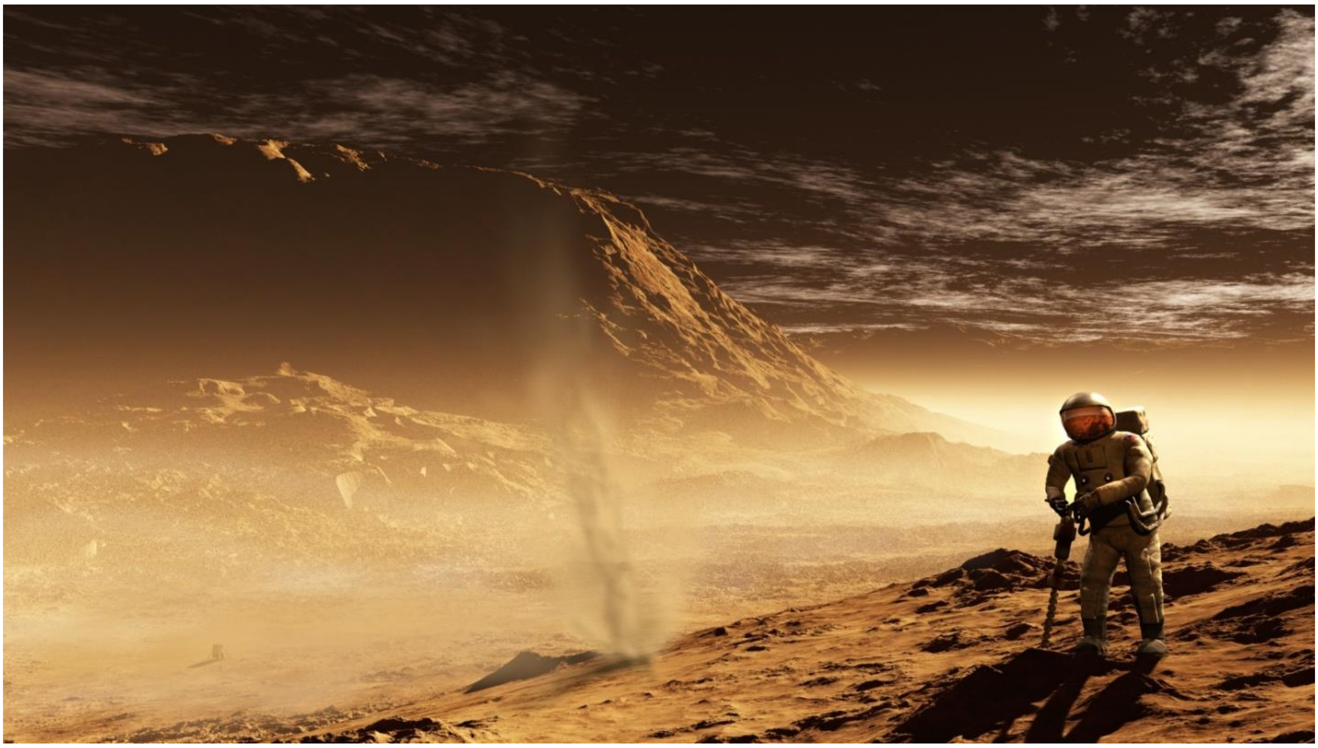
> *…Percival Lowell and his intent to describe what it is that he was seeing in his telescope in Arizona just took hold of the popular press. He talked about the possibility that there might be intelligent life on the planet and that persisted for such a long time that to me it was such a great story. The people who thought there were canals said "alright perhaps the beings on the surface are trying to move water from the polar caps which we could see from our telescopes down to the dry equatorial regions". This idea was present even as we sent the first Mariner spacecraft there. In fact I have in my office a globe painted by an JPL astronomer and it shows the linear lines, it shows greens and darker colours and these were all laid down on a sphere just as the spacecraft was travelling to the planet. It was really an incredible contrast with what the Mariner spacecraft actually saw."*

So far Mars remains the most Earth-like planet that can actually be studied close-up. As a result, the Red Planet has inspired more than its fair share of artwork. In fact, we have imagined our way to Mars through artwork, books, film and television more than any other place in the Solar System. Much of this early art, although wrong, inspired the space age as we know it today. One of these pioneers is David A. Hardy, who being the longest established living space artist, has lived right through the inception and advancement of the space age. The painting on the top left is one of Dave Hardy's early visualisations of Mars before the start of the space age. David A. Hardy: When I became interested in astronomy, around 1950, it was generally accepted that because Mars has white polar caps, and dark areas (often thought to be greenish, probably because of contrast with the red surface) appear to spread in a 'wave of darkening' in the Martian spring, there must be vegetation. The most extreme version of this, proposed by Percival Lowell, was that there are dark lines which appear to connect the various areas. These had been observed by the Italian astronomer Schiaparelli, who called them 'canali', meaning 'channels', but Lowell interpreted this as 'canals'. This inevitably led to a belief in intelligent Martians, attempting to save their drying and dying planet by guiding water from the melting poles. (H.G. Wells of course also seized upon this idea for his 'War of the Worlds.').

We now know that the observed colour changes are due to no more than dust being moved around by the very strong winds, causing planet-wide dust storms which reveal and obscure lighter desert and darker rocks.

Scientific understanding of the "real Mars" was certainly not smooth, to and froing between a desert with sparse vegetation and a dead Moon-like world. We know a lot more about Mars today. Over the decades increasingly sophisticated robots, such as Curiosity, have revealed a fascinating, and very diverse planet (top right). Yet even with gigabytes of scientific data, Mars still continues to inspire art.

Mars is a forbidding and inhospitable place, but this may not have always been so. There are signs of ancient oceans on Mars, and the red planet once had a denser atmosphere than it does today. We once believed that modern Mars was a totally lifeless desert, but we now know that it has periods where briny water (recurring slope lineae) runs down channels in its mountains. Now, scientists are actively on the hunt for signs of life, and young astronauts are training for what they hope will be our first manned mission to Mars! My art is inspired by everything we're learning about Mars, and its potential as humanity's next home.



An astronaut drills for samples in Gale Crater, thought to have hosted an ancient lake (Digital art by Steven Hobbs).

When Dreaming Ends

One successful space mission actually jeopardized future space exploration. Mariner 4, later called the 'Great Disappointment', almost killed Mars exploration overnight. In 1964, US Mariner 2, the first successful interplanetary flyby, was just two years old. Russia's first attempts had failed and it was America's turn to reveal Mars. Mariner's 3 and 4 had a 0.02 megapixel digital camera mounted outside the bus and would reveal the true Mars to the world. Although Mariner 3 never left Earth orbit, Mariner 4 was launched successfully on 28 November, 1964.

In the months preceding the encounter, Mariner 4 was tracked by NASA's Deep Space Network stations in California, South Africa and Australia. A disturbing message from Australia was received by the Mariner tracking team during transit: "Sorry, we can't track the spacecraft … Galahs have eaten the radome".

Despite this, Mariner 4 arrived on schedule at Mars on 15 July, 1965. Such was the excitement of the imaging team that they didn't wait for the completion of the first image and set about developing what they had. Jack James and his assistant hand coloured graph paper with crayons according to image brightness values received on a long printout. When completed, the first Mariner 4 image didn't reveal much about Mars. The planets hazy edge, lit by a full sun that hid most of the surface features, was all they had. Lowell's canals and primitive vegetation still seemed possible, but the world would have to wait for more data.

Hand coloured graph paper with crayons according to image brightness values received on a long printout, the first Mariner 4 image didn't reveal much about Mars.

The seventh image finally showed meaningful surface features. There was no sign of Martian canals or vegetation regions. In their place were craters. Active planets such as Earth have volcanoes and weather to destroy old craters, but Mars seemed to be as dead as the Moon.

Former JPL Chief Scientist Dan McGleese was in charge of many Mars missions between 1994 and 2006. He explained: "There were two things that happened at the same time. One of them [was that] people thought it looked more like the moon and therefore quite disappointing. There weren't vast fields of organisms on the surface that might give a changing seasonal colour to the planet. …At the same time of those discoveries from the spacecraft ground-based astronomers were realizing that they had the atmosphere completely wrong. They had [originally] concluded from the spectra that they took that Mars had an atmosphere that was very dense like the Earths. …In fact it's mostly CO_2 and … there was very little of it. These two things: the pictures and the knowledge that the atmosphere was very thin didn't have a lot of content of water really led people to feel a disappointment that this was probably not a living world."

Mariners 6 and 7

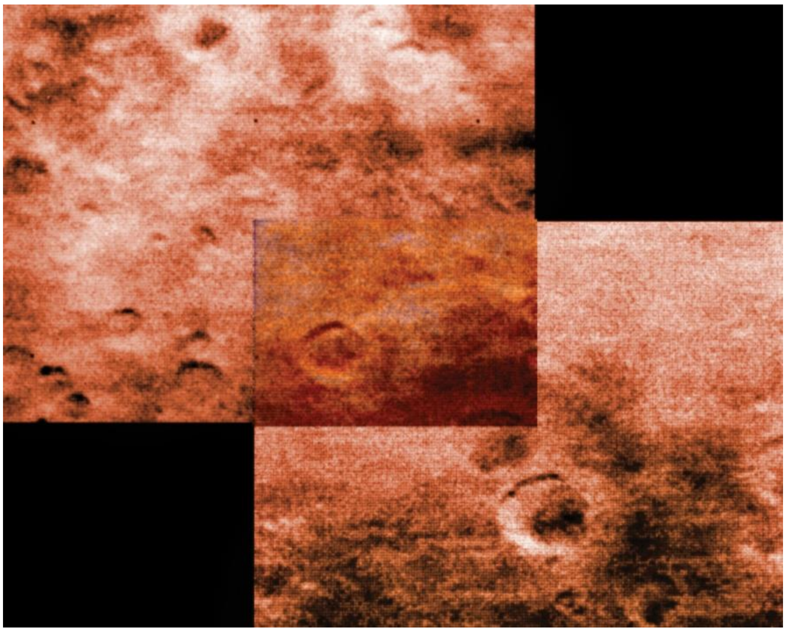
Despite US Congress's reluctance to fund more missions to Mars the dogged determination of Mars advocates, and perhaps the vestiges of the Lowellian romance, led to two more Mars missions being built. Mariners 6 and 7 were far more sophisticated than their predecessor. Arriving in 1969 they flew past Mars and returned 1100 images, covering 20 percent of the Martian surface. The higher resolution images merely showed the Martian craters in better detail. No trace of any biological, or even recent geological activity could be seen. Mars looked to be a cold, inert world, merely a larger and redder version of our moon. In fact Mars seemed even less interesting geologically than the moon. Professor Robert Leighton, then in charge of the Mariner television experiments remarked in 1970:

> *"Everything in the Mariner pictures indicates very gentle slopes on Mars. There are no mountain ranges, no great faults, no extensive volcanic fields, in fact no evidence of volcanic activity. You could stand in one crater on Mars and never know it – even one that appears sharp and clear in the pictures."*

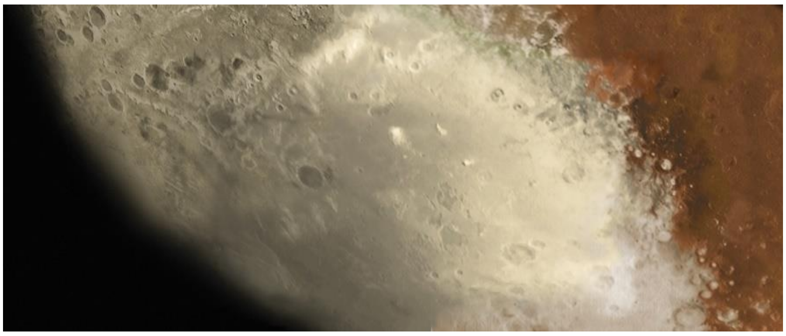
In 1971, Mars approached Earth closer than it had done since 1924. NASA designed Mariner 8 and its twin, Mariner 9 to not just fly past a planet but to orbit it. These latest Mariners were also equipped with colour cameras. For the first time Mars would be seen in close up and in colour. Mariner 8 was launched on May 8, 1971, but made a short, spectacular trip into the Atlantic Ocean. Mariner 9 entered Martian orbit on November 14.

A dust storm, more powerful than had ever been seen before had enveloped the planet and hid the ground from view. It was this storm that almost

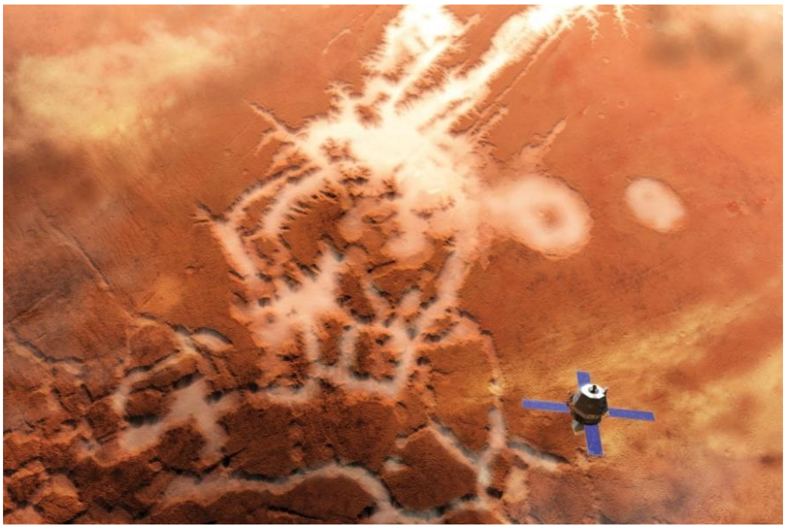
Early images of the Martian surface



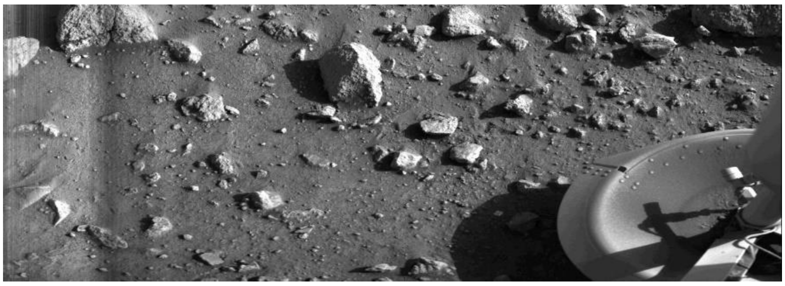
Colourised Mariner 4 image from 1965 showing a strongly cratered surface. Source: NASA.



Colourised Mariner 7 mosaic of the Martian south pole. Source: NASA.



Mariner 9 over Mars showing part of Valles Marineris (named after Mariner 9).
Source: NASA



The first photograph taken on the surface of Mars, by Viking lander 2 on 20 July 1976. Image PIA00381 NASA/JPL

certainly destroyed two Soviet Mars landers, arriving at Mars that year. As the storm subsided, the first features to be seen by Mariner 9 were four dark spots, thrusting up above the dust. The spots revealed themselves as the four largest volcanos in the solar system. The largest, Olympus Mons, was so large that a theoretical Martian traveller standing on its slope would never see it completely. The planet's curvature would forever hide the rest of the volcano from view. The last of the dust storm cleared and scientists found another surprise of gigantic proportions. Cutting Mars in half lay the largest canyon system in the solar system. Seven kilometres deep in places, it could easily have swallowed up Earth's Grand Canyon several times. Massive outflow channels, braided stream beds and tributaries were photographed, suggesting Mars was once inundated with water. Although Lowell's canals were nowhere to be seen, Mars was revealing itself to be a mysterious, exotic and at some point in history to be a watery place. The infamous craters, almost the death knell of Mars exploration were found to be restricted to the Southern Hemisphere.

Jon Clarke, Mars Society Australia President:

> *The early Mars missions were as much a hindrance as a help. Mariners 4 and, 6, and 7 imaged one to ten percent of the planet in some detail. They showed the atmosphere was very thin and the surface had many craters. However the areas imaged at the highest resolution missed all of the important features such as the giant volcanoes, polar caps, Valles Marineris and outflow valleys. So Mars was incorrectly seen as Moon-like with minor ground ice collapse and a trace of atmosphere, moving dust round and forming seasonal frost. This mis-comprehension probably led to the abandoning of the manned Mars program and the Mars Voyager unmanned missions.*

Despite the cutbacks, for the first time since 1964 Mars seemed more hospitable to life as well as more geologically active and interesting. Mars had earned a closer look and already a mission was on the drawing board to bring back even more data and find out if life existed on Mars. The mission would be called Viking.

Landing on Mars

Viking was designed from the successful Mariner series spacecraft that had already explored Venus and Mars. A conjoined spacecraft was proposed, containing an orbiter that would circle Mars and a lander that would touch down on the surface. The Viking landers were built to contain experiments to monitor the Martian environment, send back pictures and test for life. Nuclear batteries would provide the 50 Watts of power required to run the lander. Problems in the initial design process cropped up from the start. Dr Tobias Owen, involved in the Viking project at the time explains one problem.

> *At that time ... everyone thought the atmospheric surface pressure on Mars was around 83 mb. By 1967, ground-based spectroscopy had demonstrated clearly that the surface pressure was around 7.5 mb, too low for a parachute descent.*

There was no way a parachute would be able to slow a lander down enough to survive in Mars' tenuous air. Soft landing rockets would be required to help slow the spacecraft enough to survive. The never before designed camera systems for the landers, presented issues. Their power usage and weight would have to be low enough for the lander constraints, yet would have to be able to survive massive temperature swings, near vacuum conditions and ultra-fine dust. Getting permission to take the cameras outside the laboratory proved surprisingly difficult, as some team leaders didn't want their expensive and irreplaceable equipment to leave their safe clean-rooms. The excursion team had wondered how they could build a camera that could survive a descent to Mars when they couldn't take it a short drive down the road on Earth.

By July 20, 1976 after a journey of over half a billion kilometers Viking had safely entered Martian orbit but after weeks of searching had found nowhere safe to land. The landing plains, selected months earlier from Mariner 9 images, proved to be full of probe destroying geology. The celebratory July 4 touchdown was postponed as 800 new images were pored over in an attempt to find a safer resting place.

Finally, with the Viking lander team near the end of their tether, the project manager had made a decision. The jeep size lander, protected in a saucer like aeroshell departed forever from its orbiter to begin its 30 minute journey to the surface. Back in the control room, what little nervous conversation there had been died down to a cemetery-like silence. All knew this was the most hazardous part of the mission. Four Russian landing attempts had failed. Richard Bender, chief landing engineer called out the landing events as they happened:

> *"400,000 feet…74,000 feet…2,600 feet…Touch-down! We have touchdown!"*

All out once cheers and applause broke out as the news of a successful landing sank in. Viking 1 was down.

Finally, Viking 1 had landed and was taking the first picture within seconds of landing in order to safeguard against any catastrophic failure. First soil, then rocks and finally the Viking lander footpad resting safely on Mars was revealed, the whole process taking twenty minutes. The second image taken immediately afterwards was even more magical. Planned to be a full panorama Viking revealed a surprisingly Earthlike desert scape of sand, rocks and dunes. Tim Mutch, head of the lander imaging team couldn't contain himself.

> *"It's just a beautiful collection of boulders, a geologists delight!"*

The cameras were proving to work better on Mars than they ever had on earth. A somber revelation was later to give pause to the Viking 1 team on how lucky they had been. A three meter long one meter high Martian boulder lay just eight meters away from Viking's camera, affectionately dubbed 'Big Joe'. Viking 1 missed becoming a billion dollar space wreck by eight meters.

On schedule, the first colour image was received at JPL. Almost immediately a problem became apparent. No one actually knew what the true colours of Mars were supposed to be. Former Deep Space Tracker John Saxon:

> *On Viking. How do you get the colours right? They thought they had the answer. They put a colour chart that the camera could look at and they'd know. But what they didn't think of properly was that the light that was falling on the colour chart was not sunlight as we see it. But that is was going through [the Martian] atmosphere which was different.*

Scientists had been expecting an almost black sky caused by the ultra-thin air with just a faint tinge of blue near the horizon. Instead what they received was a bright reddish glow bathing both ground and sky alike. Not believing the results and fighting an eight hour deadline the image was hurriedly reprocessed to show a blue sky and grey rocks, a supposedly more logical scene.

The press had a field day, comparing the earthlike colours of the scene with rocky deserts on Earth. However the blue sky lasted less than a week. Further data supported the presence of a red sky. Somewhat sheepishly a reprocessed version of the image showing the true salmon pink Martian sky was released to the press. The imaging team was rather nonplussed when asked by a reporter whether the Martian sky would turn green in the next release.

What no one had counted on were the tons of finely grained dust particles suspended in the Martian atmosphere, making the sky much brighter than anyone had predicted.

The images poured back to Earth by the hundreds, the Viking team struggling to keep up. Dr Tobias Owen, involved in the Viking project describes a typical day in the life of the Viking team during this time.

> *"Long hours at JPL, supplemented by homework to analyse the data as they came in, and plan for next series of experiments, listen to reports from other teams, endless discussions of all these exciting data! Now and then a press conference [was held] when we tried to convey both our excitement and the new knowledge we were acquiring."*

Viking 2 entered Martian orbit eight weeks after its twin and as with its predecessor, an exhaustive search was undertaken to find a safe landing site. On September 3, after some heart stopping moments when Viking's scheduled landing time came and went, flight controllers detected Viking 2's signal and the control room exploded in shouts and cheers.

Both Viking landers returned multitudes of stunning Martian panoramas, and reported on the intensely cold, dry Martian environments. Soon, attention turned to the Viking biology experiments to determine what, if any life could survive on the red planet.

Squeezed into one cubic foot of space within each Viking lander were three experiments that would normally fill a terrestrial laboratory room. The Pyrolytic Release (PR), Gas Exchange (GX) and Labelled Release (LR) experiments would moisten, feed, cook and fry Martian soil in the hope of detecting microbial activity. Following this analysis a final, fourth experiment would try to detect any organic compounds to clinch the presence of life on Mars.

The results of two of the tests would later become so controversial that debate over the Viking tests would rage for decades, and lead to the ostracizing of the LR experiment designer, Dr Gil Levin. Levin had developed the LR experiment during his days as a public health engineer as a way of testing water for human consumption. Eight days following Viking 1's successful landing the command was given for Viking's soil scoop to dig a sample of Martian soil and deliver it to the biology instrument for processing. The first tests delivered promising results though the researchers were cautious, citing the possibility of exotic chemical reactions as opposed to the presence of living microbes. It was Gill Levin's LR experiment that would capture the media's attention:

> *At Viking's two landing sites, 4,000 miles apart, my experiment, the Labelled Release (LR) experiment got results that satisfied the criteria for life established before the mission. I and my indispensible co-experimenter, Dr. Patricia A. Straat, were very excited, but we were cautioned to await the results of the Viking Molecular Analysis Instrument (GCMS) that was to identify the organic matter everyone knew had to be on Mars.*

So astounding were the LR results that a printout of the experiment data was solemnly signed by the team. The ramifications of the results were such that a press conference was held even before the results of the GCMS experiment had come in. Before long, the world was being told by the media that life on Mars was almost a certainty. Even as the press releases went out doubts from the biology team were increasing. The presence of oxidizing chemicals in the Martian soil could account for the positive reactions in all of the biology experiments run so far. Scientists looked to the GCMS to resolve the life issue once and for all. If it could detect carbon based compounds in the Martian soil then the case for life on Mars would be strengthened. Gil Levin explains what happened next:

> *The GCMS failed (and I use this word meaningfully!) to find any organic matter. NASA and its coterie of scientists immediately opted to believe the GCMS, and said "no organic matter, no life," and has pretty much maintained that position ever since.*

No organic compounds could be found by the GCMS in the Martian soil by either lander, even despite Viking 2 shoving aside a rock to retrieve soil protected from direct sunlight. Tobias Owen summed up the final verdict:

> *Viking showed that the surface materials on Mars were even more highly oxidized than we had thought: not only was there no indication of biological activity, there was no evidence for the presence of organic compounds.*

As far as NASA was concerned, Mars was a sterile desert. Centuries of speculation of life on Mars had suddenly ended, and dissenters from this view, such as Gil Levin, were largely ignored.

Dr Dan McGleese:

> *I think the consensus in the scientific community to today is that Viking did not find organics, that the surface is very, very pristine, that there are organics that you can find in the interior of rocks but that's not what's been seen by Viking. And there was so much press and to some extent science hype about the possibility that it would find life that there was a huge disappointment and that disappointment changed the course of Mars exploration so that we did not have another spacecraft go to the planet for two decades. Mars was basically written off as an interesting place to visit with our robots. The "life" thing had so tainted the expectations about why you would be interested in Mars that nobody at NASA wanted to talk to us because the "L" word would come up and they'd say 'well we know it's a dead world and we're not going to go back.' …Really the impact of Viking as it closed our eyes to Mars as an interesting place.*

Roving Mars

Following the success of Viking Mars would not be landed on again for 20 years. Throughout this period, one of the regrets of the Viking team was not being able to move the lander once it was on the surface. To truly explore a planetary surface, the landing craft would need to be mobile, with the ability of negotiating terrain to reach areas of interest. A rover like vehicle would be ably suited to this task.

The result of this thinking was a small roving vehicle about the size of a microwave oven as part of a novel lander mission designed with a budget ten percent of that of the Viking missions that preceded it. Sojourner, as the rover was later named, was made possible through a combination of technological advancement, an engineer playing around in his garage and by a borderline hoarder. Firstly, computers had taken off as a "thing", meaning that the central processing unit required to control a small rover could fit in a lunchbox as opposed to a suitcase. Secondly, Don Bickler, while playing around with metal struts in his garage, devised the novel rocker bogie suspension system that would be used on all future Mars rovers. Finally, Big Blue, a monster rover left over from the Apollo days was covertly moved between storage sheds to save it from disposal in case it would be "useful" one day. On the lander side, the design costs were saved by deciding not to carefully descend via expensive rockets, but rather smack into the planet using airbags and bouncing to a soft landing.

Never before had a lander mission been designed, built and tested for such a small sum of money. Top end, custom designed equipment was dropped for off-the shelf solutions, while the end goals of the Pathfinder mission were pared down to the bare essentials: land on Mars in one piece, take at least one colour panoramic photograph, deploy the

Sojourner rover. Finally, after years of last minute testing and fixes, on July 4, 1997, the Deep Space Network station in Spain sent a message to the mission control room: "I see a weak signal…" Pathfinder was on the Ares Vallis flood plain of Mars. Over the next hour and a half Pathfinder deflated and retracted its airbags and prepared to deploy the little Sojourner rover on the Martian surface the next day. As Sojourner raised itself up and gingerly rolled off its platform until all wheels were coated red with Martian dust, the rover team realized that for the first time in history a mobile vehicle was operating on Mars. Sojourner helped Pathfinder capture the imagination of the public once again. Pathfinder was the first planetary landing a generation born after the last manned Moon landings had seen and there was a new tool to keep up to date: the internet. Mission scientist Matt Golombek explains:

> *This was one of the first global internet events, with interest peaking on Monday (when folks got back to work and their computers). A total of about 566 million Internet "hits" were registered during the first month of the mission, with 47 million "hits" on July 8th alone, making the Pathfinder landing by far the largest Internet event in history at the time.*

Sojourner investigates a rock named "Yogi Bear" in 1997 (NASA/JPL-Caltech)

Images from the mission were being released to the World Wide Web almost immediately, allowing people at home to view the explorations of the Sojourner rover for themselves. In 1997, Pathfinder began a process of imagery dissemination to the internet that has continued for every JPL mission to this day. It wasn't until Princess Diana died later that year that Pathfinder's internet hit record was broken. Although Pathfinder was designed to last 30 days, and Sojourner just a week, both machines operated for nearly three months. During that time Pathfinder mission had returned over 17,000 images and Sojourner had traversed over 100 meters of terrain, sampling a number of rocks in the process. Data received from the dynamic duo hinted that the Pathfinder landing site had once been more Earthlike, and had been subjected to torrential flooding by water at an early time in Martian history. By the time Pathfinder fell silent months later; the mission had exceeded all expectations and ushered in NASA's modern plans for Mars exploration.

Pathfinder, along with Mars Global Surveyor, another successful low-cost Mars mission promised a virtual gravy train of cheap to design and cheap to build missions that would turn Mars inside out. Unfortunately in 1999 the gravy train derailed. Two back-to-back Mars missions failed, mainly because not enough money had been spent in testing. First, a faulty imperial to metric conversion oversight sent Mars Climate Orbiter to burn up in the Martian atmosphere. Next, a gravity switch installed upside-down caused Mars Polar lander to shut off its descent engines early, splattering it so well that its remains have yet to be found.

Dan McGleese:

> *… I can remember a very senior committee getting ready for the Mars Polar Lander sitting and evaluating what had gone wrong with the Mars Climate Orbiter and they said "we are the best and brightest that the nation has, we will not fail to land." And so when it did fail everyone was just devastated and totally embarrassed.*

Two years later the US suffered a devastating terrorist attack that shook its society to the core and overshadowed the successful insertion of Mars Odyssey into Martian orbit. The tragic loss of the Space Shuttle Columbia in 2003 led many to question whether NASA, could be trusted with continued space exploration. Given these events, the pressure on Steve Squyres, for his Mars Exploration Rovers (MER) Spirit and Opportunity to land safely on Mars and perform was overwhelming. As it was, MER was the successful contender of the many proposals that Squyres had submitted over 16 years, and NASA had allowed not one but two rovers to be built. Spirit and Opportunity, their names given in a student contest, were massive upgrades to Sojourner, the last rover sent to Mars. The golf cart size robot geologists contained all the engineering and instruments for them to leave their landing site forever and explore up to a football field worth of Mars a day.

"The instrumentation on-board these rovers, combined with their great mobility, will offer a totally new view of Mars", said Dr Ed Weiler who helped administer the mission. Their design, including the cameras, promised offer the most human-like view of Mars ever achieved, while a custom made arm complete with rock abrasion tool

would provide *"a microscopic view inside rocks for the first time."*

Dan McGleese:

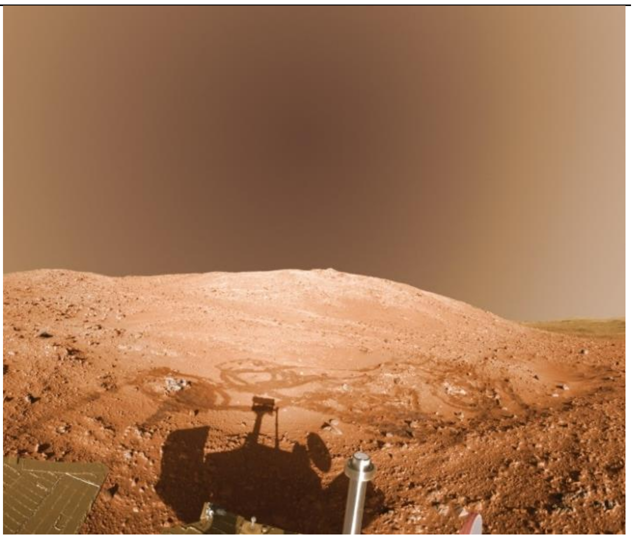
> *We had to succeed and we had to do something new and very exciting and so the rovers became really the major approach. We had the Pathfinder lander so we knew that rovers worked on the surface and that you could do science but we wanted to do something really bold and the two landed rovers were the way to go. When JPL conceived of the mission with a lot of committees and everything overseeing the process it decided that one rover was all that was necessary. But the head of NASA at the time, Dan Goldin, said you are going to send two, because I don't want to risk a failure.*

Finally, after years of testing and last-minute fixes, both rovers landed on Mars in early 2004: *"we're two for two! One dozen wheels on the soil"* said flight director Chris Lweicki.

Both rovers found past evidence of liquid water. Opportunity literally bounced into a crater filled with sedimentary rocks and water-eroded blueberries. Spirit became the first Mars mountaineer by driving three times longer than planned to distant "Columbia Hills". By chance Spirit's front wheel jammed and,digging a trench, discovered evidence of an ancient hot spring. Steve Squyres:

> *"Spirit's unexpected discovery of concentrated silica deposits was one of the most important findings by either rover, It showed that there were once hot springs or steam vents at the Spirit site, which could have provided favorable conditions for microbial life."*

Although, if found on Earth most geologists would have routinely classed these as fossilized life there was no way for Spirit's limited instruments to find out for sure, and soon afterward the rover itself struck disaster and got bogged in loose sand. All efforts at freeing Spirit failed and the rover ceased to function in 2010. At the time of writing her twin, Opportunity, continues to investigate Meridiani Planum, having completed the furthest extraterrestrial traverse in human history. Opportunity has lasted so long that some of the current mission team, such as Bekah Sosland, were in school when Opportunity first landed: "*I certainly never thought I'd have an opportunity to work on Opportunity*," she said. *"That only became possible because this mission has been going so incredibly long ...I'm loving that I can be a part of this team now."*



Opportunity, one of a pair of rovers sent to Mars, makes wheel tracks on the Red Planet. Source: NASA.

Spirit and Opportunity also gave the US some solace after 9/11. The attack occurred just over a kilometre away from where rover components were being built in Manhattan. Rover team member Stephen Gorevan was riding his bike in lower Manhattan when a plane hit the World Trade Centre: *"…I stopped and stared for a few minutes and realized I felt totally helpless, and I left the scene and went to my office nearby, where my colleagues told me a second plane had struck. We watched the rest of the sad events of that day from the roof of our facility."* Although feeling helpless about the attack, the engineers decided to make a tribute to the 9/11 victims by building part of the rover arms out of metal from the World Trade Centre. Metal was delivered to the robotics company and made into abrasion shields for the rover arms. The "quiet tribute" to 9/11 has been a part of Mars since 2004.

Following MER, left over hardware from "faster, cheaper, better" was able to fulfil a polar mission in 2008 as the aptly-named Phoenix. Racing against tim,e before the onset of the polar winter, Phoenix sampled the weather, detected snowfalls and dug up parts of the icy Martian surface. One of the most surprising finds of the mission happened directly underneath the lander. Phoenix's braking rockets had blown away the topsoil, revealing pristine ice underneath. Some of this ice had spattered on the lander's legs, and sequential images showed this ice appearing to melt and form spherical blobs. If true, this controversial find would prove the existence of liquid water on present day Mars.

Curiosity

Although airbag landings had been used successfully three times on Mars, something different was needed to land the next rover NASA was building. The Mars Science Laboratory, later named Curiosity, was the biggest vehicle ever to be landed on the surface of Mars. Weighing close to a tonne, the airbag landing system would not work for this mission. JPL's Landing team member Adam Steltzner said:

> *"Unfortunately, we don't have fabric here on Earth strong enough to build airbags that would work for a rover the size of Curiosity: The bags would shred, not giving Curiosity any protection".*

Curiosity was also too heavy to carry on a beefed-up Pathfinder-style lander. Adam Stelzner, leading a team of landing engineers, came up with a radical solution; use a sky crane. This never-before-tried process used a rocket descent module that would lower the rover gently to the Martian surface with four nylon ropes before flying away and crashing. *"It looks a little bit crazy. I promise you, it is the least crazy of the methods you could use to land a rover the size of Curiosity on Mars,"* said Stelzner to reporters. NASA worked hard to test for every potential problem (the sky crane descent module crashing on top of the rover was a serious consideration), delaying the launch by two years and blowing out the budget to US$2.5 billion. Finally, on August 2012, the "seven minutes of terror" where Curiosity would land, or crash, on the Martian surface had begun.

We travelled to Tidbinbilla, one of NASA's deep space tracking stations in Australia to watch the Curiosity landing live. Mars was favourably in Australia's skies at the time for Tidbinbilla to carry the signal of Curiosity's progress. The visitor centre was packed, all watching the images of nervous engineers at JPL mission control monitored the progress of the spacecraft. An animation was also showing on screens at Tidbinbilla to show what was supposed to be occurring on Mars. The time lag between Earth and Mars made it impossible for mission control to intervene if anything went wrong. Although watched from a world away, the landing sequence strongly echoed that of Viking, decades before.

In an echo back to the Viking landers decades before, Mission Control were spectators as they called out critical goalposts of the Curiosity landing:

> *"Vehicle reports entry interface …We're beginning to feel the atmosphere as we go in here…Parachute has deployed…We're down to 90 meters per second at an altitude of 6.5 kilometers and descending… We are at altitude 1 kilometer and descending…Sky crane is starting…Touchdown confirmed! We're safe on Mars!"*

The visitor's centre at Tidbinbilla erupted into applause as hugs and cheers were exchanged at Mission control. Curiosity was safely down and almost immediately started returning images of its landing site, Gale Crater. Gale Crater, named after an Australian astronomer, was chosen above over 50 regions of Mars as the favoured landing site for Curiosity. The rover carried an array of cameras, soil samplers, and for the first time, a Mars laser that could blast rocks up to 15 m away.

Dan McGleese:

> *We have now got to the point where Curiosity is making the kind of measurements on the surface that geologists would make on the rocks in their laboratories. And that level of sophistication is absolutely amazing and is a consequence of sending ever increasingly difficult and rewarding instruments every 26 months.*

Following weeks of analysing data returned from the landing site with an abundance of cameras and instruments, NASA announced:

> *"Rounded pebbles that hint of an ancient river, and a delta, where a river emptied into an ancient lake. Lakes spanned the crater floor, leaving mud that built the lower part of the mountain, inch by inch. The lakes came and went, and eventually dried up. But groundwater persisted, leaving minerals behind."*

Gale Crater was revealed as perhaps the best part of Mars yet explored that was most favourable to past life. The ground on which Curiosity rolled was once underwater as part of an inland lake. Streams of water knocked the corners of the rocks, and rounding them, just like on Earth.

Was the Lowellian vision of a habitable early Mars finally coming true? The story of Curiosity is still unfolding and may one day come up with an answer. The nuclear powered rover is slowly being driven up Mount Sharp, a 5 km high mound in the centre of Gale Crater. As Curiosity climbs, she will be moving forward in Martian history. It is a race against time, as the rover's wheels have started to fall apart. Small pinpricks, then major tears have appeared on the wheels as sharper than expected rocks wear away at up to 60 % of their design life. The rover team remain optimistic: "*All six wheels have more than enough working lifespan remaining to get the vehicle to all destinations planned for the mission*," said Curiosity Project Manager Jim Erickson. *"While not unexpected, this damage is the first sign that the left middle wheel is nearing a wheel-wear milestone."*

A panorama of Mount Sharp taken by the Curiosity rover (image PIA16768 NASA/JPL-Caltech).

Eyes for Mars

Imaging Mars from orbit is technically easier than sending a lander to the surface. Floating serenely above the abrasive dust storms and the lander killing temperature shifts, the Mars orbiter has nothing but ageing electronics and dwindling attitude control gas to worry about. Following the end of Viking a NASA team proposed sending a new orbiter to Mars without a camera**:**

Dan McGleese:

> *The first spacecraft to go back was thought of initially as a very low priced mission. And the scientists who were managing the space exploration program at NASA felt that the most expensive thing you could do on a spacecraft is to take pictures. And if we wanted this mission to be cheap then that spacecraft which was called Mars Observer should not have a camera. And then it would be a cheaper mission. Well that idea was wrong, and eventually the NASA leadership said no way are we sending a planetary spacecraft without a camera and so while it's true there were a lot of pictures I think that trying to do it cheaply really drove the mission but that was then reversed by people who understood that the pictures were really the way of conveying the exploration to the public.*

Advances in imaging technology allowed Mike Malin to convert the 'cheap' imager proposal to a Martian telescope whose image resolution would rival that of aerial photography taken of Earth.

In 1991 the billion dollar Mars Observer, as the mission was later called, was lost three days before entering Martian orbit from a ruptured fuel line. However copies of most of the instruments, including the camera, were able to be flown on a budget orbiter, Mars Global Surveyor in 1997. This later mission, and the orbiters that followed have proven so successful that Mars is the most accurately mapped planet in the known universe (Earth's clouds and oceans make this hard for our planet). The orbiters have mapped large swathes of Mars down to 25 cm resolution; discovering gullies, evidence of subterranean water and surface ice activity, and revealing the fantastic geology of Mars. In addition to mapping Mars, orbiters play a vital role in acting as relay stations between landers on the surface and Earth.

International Efforts

Although the US has dominated Mars exploration, other nations have launched missions to the Red Planet. The European Space Agency (ESA) got it half right. Mars Express and ExoMars have returned a wealth of data since arriving in Mars orbit. Unfortunately their landers, Beagle 2 and Schiaparelli, failed. Beagle 2 was the first semi-privately funded Mars mission and its loss was particularly devastating to its creator, Colin Pillinger. Perhaps even more devastatingly, later images from orbit revealed Beagle 2 had almost worked, but was unable to deploy the last of its solar panels and uncover its radio antenna. Schiaparelli, in an echo to the failed Mars Polar Lander, shut down its rockets early and exploded on the Martian surface.

The old Soviet Union and the new Russia have tried for Mars almost more times than the US. All of their missions either failed or their results were eclipsed by more sophisticated US probes. One of the failures almost sparked World War Three when its debris was mistaken for a Soviet nuclear attack during the Cuban Missile Crisis. The latest attempt, Phobos-Grunt became stuck in Earth orbit in 2012 before finally burning up months later.

In 1963, the Soviet Mars 1, suffered a mission ending transmitter failure, but nevertheless became the first human made object to reach another planet. The massive Mars 2 and Mars 3 actually made it to the Red Planet, just in time for the global dust storm that had affected Mariner 9 and returned images of a dust covered Mars from orbit. They also deployed two landers into the swirling dust, one of which was never heard from again. The Mars 3 lander on the other hand continued working and when tracked altitude readings levelled out; the Soviets knew that Mars 3 had made the first ever successful landing on the planet. Scientists then impatiently waited for the lander to begin transmitting the first picture of the surface of another planet. A tele printer stirred to life, showing a noisy image. Then, after 14.5 seconds, the data stoped. The lander was never heard from again and the cause was later blamed on the dust storm overwhelming the lander's electronics.

Although controversial, the image appears to show an upside-down view of the Martian landscape with lighter sky in the background. If true then the Soviets, and not the Americans were the first to image Mars from the surface.

The latest international effort has been from India. Reversing the trend of failures before success, the Indian Space Research Organisation (ISRO) succeeded on reaching Mars with its Mars Orbiter Mission (MOM) on its first attempt. Moreover, it succeeded in the face of some international derision. Some commentators refused to believe that a country that couldn't provide flushing toilets to its population could successfully fly a spacecraft to Mars. ISRO spectacularly proved them all wrong by keeping its design simple. MOM relied heavily on existing Earth orbiting satellite hardware, and the use of space-proven technology kept the costs down. In fact, MOM cost less to run than the Hollywood movie Gravity which was released the same year MOM launched. Much of the western criticism was unfounded, quite offensive and didn't even bother to address the massive morale boost MOM's success had on India's scientists and engineers.

The impact of MOM was felt across India The impact of MOM was felt across India and has inspired the next generation of engineering students:

> *Long before MOM, back in 2008, India launched its first orbiter to the moon, Chandrayaan-1. This was India's first exploration mission that discovered liquid water on the Moon and it left a deep imprint on me as an undergraduate student. I still remember I used to closely follow the mission updates and read about the mission on my way to classes. It was very exciting to see that my country had decided to embark on its space exploration phase. Then in 2012, the government approved plans for a Mars mission. What really impressed me was the efficient manner in which ISRO progressed from mission concept to launch within a time period of 3 years. Mangalyaan (or Mars Orbiter Mission (MOM)) was launched on Nov 05 2013, at a time when I was working with a spaceflight team at NASA Ames, developing a bioscience payload for the International Space Station. At the time, the mission was mainly covered by the Indian media and it was only upon its Mars Orbit Insertion on September 24 2014 (incidentally my birthday!) that the whole world took notice. For me, it was a moment that India delivered a clear message to the world that planetary science missions do not need to be overtly time and cost intensive. The sheer grit and technical rigor of the mission was clear in the achieved orbit precisions, India was among the first nations to achieve a successful Mars mission on its first attempt. Personally, I would love to be a part of the Indian Mars exploration program. The exploration roadmap presented by the ISRO chairman includes a second orbiter mission in 2020. Hopefully, I would be one day a contributor to the nation's grand Martian adventure!.*

Mars Today

Following half a century of space exploration, what is the real Mars? Why do we keep sending spacecraft there? Planetary researcher Graziella Capririlli:

> *With more recent missions we have better spatial resolution of the observations you can make… This has not only revealed new features that you couldn't see before but the characteristics of features that were observable before have changed dramatically from our perspective. For example in the past we thought the northern plains were this large flat expanse... We are able to observe things at different scales and we start seeing that they are not flat at all. We can see roughness that roughness is a characteristic of the surface and it may very well reflect what is happening in the sub-surface so we do understand much, much more as long as we continue to send missions to Mars.*

Perhaps the greatest finding is that Mars is not Earth-like, nor Moon-like, but Mars-like. The Lowellian Mars bustling with intelligent life desperately irrigating crops via canals has gone forever. Instead, what we know of Mars today is a surprising world that is exciting and mysterious in its own right. Each new mission and discovery adds new layers of understanding and raises new questions. Like Earth, water has played a key role in shaping Mars throughout most of its history. Early Mars was a much wetter place, with oceans of water carving out outflow channels reminiscent of the Lowellian canals of the early 1900's. Whether the abundant water was freely deposited on the surface via rainfall or locked under sheets of ice is a topic of robust discussion and disagreement among researchers today. Most researchers agree that the role of liquid water has reduced greatly over the aeons, though has not entirely vanished. Smaller scale gullying on young craters and orbiter images of slope streaks that darken during the Martian summer offer tantalising glimpses to a world that isn't totally dry and dead.

Other processes have been at work on Mars too. Massive volcanoes, faulting that has almost split the Martian surface in two and billions of years of wind have built the Mars we know today. We now know that the simple answers we were looking for even a generation ago don't exist. Mars is just too complex to look for simple fixes and sound bites. There is plenty left to explore on the Red planet for generations to come.

So where does that leave Mars on the scale of possibly hosting life? Has our knowledge of Mars increased the possibility of life there? Opinion is divided.

Dan McGleese:

> *The answer to that question is really at the root of our exploration of Mars. Curiosity has shown that the planet was habitable in the distant past, that there was water present that there were sources of energy, the sun, that there are layers of rock present on the surface that show all of the components that are required to make life possible and that the ancient climate was also conducive to making a habitable world. So it's really opened our eyes to the possibility that in fact there may be evidence of life on the surface.*

Graziella Caprielli:

> *The short answer for me is no ...From the time of Schiaparelli [it was thought] there were people living there and that then naturally there was Mariner which went the other way, that it was not possible to have any life on Mars, there was no water, it's not active, so you had the two extremes… I would say that the jury is still out and we still do not know hence we need to keep researching if the focus of researching on Mars is about finding life past or present but certainly we also cannot rule out 100 % because we do find traces of microenvironments that on Earth are capable of sustaining life. So we still don't know.*

NASA Ames Researcher David Willson: What changes have taken place since the Viking mission concluded "no evidence for life" in 1976? I think there has been a major change in the understanding of the possible existence of life on Mars. Now it is thought that ancient life could have existed in the distant past and extent life (life that exists in recent times) could exist as well. There are many pieces of evidence.

Firstly, the Viking mission mass spectrometer result of "no carbon in the soil", has been questioned by the discovery of Perchlorates in the martian soil by the Phoenix Lander. The mass spectrometer heats up soil in an oven until it is an ionised gas then passes the gas over a magnet to distribute a spectrum of molecules of ascending masses on a detector. The pryolytic (heating) process results in the soil Perchlorates reacting with organic carbon, destroying the organic molecules. Thus Viking's mass spectrometer instrument built to detect organic compounds was actually destroying them.

The world that inspired more people to become involved in space exploration than any other planet has still refused to give up its secrets on this enduring question. Perhaps the only way to find out for sure is to send humans there. Serious plans to go to Mars have existed since post Apollo, however have tended to be two decades away since the 1980's.

Dan McGLeese:

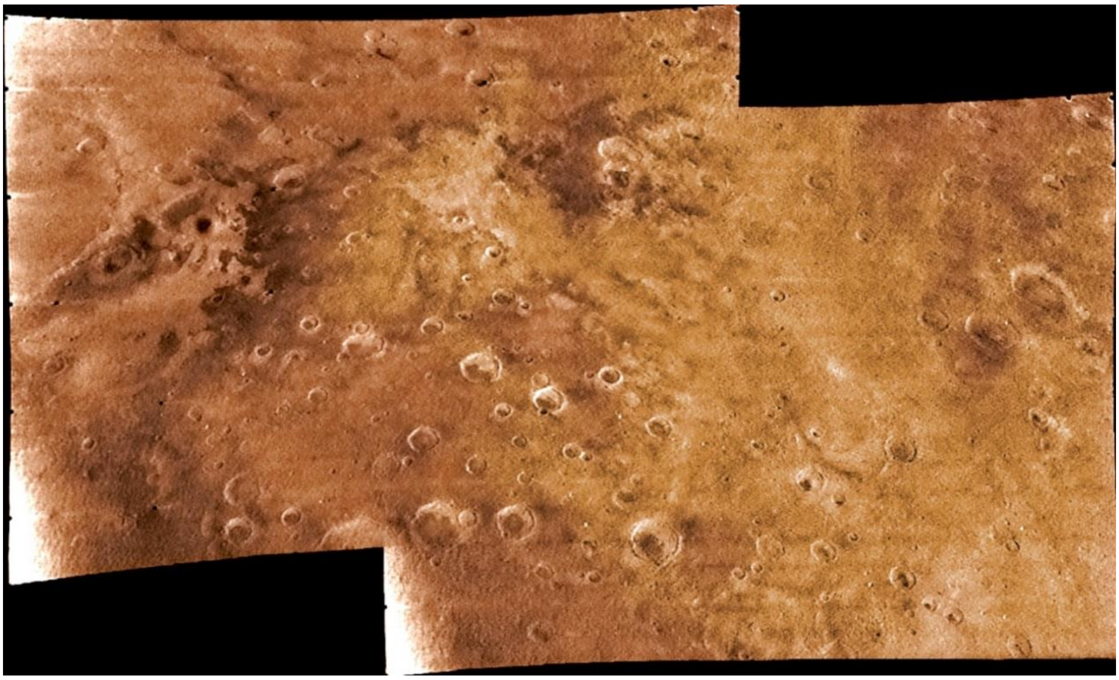
> *I was a young scientist at JPL [in the 1980's] we had a committee come of distinguished people come to the laboratory to speak to young scientists and engineers about the future… They asked 'when did I think humans would land on the surface of Mars?' …I said my best estimate based on what I've seen from NASA up to this time is that the earliest we could send humans was 2025. The committee went crazy. They said that they'd never heard a more pessimistic estimate of the future, particularly from a young person...Well clearly we're at least another decade, possible two, away from seeing this happen which would make it 2035, 2045 at the earliest? So it's always kind of been a goal that's always beyond our reach since the 1980's.*

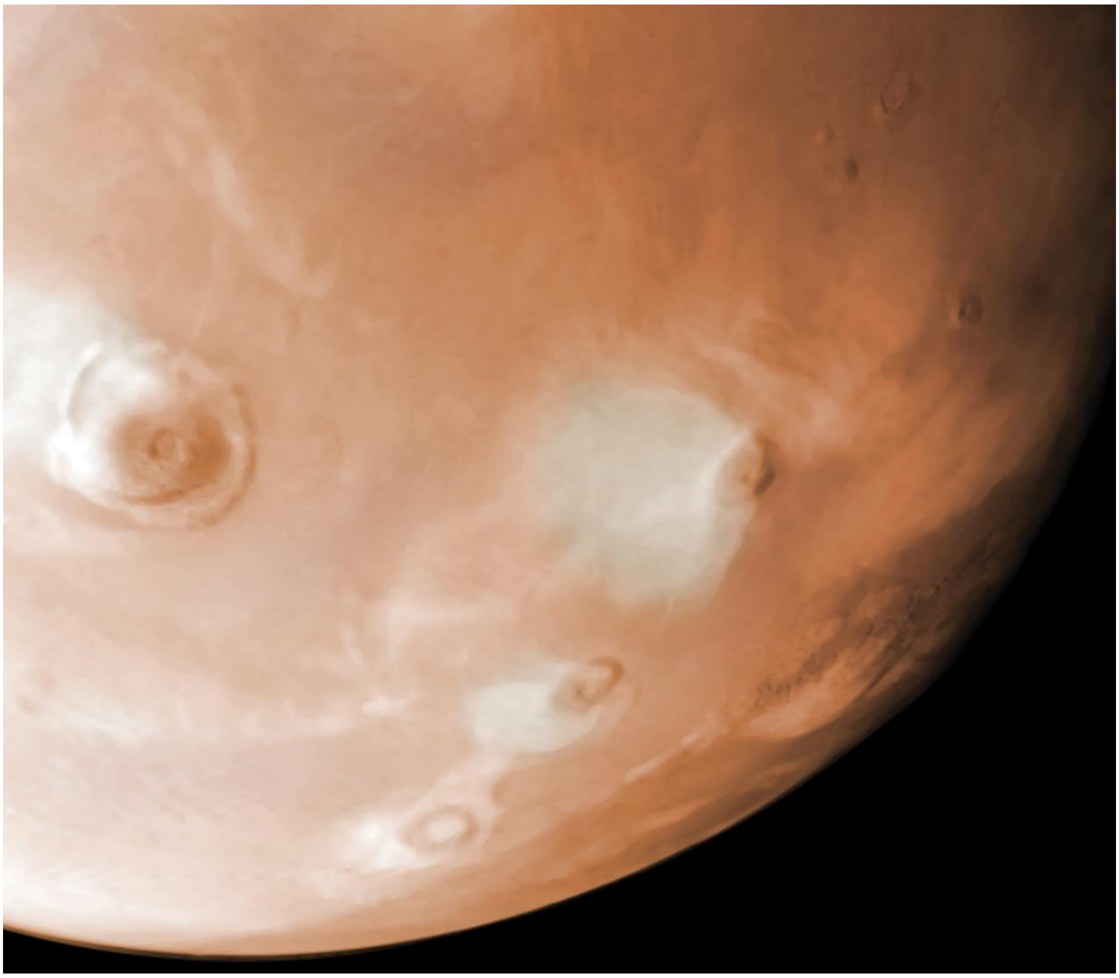
Since the 1980's a host of new contenders, including private companies have joined the quest for Mars. Elon Musk, PayPal founder and CEO of Space X, has been working on plans to send a capsule to Mars. United Arab Emirates and China are planning Mars mission in the future. ESA, despite the Schiaparelli crash are pressing ahead with their Mars plans. Even if Mars may not be the first thing on NASA's list it certainly has been a priority for other nations.

Lowell's Legacy

Despite investing much of his personal fortune and countless hours of effort into studying Mars, Percival Lowell was profoundly wrong about the Red Planet. The Martian canals, irrigation streams and dying civilisations and the idea of Mars as an abode for life, led much of US Mars exploration astray for decades, making the impact of the Mariner 4 mission harder. Many might question the soundness of the preservation of the Martian view for so long, when there was mounting evidence to the contrary, even before the space age. Without Lowell's visions of this "exciting Mars" space exploration as we know it might never have happened. Many of the space pioneers, including Wernher Von Braun, were inspired by the fantastic

Martians penned by Edger Rice Burroughs and other science fiction writers. Would these first pioneers, and a willing public to back them, have tried so hard to reach into the unknown if they knew evidence life on Mars would still be elusive over a century after “Mars and It’s Canals”? The search for life outside of Earth remains one of the biggest drivers for unmanned space exploration. Announcements of the existence of water or habitable conditions of life on Mars continue to make headlines, and more missions continue to be sent to the Red Planet than anywhere else in the Solar System. Perhaps this is the greatest legacy Percival Lowell left behind–a robust and enduring interest in space exploration that seeks to answer one of the last enduring questions of humanity: are we alone?





Mariner 9 discovered the extreme geology of Mars, including the largest volcano in the Solar System. Four of these volcanoes are so high they poke out of most of the Martian atmosphere. Source: NASA.

Landforms and Regolith of Mars

Colin Pain

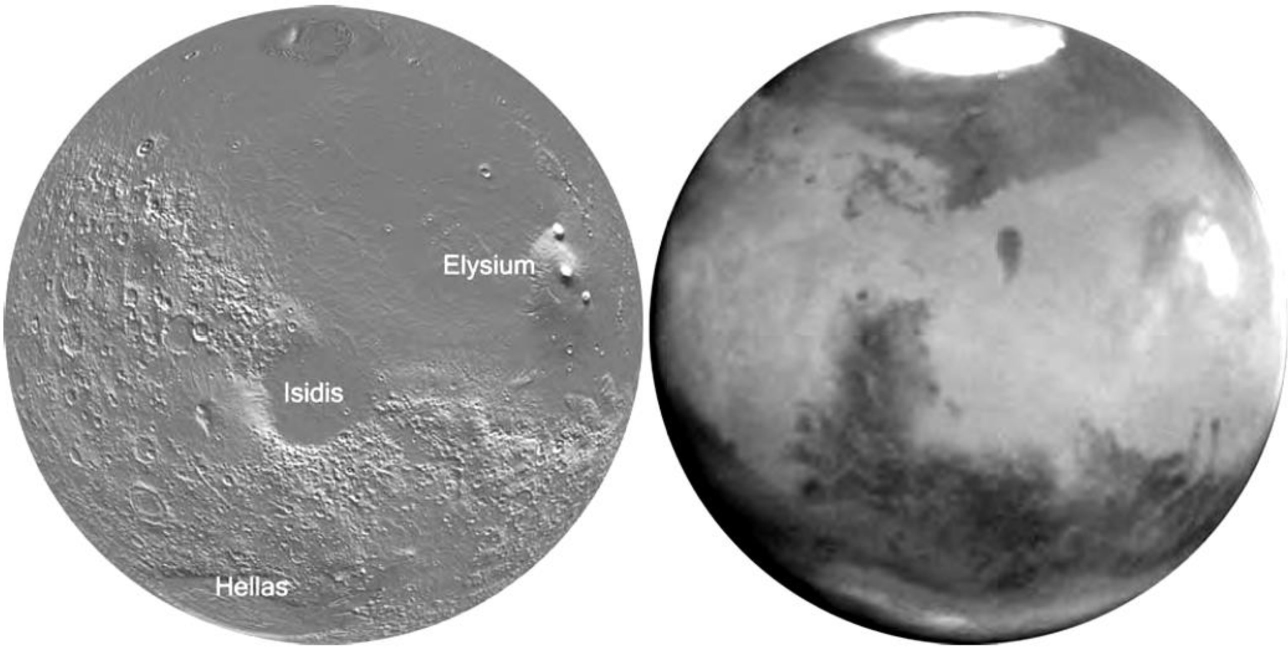
Beginnings

In 1965, on the eve of the receipt of the first images from the Mariner 4 mission flyby, it was well known that the planet varied from place to place. This could be seen from telescopic observations from Earth, which provided the basis for Percival Lowell's maps and ideas about canals on Mars as well as a background to much science fiction – see for example Arthur C. Clarke's "The Sands of Mars". The surface of Mars was thought to probably be covered, at least in part, by vegetation, and that there might even be animal life. On some parts of Mars the albedo changed on an annual basis (the Martian year is 687 Earth days long) giving rise to hypotheses that vegetation cover was expanding and contracting. Other, usually smaller, parts changed on a daily basis (the Martian day is 24 hours and 37 minutes long).

However, the first images were not encouraging, and later images from Mariner 9 (1971), which was the first satellite to orbit Mars, seemed to confirm that Mars, whatever else it might have, did not show any signs of life. The Viking missions, 1 and 2 in 1976-1987, gave a much clearer picture of the Martian surface both from orbit and from the ground. This put to rest any ideas about vegetation being present. These early images, and the many more that have been received since then, make it clear that the surface of Mars as seen through telescopes is very different from the reality. Annual changes in the appearance of the surface are now thought to be related to the movement of dust blown around by seasonal variations in wind patterns. Daily changes such as those that occur on the highest, usually volcanic, peaks are related to daily formation and then dispersal of clouds. We now have hundreds of thousands of images showing the surface of Mars, from both orbiters and landers. These images range from those showing the whole disk to those showing features only a centimetre or so across. The former allow us to divide the planet into regions with similar features while the latter help us explain the origins of many of the landforms.

At present the geological timescale of Mars is much simpler than that of Earth (see box), mainly because of the lack of information about Martian geology. There are four eras:

Pre-Noachian Era (4.5 – 4.1 billion years). The time from when Mars became a globe to the formation of the Hellas impact basin. Most of the geologic record of this interval has been removed by subsequent impacts and erosion. The crustal dichotomy is thought to have formed during this time, along with the Argyre and Isidis basins.



Comparison of the terrain on Mars with what can be seen in a telescopic image. The left shows the surface relief of Mars as obtained from the Mars Orbital Laser Altimeter, an instrument carried by the Mars Global Surveyor. It measures the surface elevation of Mars and is used to construct digital elevation models (DEMs). The right comes from the Hubble Space Telescope and shows differences in the albedo of the surface and the air. Comparison of the two images shows that the bright and dark features on the telescope image show very little correlation with the physical features of the surface shown on the left. Source: Carr 2006.

Noachian Era 4.1 to 3.7 billion years. Named after Noachis Terra, this was a period of intense bombardment and volcanism, cooling, and erosion. The early Martian atmosphere was denser than today. Water from rain flowed and changed the surface. The oldest surfaces of Mars that we can still see are scarred by many large impact craters. The Tharsis bulge is thought to have formed during the Noachian, along with extensive erosion by liquid water producing river valley networks. Large lakes or oceans may have been present.

Hesperian Era 3.7 to 3.0 billion years ago. Named after Hesperia Planum, the Hesperian Era was a time of transition from the violence of the Noachian Era to the Mars of today. It was marked by the formation of extensive lava plains. The formation of Olympus Mons likely began during this period. The planet experienced significant cooling, and surface water settled into and froze in subsurface rocks. Rivers continued flowing but at greatly reduced rates. Rapid melting of frozen groundwater led to “breakouts,” resulting in massive local floods that carved extensive outflow channels around Chryse Planitia and elsewhere. Ephemeral lakes or seas formed in the northern lowlands.

Amazonian Era 3.0 billion years ago to the present. Named after Amazonis Planitia the Amazonian Era is characterized by a thin atmosphere, dry and dusty conditions, freezing surface temperatures, glacial and periglacial activity, and minor releases of liquid water, probably from localized ice melting from glaciers of frozen groundwater. Volcanism and debris impacts continued but at a significantly lower rate than in the previous eras.

Global Physiography

At the global scale the most obvious physiographic feature of Mars is the ancient dichotomy boundary that separates the southern, cratered highlands from the northern lowlands. Approximately half of the planet, the southern highlands, is mountainous, with extensive cratering and much erosion. The highlands contain the most ancient surfaces of Mars. The northern half of Mars’ surface, the northern lowlands, are a broad and relatively smooth series of interconnecting plains consisting of basaltic lava flows and sedimentary deposits. The two halves of Mars are separated in some places by a 2 km-high scarp and in others by a gentle surface rising to the highlands. Both poles have large areas of water ice and dry ice that vary in surface extent and thickness with the seasons. Because there are rapid changes at the poles, these regions have some of the youngest surface features on Mars. A third distinctive region is the Tharsis Rise.

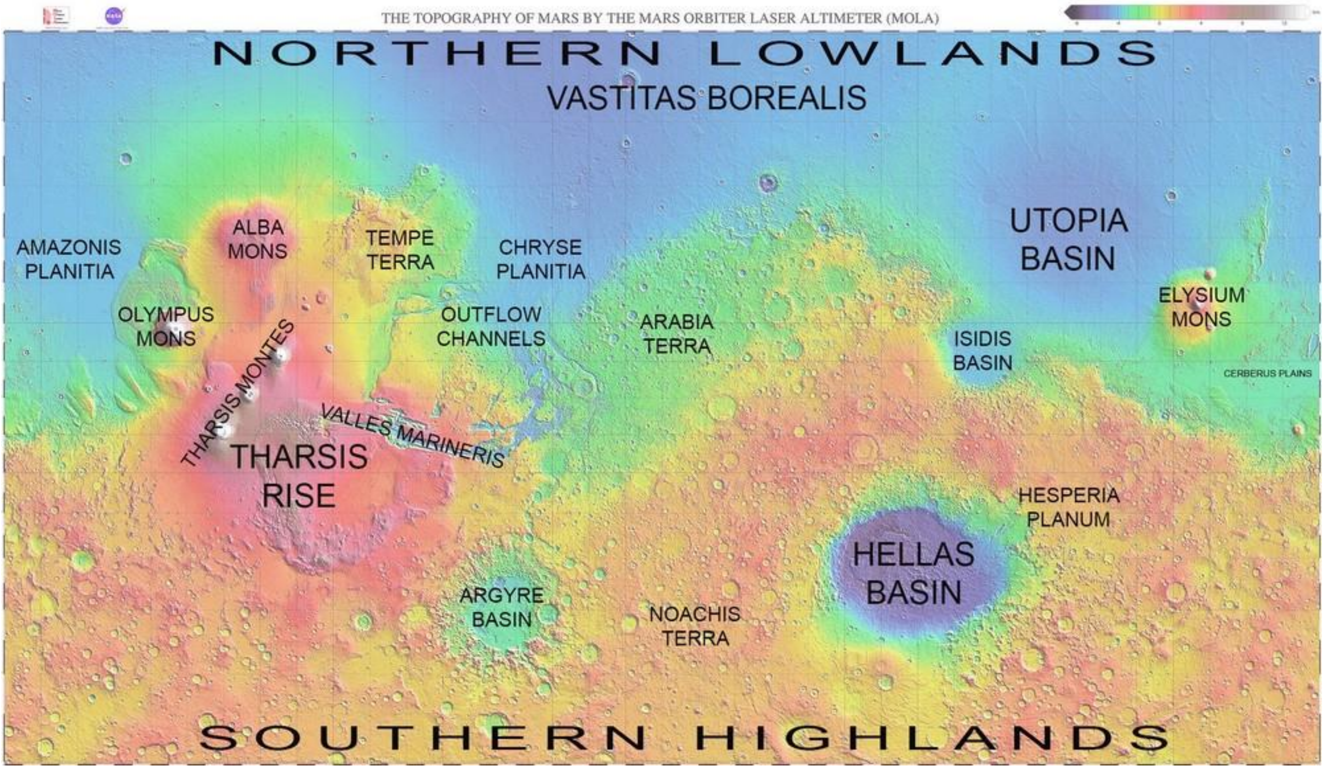
There are three impact basins: Argyre and Hellas in the south, and Isidis near the equator. The Northern Lowlands consists of the Vastitas Borealis, with three "bays" jutting to the south: Amazonis, Chryse, and Utopia Planitiae. The Tharsis Rise is a huge bulge on the equator associated with the three volcanoes of the Tharsis Montes. Three more volcanic provinces lie on Tharsis' northern edge, Olympus Mons, Alba Mons, and Tempe Terra. Elysium Mons is a lonely volcanic complex some distance away. In the southern highlands, Noachis Terra is some of the most ancient terrain on Mars, and the source of the name of Mars' Noachian period. Volcanic deposits in Hesperia Planum gave their name to the middle, Hesperian period.

Several ideas have been proposed to explain the origin of the dichotomy boundary. These include excavation of the northern lowlands by one or more large impacts, mantle convection, and overturning of unstable materials in an early magma ocean. Another interpretation suggests that the northern lowlands are a result of sea-floor spreading in the north, and that the southern highlands are a kind of supercontinent.

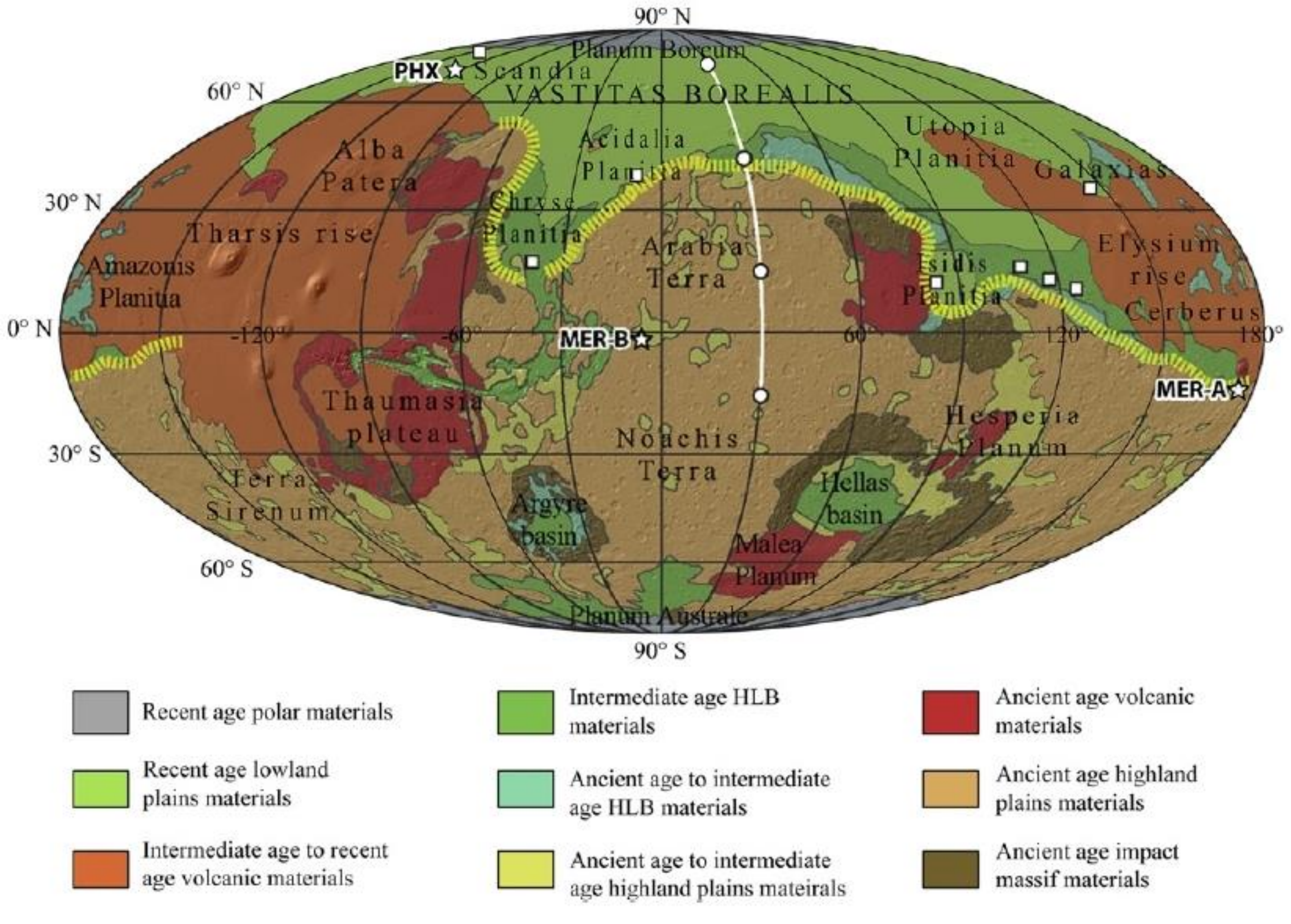
Landforms reflect the rocks on which they are formed, so maps of the geology of Mars play an important role in our interpretation of surface physiography. These maps, produced using standard image analysis, provide essential information about the distribution of landforms and materials on the planet. Early work suggested that much of the Martian surface was covered with basalt, but it is now realised that surface materials include large areas of pyroclastic rocks, impact-generated materials, and detrital sedimentary rocks.

Although Mars has no oceans, it is possible to draw drainage divides that outline topographic basins of internal drainage. Most of these basins have higher elevation areas from which water and sediments could flow to lower elevation plains. Most have an overflow outlet to adjacent, topographically lower basins. The lack of present-day oceans means there is no global sink for sediment, and the lack of plate tectonics means that sediment recycling has happened only at the surface through impact, fluvial, aeolian, and glacial processes. Mars’ surface preserves a long record of erosion and deposition that undoubtedly contains billions of years of sedimentary history.

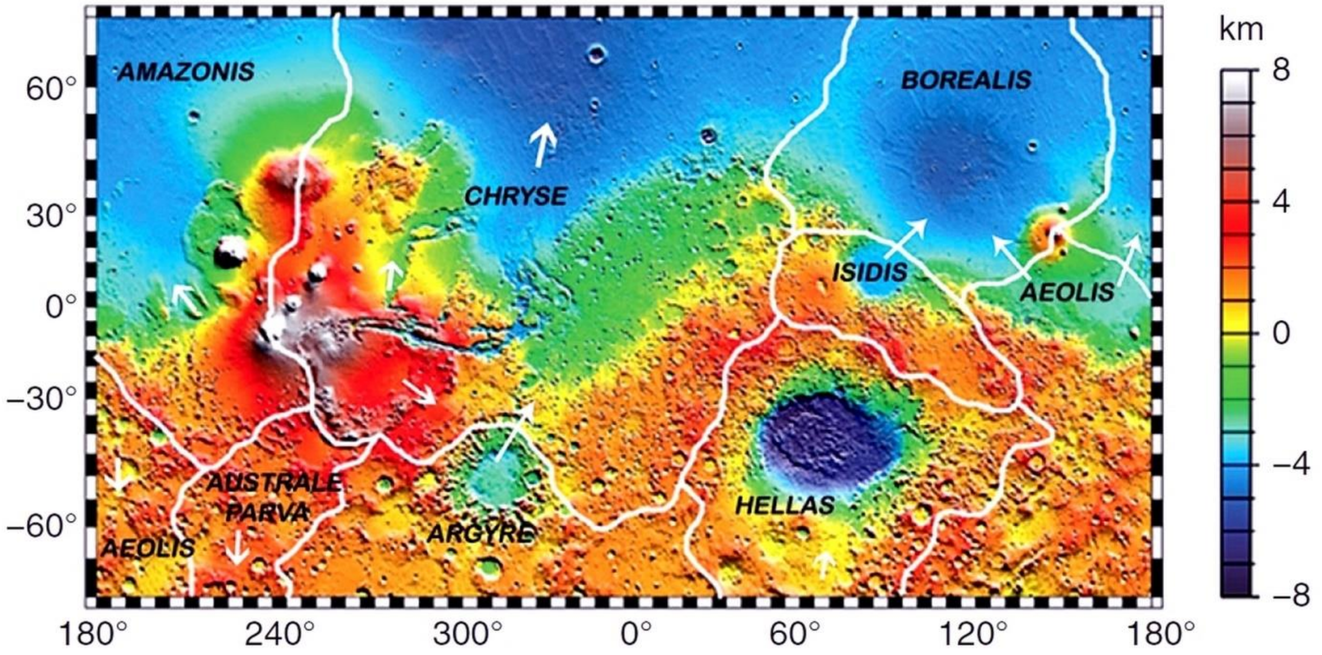
There are also volcanoes. Twenty four have been recognised, including Olympus Mons, the largest volcano in the Solar System. Many are very old but there are some that are much younger, and there have been suggestions that some may be dormant rather than extinct and that we may see eruptions in the future.



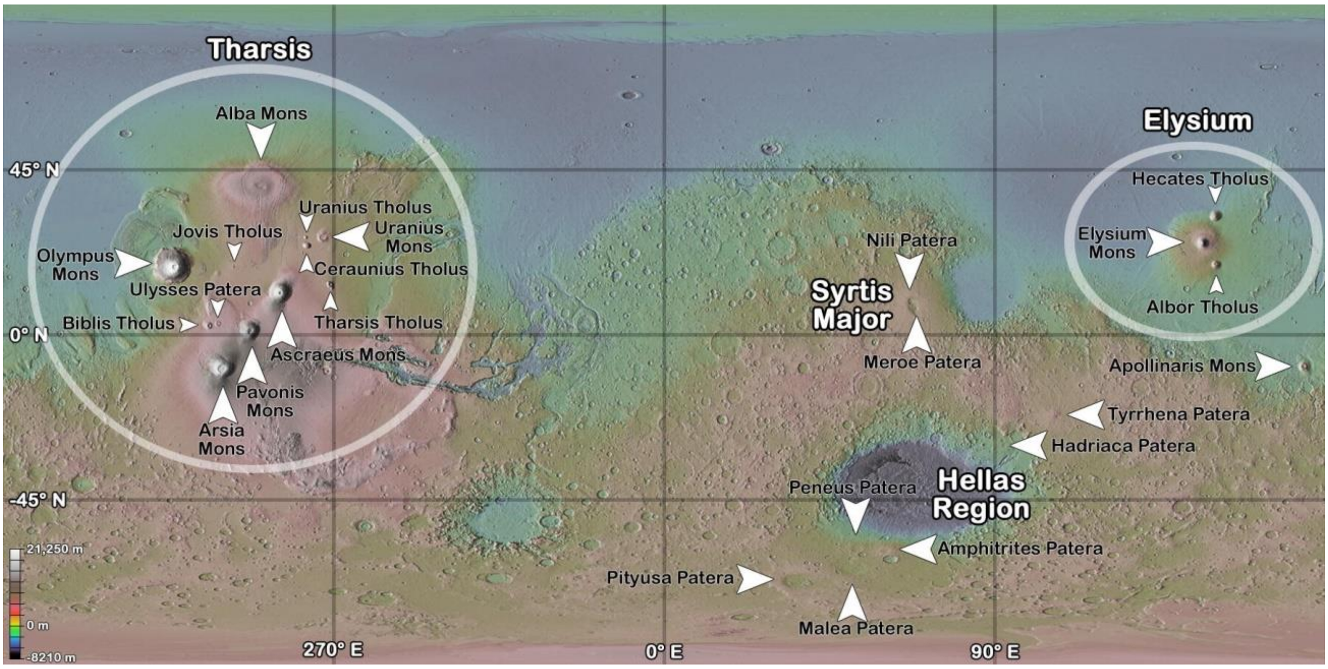
Main global physiographic features of Mars. The base map is a Mars Orbiter Laser Altimeter topographic map of Mars. MOLA map: NASA/JPL/GSFC. Map by Emily Lakdawalla, The Planetary Society.



Simplified geology map of Mars (from Skinner and Mazzini 2009). The yellow hachured line is the dichotomy boundary between the northern lowlands and the southern highlands. The major volcanic provinces are younger than the dichotomy boundary.

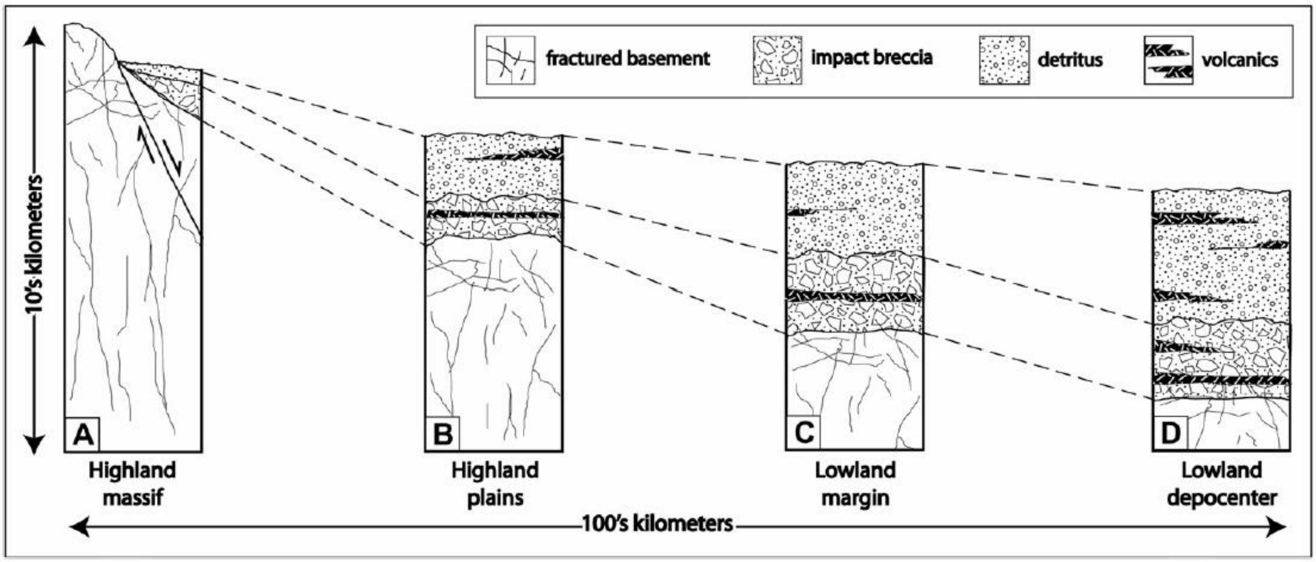


Major drainage divides of Mars, shown in white. Long arrows show overflow outlets and shorter arrows show general drainage directions (from De Hon 2010).



Volcanoes on Mars (from Robbins et al. 2011).

So far we have looked almost entirely at the surface forms of Mars, without considering the regolith, the material between fresh rock and the surface. Regolith thickness and character depends to a large extent on the evolution of the landscape in which it is found, and therefore is better studied at a regional or local scale. However, before looking at these more detailed scales it is worth making some generalisations about regolith at a global scale. There are two very broadly different layers overlying basement rocks. The lower layer, fractured basement or mega-regolith, overlies solid basement rocks. This layer is a consequence of intense bombardment that took place around 4 billion years ago. It could be as much as 10 km thick, and also porous to this depth, so there is a high potential for water storage in this zone. The second layer consists of volcanic products, weathering products, sediments, and ejecta from smaller impacts, the latter going by the delightful term of impact gardening. Processes in and on this upper layer profoundly modified the lower one, and are responsible for the surface features we see today. These processes include flowing water, wind action, volcanism and impact gardening. These layers are thinner in the highlands and thicker in the lowlands.



Diagrammatic illustration of the distribution of regolith on Mars. Impact breccia, or mega-regolith, overlies the basement and is in turn overlain by detritus formed by wind and water processes (from Skinner and Mazzini 2009).

The View from Orbit

Several orbiters have returned images that allow study of regional variations of the martian landscape. Bedrock plains were formerly thought to be composed of lavas, but recent work shows that many are clastic rocks, not lavas. This work shows that many bedrock plains are probably composed of weak rocks, with potential origins including lithified detrital sediments, pyroclastics, or impact-generated materials. It is also clear that much of the surface of mars is covered by stratified rocks, showing that erosion and deposition have played an important role in moving materials around.

Regional variations in the landforms and regolith materials of Mars are shown in the illustration above. It shows in diagrammatic form variations that depend on the geology as well as the age and elevation of the surface. Impacts that produced large amounts of ejecta would have produced at least a meter of regolith for Late Amazonian surfaces, increasing to tens to hundreds of meters for Hesperian and Noachian surfaces.

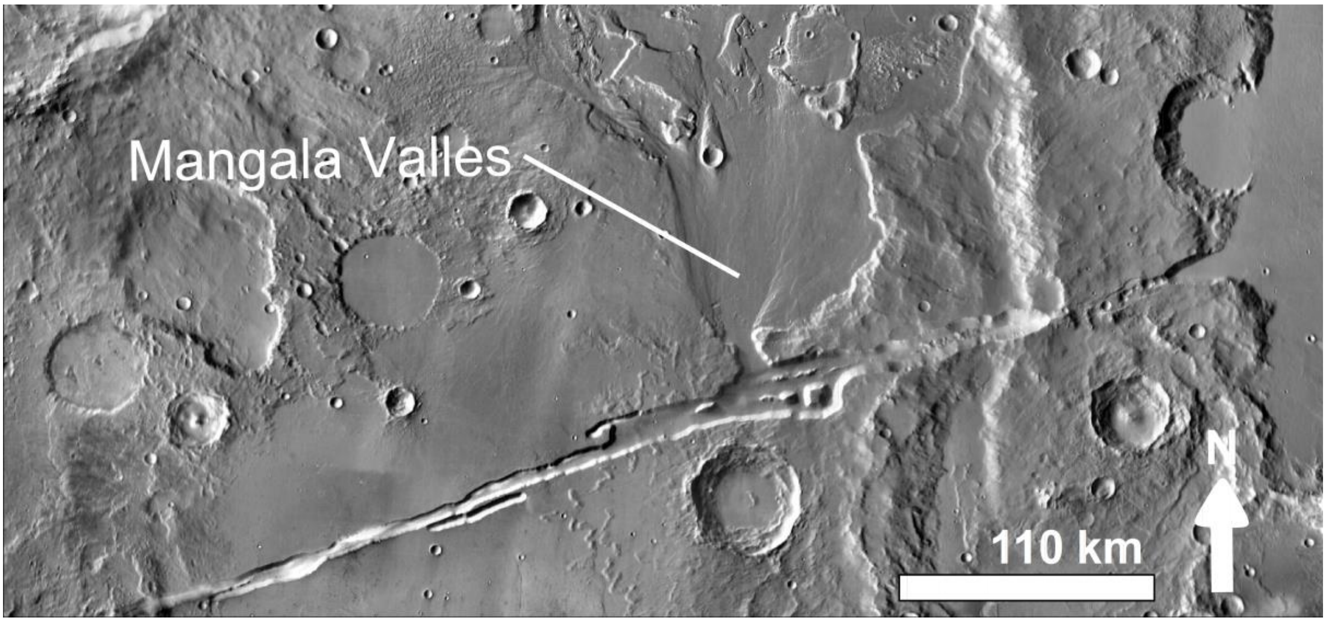
Images show that many parts of Mars are made up of layered rocks, just as they are on Earth. However, with much less tectonic activity sedimentary rocks on Mars are not deformed, and are usually flat-lying. However, some reports of vertically-dipping strata have been interpreted to indicate plate tectonic activity early in Martian history.

The mega-regolith was formed during the early intense bombardment between 4.6 and 4.0 billion years ago. The top few hundred metres of the mega-regolith have been affected by different processes since then. Among these, impact gardening was important, especially in the Noachian, but continues to the present at a much reduced rate. Crater density is a major means of estimating the age of land surfaces – the more craters the older the surface. Impact gardening provided several 10s of metres of loose regolith that could be acted upon by other processes.

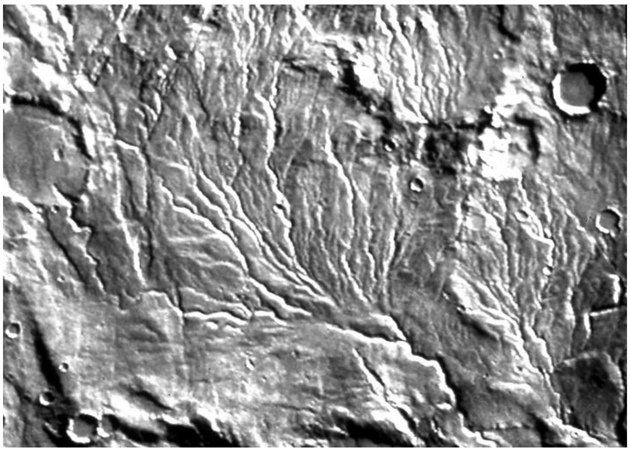
Water has played an important role in the shaping of many of the landscapes of Mars, especially in the Noachean and early to mid-Hesperian. There are two levels of water activity. First to be seen were the massive outflow channels that occur along and south of the global dichotomy. Outflow channels are 10s to 100s of kilometres wide and 100s or 1000s of kilometres long. They appear to have been formed during the Hesperian Era by the release of groundwater under hydraulic head (confined aquifers), perhaps by faulting. Estimates suggest that 20-30,000 km^3 were involved for the flood that produced Mangala Valles , and that flooding through Mangala lasted between 34 and 97 days. An alternative origin is volcanic activity, although the streamlined islands seem to require water rather than lava

Second are drainage channels and networks that developed mainly in the Noachian Era, probably as a consequence of rainfall. Water flowed into the lower areas, especially the northern lowlands, which almost certainly contained an ocean or a number of shallow seas.

It seems likely that, just as on Earth, there were river networks eroding valleys and depositing materials in floodplains, fans and deltas. However, there was a major difference – drainage on Mars was largely controlled not by tectonics and rock resistance but took place in and around numerous impact craters of various ages and sizes. Because of this, and perhaps because the period when rainfall occurred was short, integrated systems of the kind that developed on Earth (e.g. the Nile and the Amazon) do not seem to have developed on Mars. Many of the Mars



Infrared image mosaic of Mangala Valles generated using Thermal Emission Imaging System (THEMIS) images from the 2001 Mars Odyssey orbiter mission.



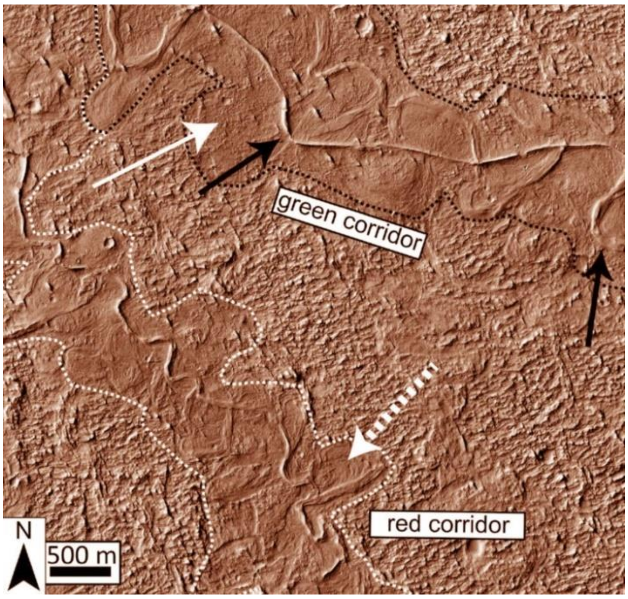
Viking Orbiter image 606A56 showing dendritic drainage patterns. Image processing by Brian Fessler (Lunar and Planetary Institute).

networks end in craters where deposition took place. Some craters overflowed and rivers leading away from them formed channels. Some channels that contained flowing water at that time are remarkably similar to those seen on Earth today. There are meander belts complete with cut-offs that probably contained oxbow lakes.

Deltas are common in craters, suggesting that the craters contained lakes at the time when rivers were flowing into them. At least some of these lakes likely lasted for thousands if not hundreds of thousands of years. These deltas will contain materials eroded from the area around the craters, so will be an important source of information about their catchment areas. As would be expected of lake sediments, at least some of them are thought to consist of clay minerals, suggesting chemical weathering of regolith in their catchments. Some researchers think they may also be good places to look for evidence of fossil life.

From about 3 billion years ago Mars became drier and presumably colder. Water became less important as a geological agent and ice and wind, especially the latter, became more important. When the surface was warmer, in the Noachian when there were rain-fed channels, water may have percolated into the mega-regolith, and frozen when temperatures dropped to form a deep reservoir of ice. Most surface ice is at the poles, with minor amounts seemingly present as permafrost, or in shallow frozen aquifers. There are a large number of tongue-shaped features on Mars that could be glaciers, or perhaps rock glaciers with ice mixtures. The height of the moraine ridges suggests that most of the ice has disappeared since formation. These features formed quite late in Martian geological history. At present the surface of Mars is much colder and drier than most places on Earth and can be classified as a hyper-arid desert. Mean temperatures are about 70°C colder than Earth (15°C) and the atmosphere is about one per cent as dense.

Although water seems to have been a dominant cause of erosion and deposition early in Martian history, the last 3 billion years have been dominated by wind. Wind erosion and transport has removed hundreds if not thousands of metres of materials from some places. Mount Sharp, a sediment pile in Gale Crater, is a fine example of what is left after wind erosion. Other wind-blown features include sand dunes and yardangs (streamlined rock forms sculpted by wind-blown sand).



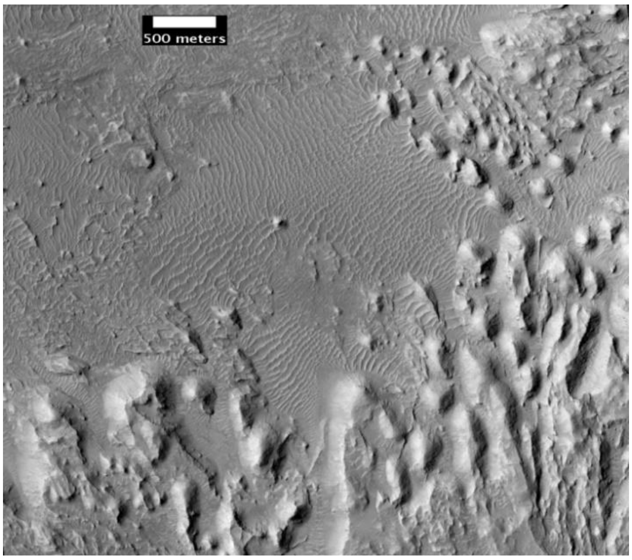
Meander belts along ancient river channels in Aeolis Dorsa. The dotted white arrow points to meander scrolls formed by point bar growth and river migration. The boundaries of the floodplains (dotted lines) show lateral river migration (white arrows). Another feature is the topographically inverted river deposits that are now ridges (black arrows) (from Cardenas et al. 2017). Inverted channels are common on Earth, and seem to be even more common on Mars.

Tongue-shaped glacial feature with lateral and terminal moraines ridges in eastern Hellas Planitia (part of HiRISE image PSP_002320_1415). There appears to be moraines from at least one older flow.

Landslides occur along major scarps that bound canyons. As with other things on Mars, the scale of landslides is large, ranging up to almost 100 km across and 80 km long. On some of them the upper part is rotated back towards the scarp and the lower part is a chaotic mix of debris. In this they are similar to rotational landslides on Earth, but much bigger. Most landslides seem to have occurred in the mid to late Amazonian.

Water seems to have maintained a role in surface modification. Gullies are widespread and occur mainly on crater walls, where they flow from at or below the rim to the crater floor. Frequently gullies end in fan-shaped deposits of material that are probably derived from erosion of the gullies.

There is evidence that some of the gullies may still be active. They almost certainly formed from action by liquid water, and have many of the characteristics of gullies on Earth.



Wind-blown features in the Northwest Aeolis Region (part of HiRISE image PSP_007382_1770). There is a field of low linear and parallel dunes in the upper part of the image, and wind sculptured yardangs in the lower part.

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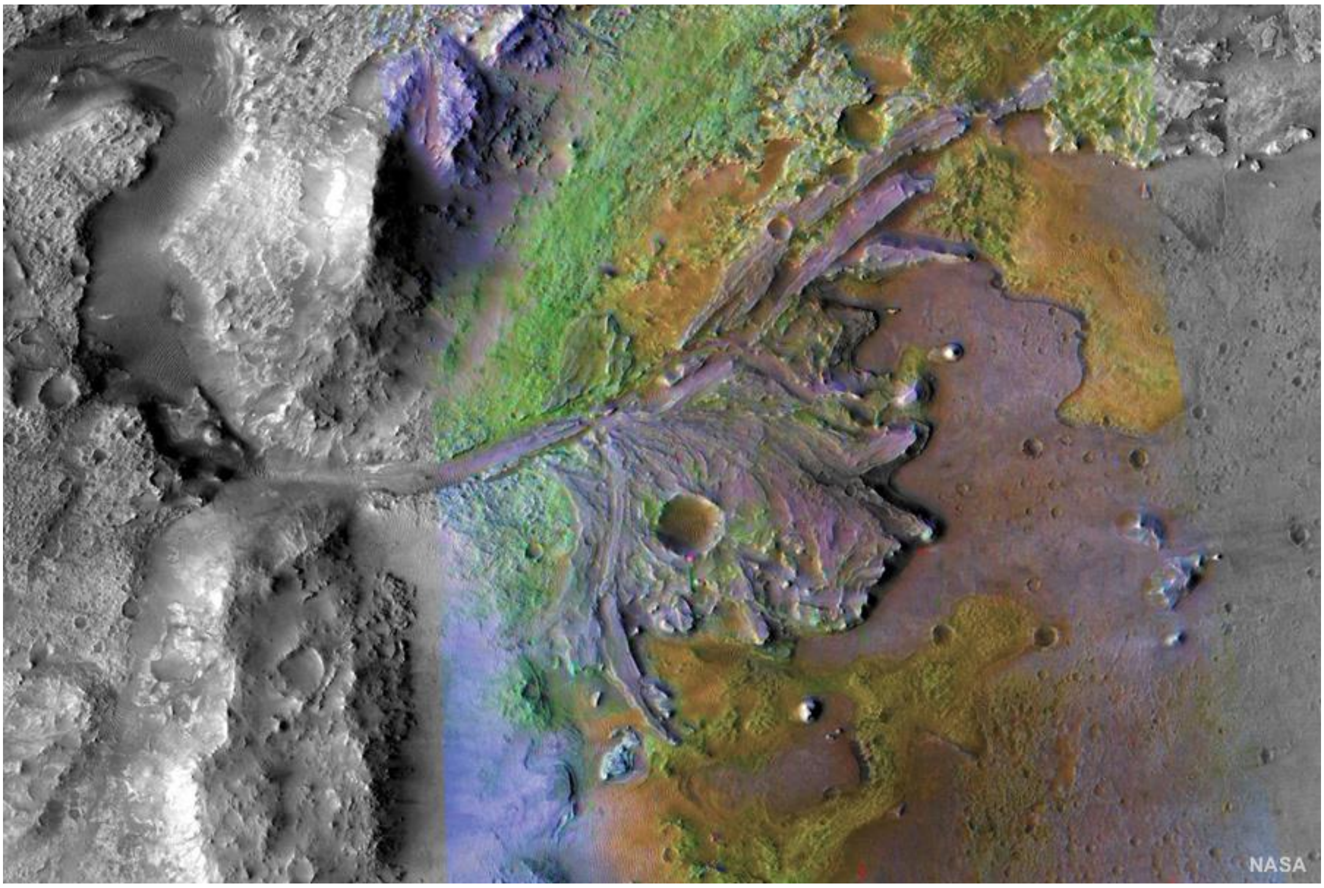
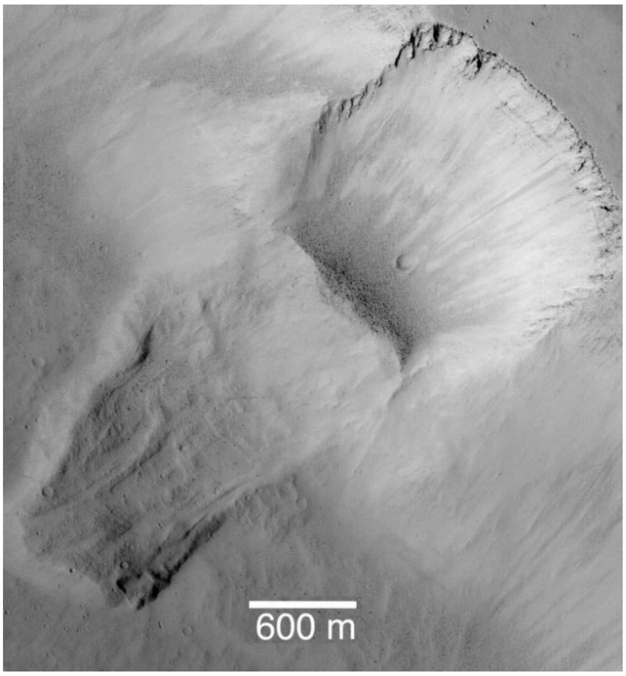
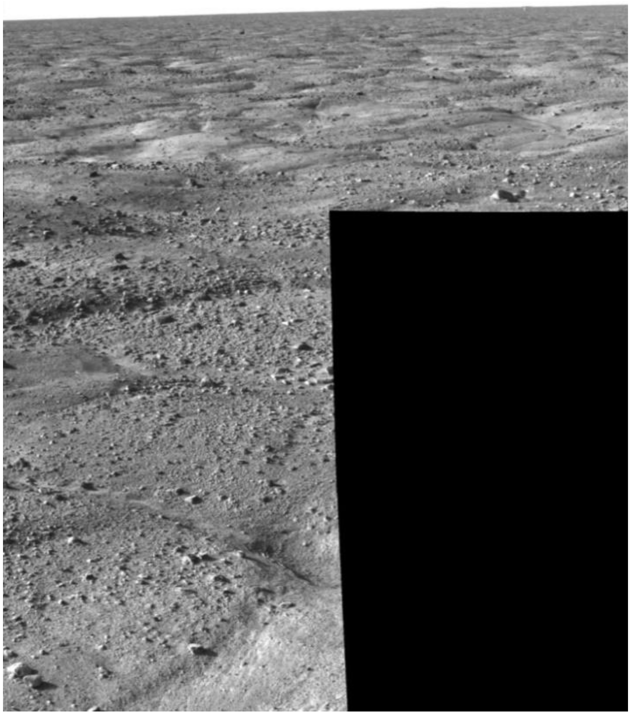


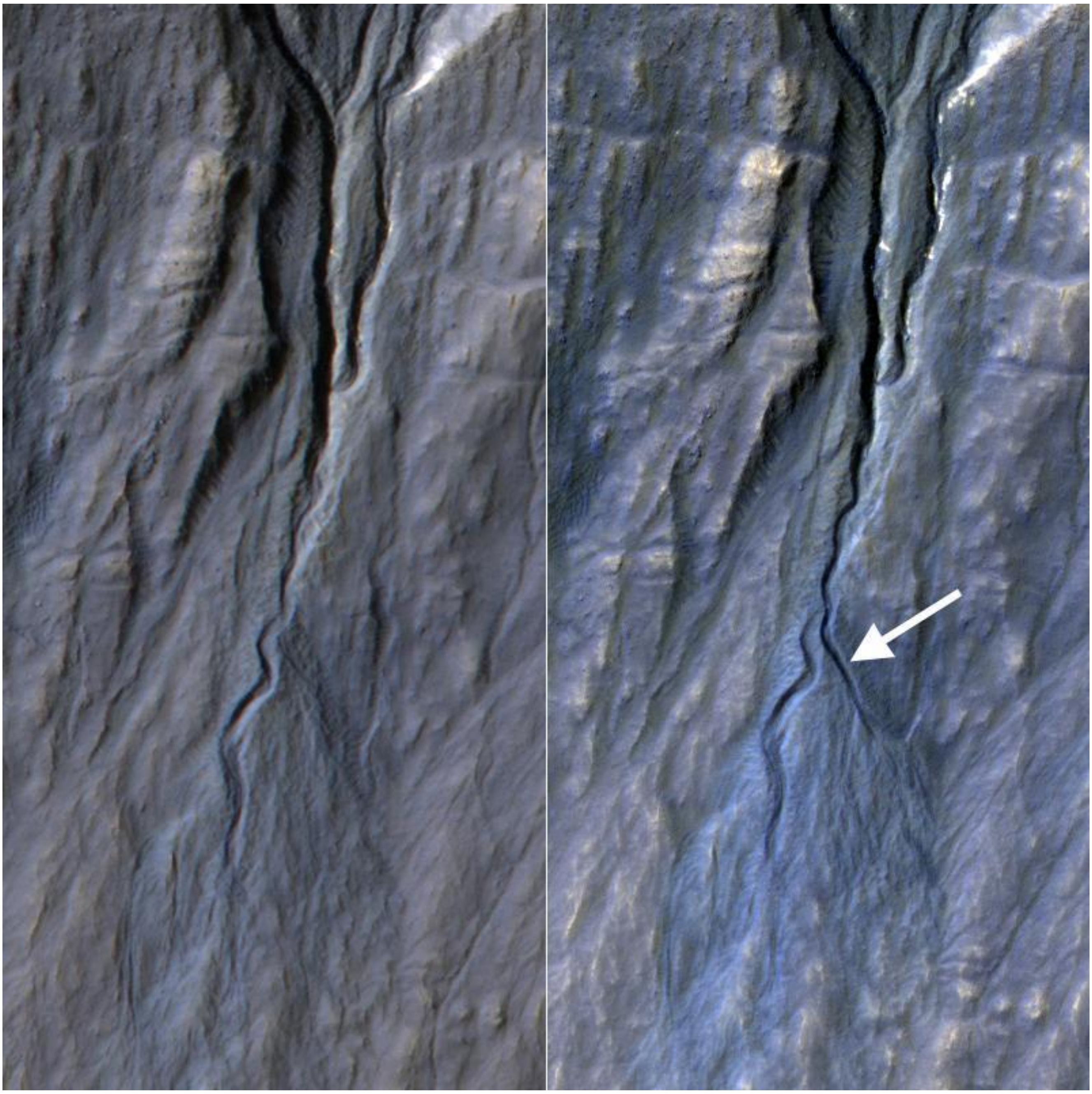
A colour image of the delta in Jezero Crater (image source NASA). This is the landing site for Mars 2020.



Landslide on a 200 meter-high slope in Kasei Valles. The scar left by the landslide reveals layers in the bedrock at the top the slope and shows dark-toned, house sized boulders that rolled down the slope and collected at the base of the landslide scar (part of NASA Photojournal image PIA04269).



Patterned ground at the Phoenix landing site (image PIA10680 courtesy NASA/JPL-Caltech).



A new gully channel in Terra Sirenum formed between 5 Nov 2010 (left) and 25 May 2013 (right) (HiRISE image PIA17958).

Local Variations seen by Landers and Rovers

Seven probes have landed on Mars, starting with Viking 1 and 2 in 1976. Two are still operating. Opportunity arrived on 25 January 2004 and Curiosity on 6 August 2012. These missions all sent back images from the surface along with increasing amounts of chemical and mineralogical data. This information has allowed considerable advances in our knowledge of the Martian surface, only some of which can be illustrated here.

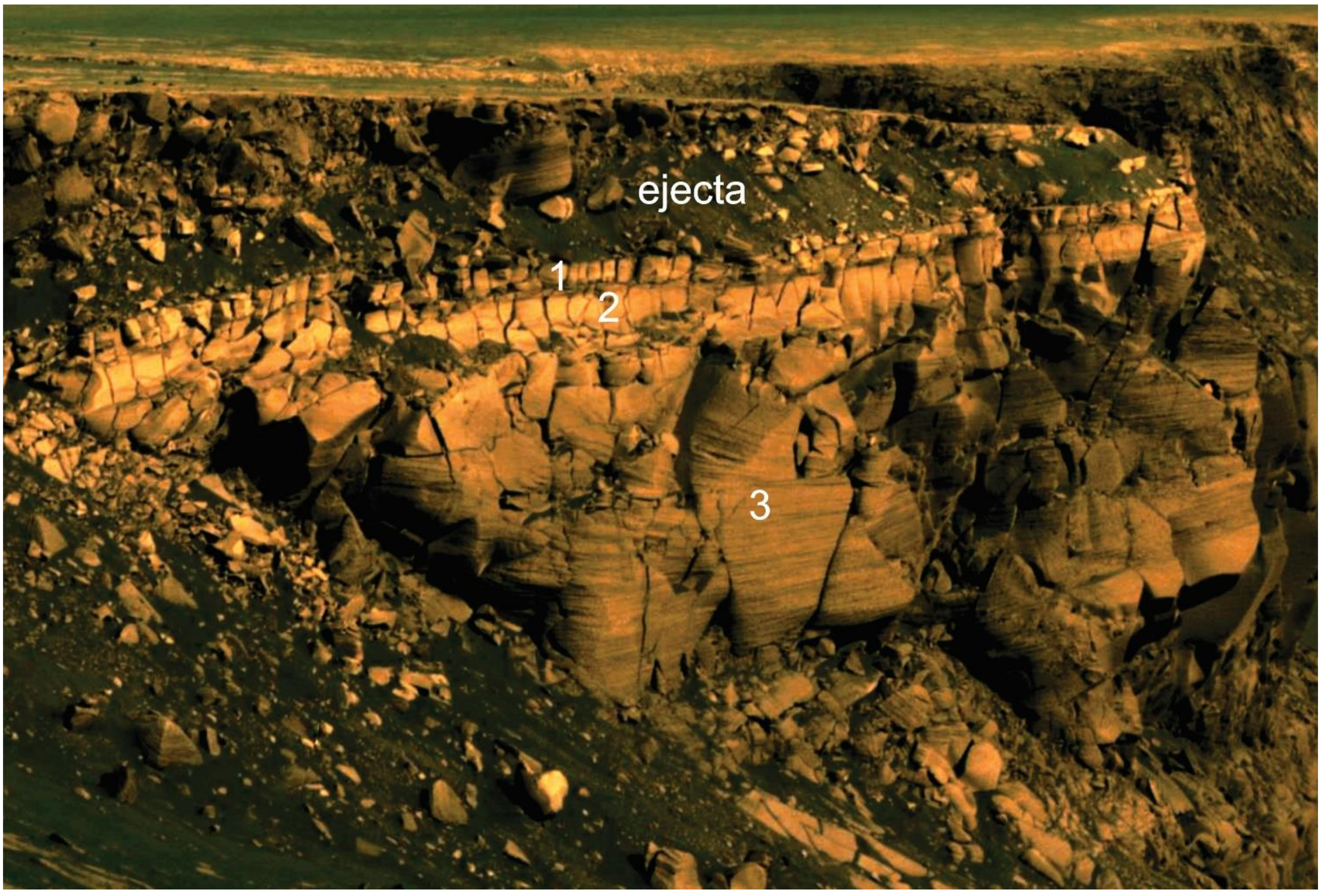
Mars is known to have patterned ground consisting of different coloured material outlining polygons. On Earth this type of pattern is common in polar areas, and in 2008 the Phoenix lander sent back images that show very similar patterns. Excavations carried out by Phoenix showed the presence of ice lenses in the subsurface of its polar landing site suggesting that the patterned ground there has a similar origin. The lander images thus allow more certain interpretations to be made of features on Mars.

Another example of the important data coming from the surface is that of Gale Crater, currently being studied by the Mars Science Laboratory (Curiosity) rover. Interpretation of Curiosity images shows that Gale was filled with inter-fingering fluvial, deltaic and lacustrine sedimentary rocks with minor aeolian beds. These are overlain by lake-bed sediments of laminated mudstones with minor inter-fingered sandstones. Both these groups of sediments were buried to a substantial depth as represented by the height of Mount Sharp in the middle of the crater.

Wind erosion then stripped away much of the material that filled Gale Crater, leaving Mount Sharp upstanding in the middle. Following the erosion the lake deposits were covered with wind-blown sands. Clever use of the chemical data obtained by Curiosity gives a potassium-argon age for the lake beds of at least 1.6 billion years, and possibly as much as 4 billion years. Different chemical data on cosmic rays suggest that the surface cut by erosion of the lake beds was exposed again perhaps 80 million years ago.

The presence of sand dunes and water-laid deposits visible from orbit shows that rocks are being broken down at least by physical processes so they can be eroded and the finer particles moved around. Rover images and analyses from the surface show quite clearly that chemical changes are also taking place, so materials on the Martian surface undergo the same kinds of alteration as they do on Earth. A good example is provided by an image of onion-skin weathering obtained from the Spirit rover in Gusev Crater. This kind of weathering almost certainly requires chemical changes in the original rock, and is very similar to onion-skin weathering on Earth.

Recent work shows that the surface of Meridiani Planum has weathering profiles that resemble the chemistry and morphology of hyperarid soils on Earth. It is now well known that water has influenced the upper parts of the Martian regolith, so the presence of distinctive "soils" with vertical trends in properties is not surprising. Even more interesting is the likelihood that these processes may still be operating, although whether the resulting profiles are soils is a matter for debate.

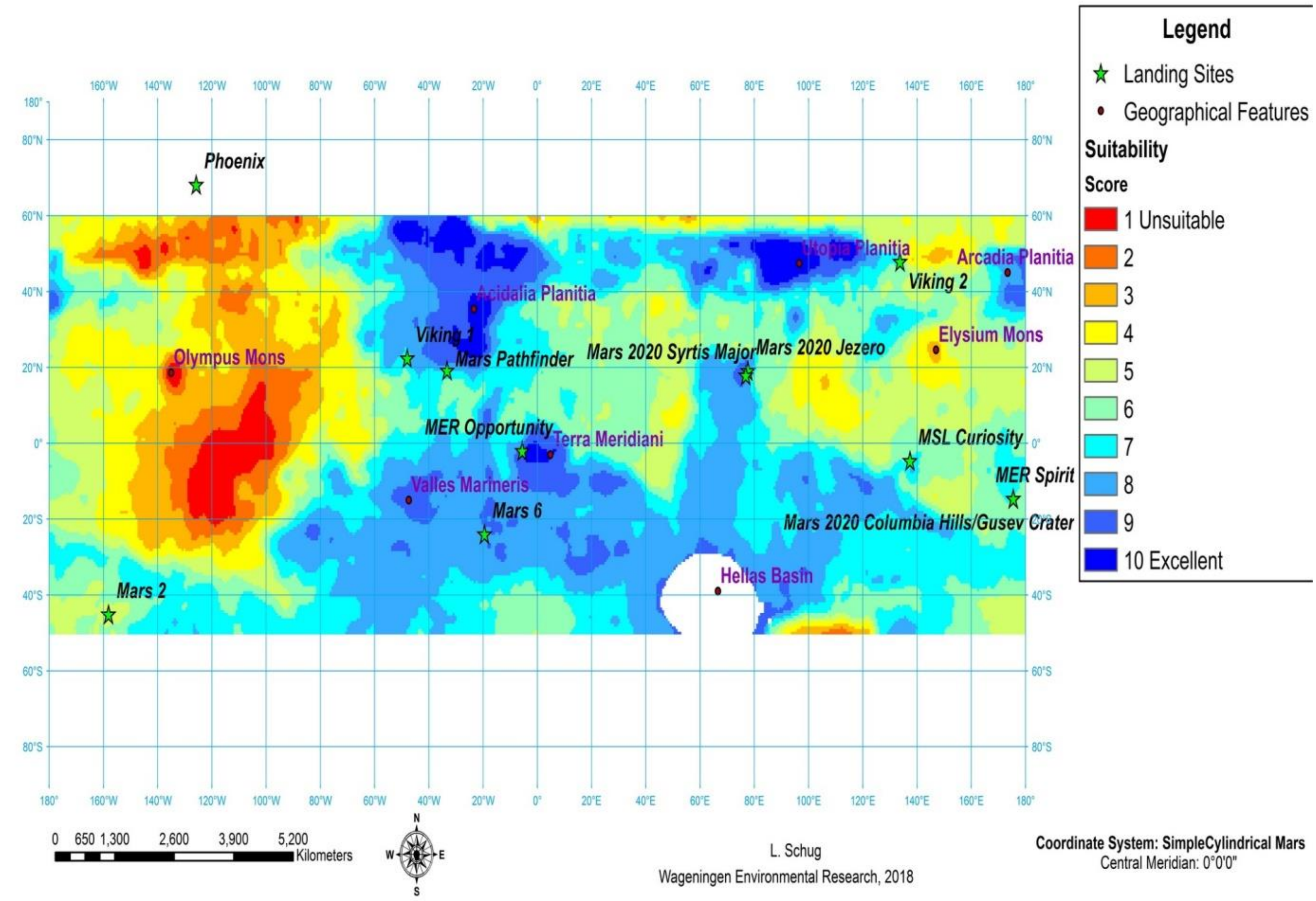


Weathering profile on the edge of Victoria Crater showing three horizons (numbered). The frequency of cracks decreases downwards (part of NASA image PIA09694) (See Amundson 2018).

What's the Use?

Much of the early work on the Martian surface was aimed at finding suitable places for landers. The main criterion was safety – the landers had to be able to land and then carry out their designated research. A second criterion was interesting geology. These two criteria tend to be mutually opposed, with many vigorous discussions between engineers and geologists. But recently there has been some interesting work on interpreting the surface from the point of view of sending crewed missions to Mars. One example is the work being done by people at Wageningen University & Research, who have identified places on Mars that may be favourable for plant species from Earth to grow. They have used maps that show the distribution of minerals such as calcium and heavy metals, as well as potassium, chloride, iron and silicon. They also use maps of radiation level, climate, terrain including altitude, and cosmic radiation. When combined the resulting map shows places on Mars that are favourable for plants to grow.

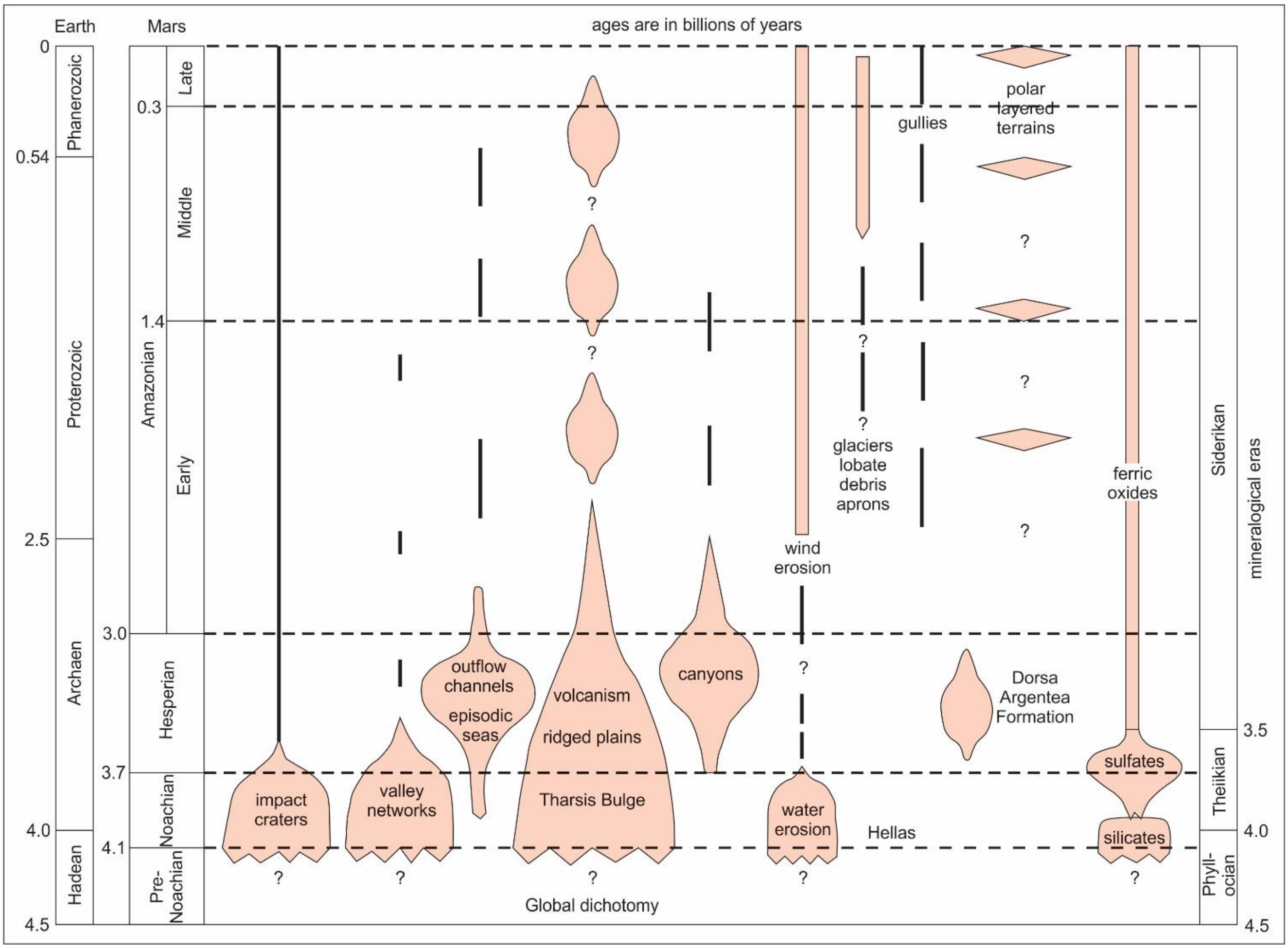
Over the past 50 years our understanding of Mars has changed profoundly from a science fiction world to a planet hosting diverse geologic processes, interesting in its own right. Mars isn't quite like the Moon, nor is it quite like the Earth. A common phrase now being used by many planetary scientists is "Mars is Mars". The dreamscape canal and vegetation-covered surface of yesteryear has instead been replaced with monster volcanoes, a massive valley system, and hard evidence of water-based outflows. When or whether Mars will actually host a crewed mission remains an open question, though Mars remains interesting enough to host robotic exploration for decades to come.



Land suitability for plant growth on Mars (from https://www.wur.nl/en/newsarticle/The-ideal-settlement-site-on-Mars-hotspots-if-you-asked-a-crop.htm).

Image of Columbia Hills acquired by Spirit. Part of NASA image PIA05728.

Martian Geological Time



A geological timeline for Mars showing the relative importance of different processes and events (modified from Carr and Head 2010). Numbers are billions of years. Boundaries of the major eras of Mars history are on the left together with the major subdivisions of Earth history for comparison. Mars was a busy place up to about 3 billion years ago, but there has been a lot less action since then. In contrast almost all the things we see on Earth's surface are a consequence of activity in the last half billion years, and most of it is much younger.

The Dorsa Argentea Formation is a set of geomorphologic units covering ~1.5 million square kilometres surrounding the south pole of Mars. It has been interpreted as the remnants of a larger south polar ice sheet that formed near the Noachian-Hesperian boundary and receded in the early Hesperian era.

In 2006, researchers using data from the OMEGA Visible and Infrared Mineralogical Mapping Spectrometer on board the Mars Express orbiter proposed an alternative Martian timescale based on the predominant type of mineral alteration that occurred on Mars due to different styles of chemical weathering in the planet's past. They proposed dividing the history of the Mars into three eras: the Phyllocian (dominated by non-acid water weathering to produce clays), the Theiikian (dominated by acidic water weathering to produce sulphates) and the Siderikan (dominated by oxidation to produce iron oxides, the origin of Mars' red colour).

A Brief History of Humans-to-Mars

Shaun Moss

In this chapter we will briefly review some of the recent history related to settlement of Mars, including some of the main events and players that have had the greatest effect on the movement. For practical reasons this review isn't comprehensive, because so much has happened around the world to boost the Mars movement to its current momentum. However, we can touch on some of the key developments.

Dawn of a Revolution

The seeds of revolution are planted long before it becomes visible. There are always a select few who become alerted to a movement early, begin to get organised, and gradually bring others into their vision so it can spread.

The idea of living in space started to gain momentum in the early-to-mid 20th century during the "Golden Age of Science Fiction", in the stories of Philip K. Dick, Ray Bradbury, Arthur C. Clarke, Robert A. Heinlein, Edgar Rice Burroughs, and others. Dreams of human exploration of Mars took root in the minds of scientists, engineers, and others within the newly formed NASA, who had grown up with model rockets and science fiction. Wernher von Braun's "Das Marsprojekt" (The Mars Project), written in 1948, is generally acknowledged to be the first technically feasible proposal for a human Mars mission.

With the success of the Apollo program, many within the halls and cubicles of NASA hoped a base on the Moon and human missions to Mars would follow. However, this was not to be. The Apollo program was achieved with a vast, but temporary, increase of expenditure in order to achieve the political goal of outshining the Russians in the emerging arena of space. Once that goal had been achieved, this inflated level of spending could not be maintained, and focus shifted to more modest space projects such as Skylab, the Space Shuttle, and interplanetary spacecraft such as Viking and Voyager.

However, the dream of sending humans to Mars did not die.

1980s

The Mars Underground

During the 1980s a group of NASA aerospace engineers and space scientists formed who were specifically interested in human missions to Mars. This group, known as the "Mars Underground", included legends such as Chris McKay and Carol Stoker, both now at NASA Ames, and luminaries in the Mars community.

The Mars Underground organised and led the "Case for Mars" conferences, which brought together like-minded scientists and engineers from across the world who believed sending people to Mars was important and a near-term possibility. These conferences discussed exploration, settlement, and terraforming of Mars.

The Space Frontier Foundation and NewSpace

In 1988, space advocates Rick Tumlinson, Bob Werb, and James Muncy established the Space Frontier Foundation, with a vision of large-scale settlement of the Solar System, emphasising private enterprise.

The organisation thus became an early advocate of the "NewSpace" paradigm, which refers to commercial space exploration and development, generally characterised as being young, modern, lean, agile, exciting, and inspired, and more focused on the development of space for industry and settlement. By contrast, "old space" refers to the centralised, bureaucratic, and highly expensive government-led space programs that have characterised most space exploration to date. These programs are more focused on science and national interests.

In the US, companies such as SpaceX, Moon Express, Astrobotic, Consensys, and others are associated with the NewSpace movement, whereas the older companies who built hardware for NASA's human spaceflight program, such as Boeing, Lockheed Martin, and Northrup Grumman, are more usually associated with "old space". Most of the old space companies are heavily involved with defence, whereas NewSpace companies often aren't.

For several years the Space Frontier Foundation has run the NewSpace Conference, which brings together space entrepreneurs, investors, and enthusiasts to discuss the emerging commercial space industry, and to network. Ideas presented at these conferences are frequently at the leading edge of thinking about human expansion into space.

During the early years, the Space Frontier Foundation focused mainly on free space (especially Earth orbit) and the Moon. However, in recent years, as the movement and industry has advanced, the discussion has expanded to include asteroids and Mars.

The Space Exploration Initiative

In 1989, US President George H. W. Bush announced the Space Exploration Initiative (SEI). This included plans to construct a large, permanently crewed space station known as Space Station Freedom, followed by crewed missions to the Moon and Mars.

Following the announcement, NASA conducted the "90-Day Study" to determine the likely cost and timeline of this program. Unfortunately, the estimated maximum price tag of approximately $450 billion was far too high for approval by the US Congress.

Space Station Freedom was the only element of SEI that survived, ultimately evolving into the International Space Station.

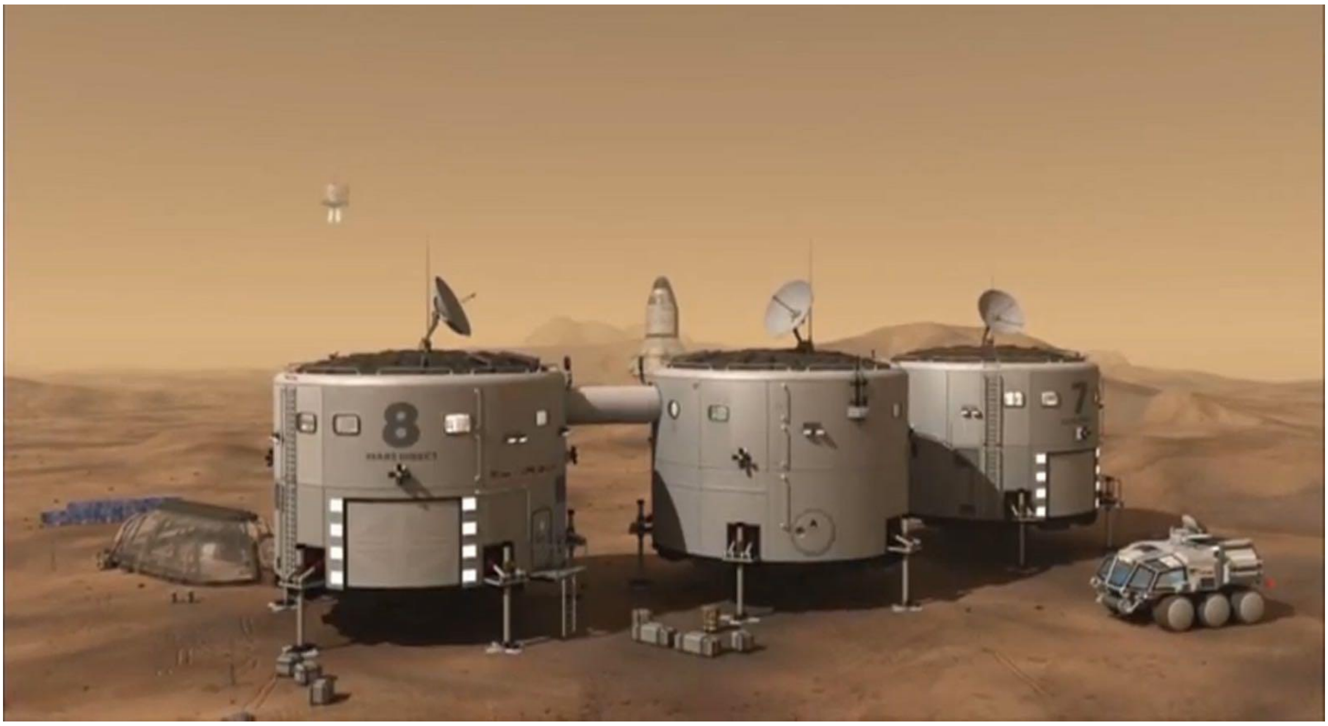
1990s

Mars Direct

One of the attendees of the Case for Mars conferences was an aerospace engineer from Martin Marietta named Robert Zubrin. An inspired and visionary science communicator, the movement received a major boost with the publishing of *The Case for Mars — The Plan to Settle the Red Planet and Why We Must* in 1996. This seminal book, by Zubrin and his colleague David Baker, described a new architecture for a mission called "Mars Direct" they had developed, which had received significant interest from many at NASA.

Mars Direct had several important features that made it significantly more focused, practical, and affordable than SEI or any other existing proposals. By leapfrogging the intermediate steps of building a space station and returning to the Moon, and utilising the Martian atmosphere as a resource for fuel production, the estimated cost of Mars Direct was about 10% of the projected cost of SEI.

The Mars Direct plan made popular the idea of the "tuna can" habitat, designed to fit neatly inside a cylindrical rocket fairing. This model became the template for the Mars Society's Mars Analog Research Stations established in Canada and Utah.



Tuna-can habitats on Mars

Mars Semi-Direct

With the publishing of *The Case for Mars*, the level of belief as to whether or when humans could go to Mars in the near term experienced a quantum leap, not only in the minds of NASA engineers and executives, but the space community worldwide. However, not everyone at NASA was convinced Zubrin and Baker's plan was optimal and expressed a variety of concerns. In response, Zubrin, with David Weaver from NASA Johnson Space Center, developed an updated version of the plan called "Mars Semi-Direct".

In Mars Direct, a vehicle known as the Earth Return Vehicle (ERV) lands on Mars autonomously, in advance of the crew, and starts producing propellant for the return journey to Earth.

By contrast, in Mars Semi-Direct, the ERV does not land on Mars but instead parks in Mars orbit. A smaller vehicle, called the Mars Ascent Vehicle (MAV), lands on Mars and starts making ascent propellant. At the end of the surface mission the

MAV carries the crew to Mars orbit and docks with the ERV, which than brings the crew back to Earth.

Since the MAV needs only to reach Mars orbit, it's smaller, making it easier to land on Mars. In addition, much less propellant is needed, which reduces risk, power requirements, and tank sizes.

While many at NASA were enthused by this new architecture, NASA still did not commit to sending humans to Mars, although they adapted Mars Semi-Direct into an official plan known as the Design Reference Mission. This plan has been refined over the years, and is now the Design Reference Architecture (DRA) version 5. It serves as a baseline architecture for a future NASA crewed Mars mission.

The Mars Society

Frustrated by NASA's lack of commitment, but now with a successful book and a following, Zubrin recognised there was considerable support in the wider community for sending humans to Mars. If NASA wouldn't listen, perhaps others would. Zubrin and some like-minded allies founded The Mars Society (TMS) in 1998. TMS has since held annual conferences that are inspired by, and similar to, the earlier series of Case for Mars conferences, except they're open to the worldwide community, including enthusiasts, academics, and others.

Chapters of TMS have been established in many other countries, although it has remained predominantly a US organisation. Numerous other Mars groups have since appeared, including the Mars Foundation, Mars Institute, Mars Initiative, Explore Mars, and others. The emergence of these groups demonstrates a growing enthusiasm for human exploration and settlement of Mars.

The Mars Trilogy

Many great science fiction writers have shown us their vision of Mars, including Edgar Rice Burroughs, Ray Bradbury, Robert A. Heinlein, Arthur C. Clarke, Isaac Asimov, Philip K. Dick, Ben Bova, and others. However, there is one who deserves special mention: Kim Stanley Robinson.

Robinson wrote the famous Mars Trilogy, comprising Red Mars (1993), Green Mars (1994) and Blue Mars (1996). These are hard science fiction novels based on realistic present and near-future science and technology. Beginning with the arrival of the first 100 settlers, the books tell the story of Mars settlement and terraforming over a period of about two centuries. The novels are inspired by the changing colours of Mars as it is terraformed: initially Mars is red, turning green as plants are introduced to the surface, and finally blue when Mars has oceans and seas, and the dust has washed out of the atmosphere.

The Mars Trilogy was important because it built a compelling and believable vision in the reader's mind, awakening them to the idea that settlement of Mars is possible, and may begin relatively soon.

Mars Homestead and Four Frontiers

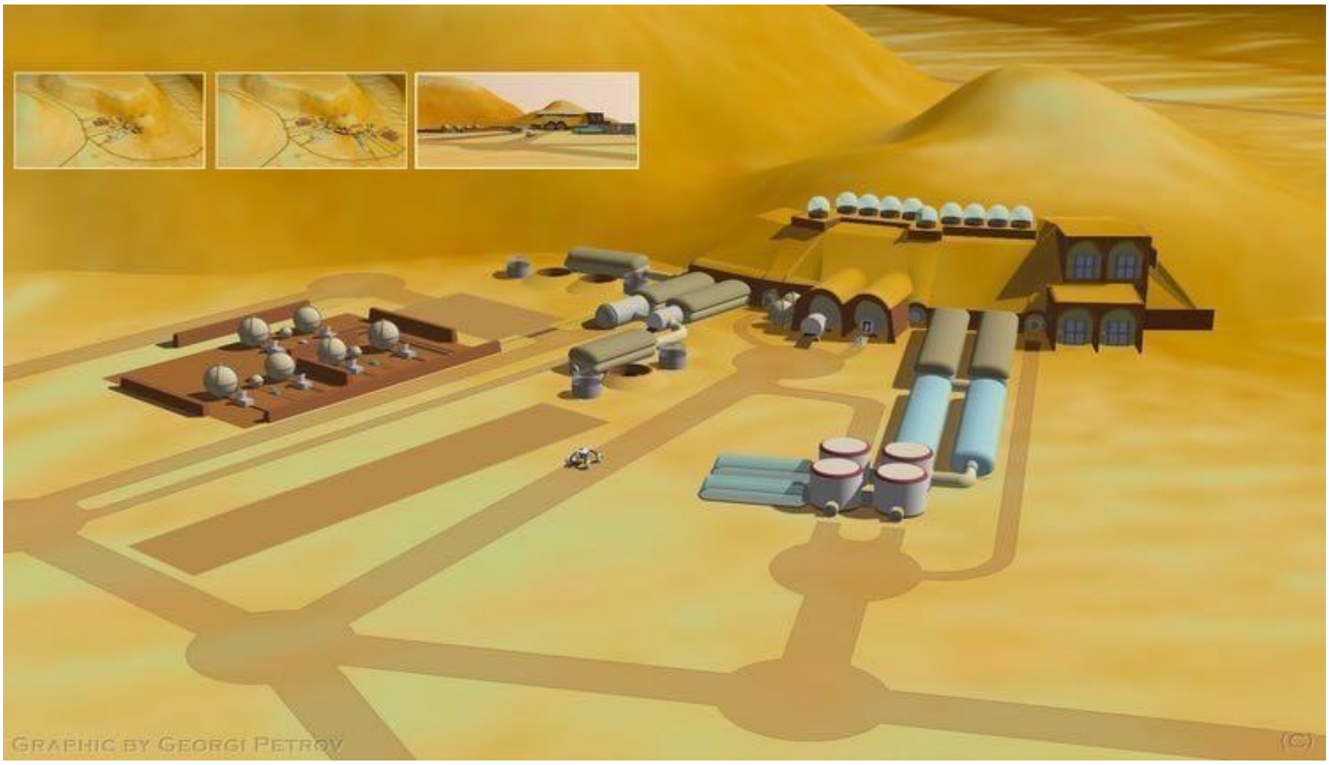
The Mars Society was primarily focused on human exploration of Mars, and convincing NASA to spearhead this effort. Many talks at the Mars Society conferences were about settlement. Given this interest, Bruce Mackenzie, Gary Fisher, and others from the Mars Society formed the Mars Foundation in 1999. Their main project, "Mars Homestead", was a plan to establish a permanent settlement on Mars.

The group had active online discussions and several in-person meetings. Their most important achievement was the development of the so-called "Hillside Settlement", which included underground habitation, greenhouses, nuclear power, rovers and docking ports, light pipes, recycling systems, and many other features. It is still one of the best-developed concepts for a Mars settlement ever produced.

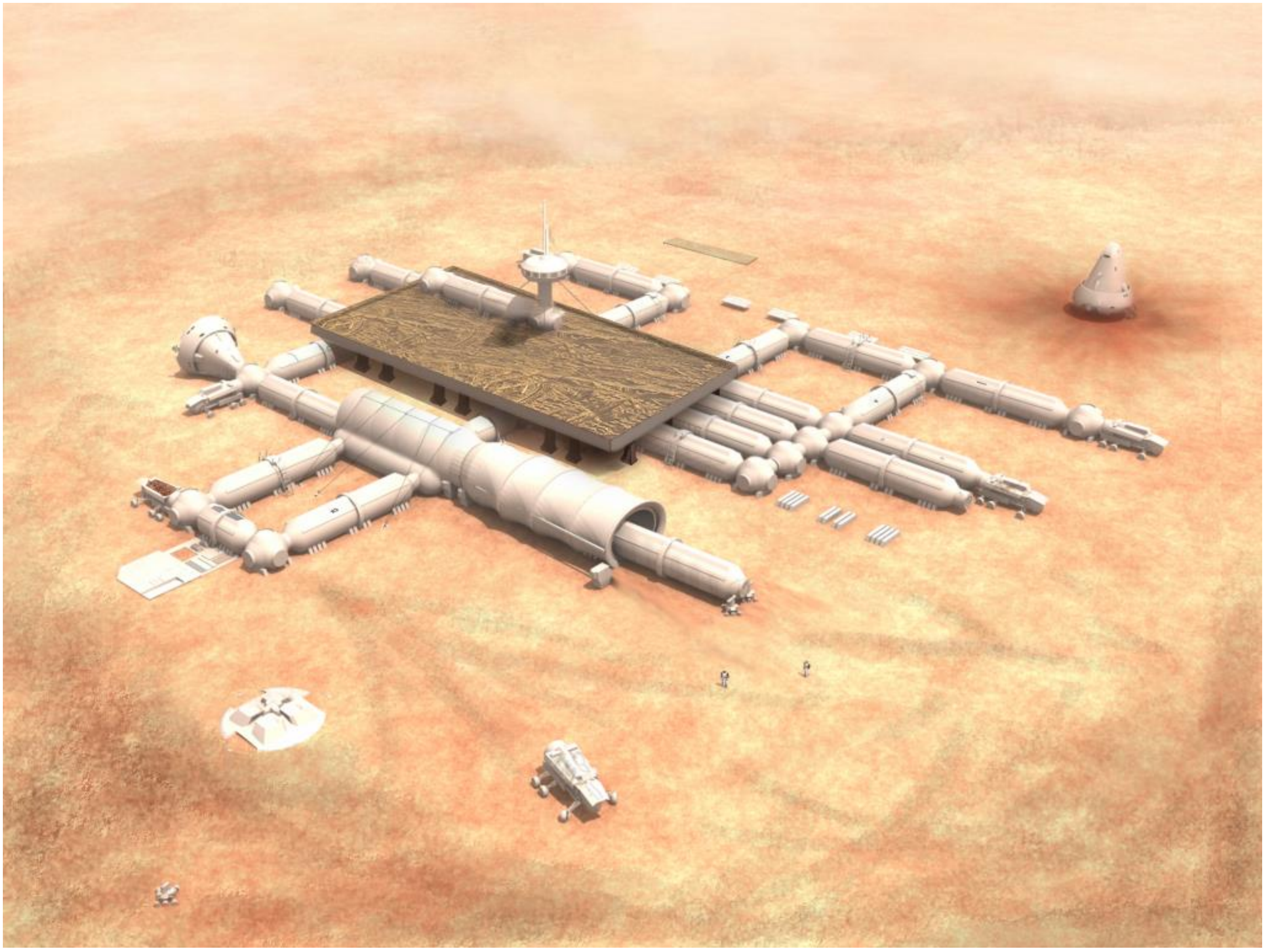
Discussions began within the group about how best to proceed. Some of the more business-minded members of the group wanted to start a company and make the designs proprietary, and develop products and services that would eventually lead to construction of the settlement. Others preferred to keep the ideas open and public, and to develop the settlement with more of an "open source" philosophy, in collaboration with the Mars community and academia.

Unable to agree, the group split, with the business-oriented members forming the Four Frontiers Corporation. This name refers to the four near-term frontiers of human activity in space: Earth orbit, the Moon, Mars, and the asteroids. Founded by entrepreneur Mark Homnick (CEO) and engineer Joseph Palaia (Vice President of Operations), Four Frontiers continued to develop the Hillside Settlement concept while also producing Mars-oriented educational and entertainment multimedia content. They also developed a concept for a space theme park called Interspace, to be located at Titusville, Florida, on 75 acres near Kennedy Space Center. However, unable to raise sufficient funds, they have gradually faded from view.

The Mars Foundation continues to work in collaboration with the Mars Society, promoting Mars settlement, and developing community software such as Marspedia and MarsVR. They have also developed an alternative, aboveground settlement concept called the Plains Settlement.



The Hillside Settlement (Credit: Mars Foundation)



The Plains Settlement (Credit: The Mars Foundation)

The Haughton-Mars Project

In 1997, Pascal Lee, then a graduate student, proposed Haughton Crater, on Devon Island in the Canadian high arctic, as an ideal site for conducting Mars analogue research. The location is cold, dry, and virtually devoid of plant life, and the terrain is very Mars-like. Being in Canada, it is also somewhat more accessible than other good Mars analogue environments such as the McMurdo Dry Valleys in Antarctica or the Atacama Desert in Chile.

Haughton's geology and climate makes it one of the best Mars analogues on Earth, and is known as "Mars on Earth". The site is now used for a wide variety of field research into both science and exploration, including biology, geology, agriculture, robotics, telemedicine, human-centred computing, surfaces vehicles, and more.

Pascal Lee is now the director of the Haughton-Mars Project at NASA Ames. The project is primarily funded by NASA and conducted by SETI and the Mars Institute, which Lee co-founded in 2002 and of which he is currently Chairman. Lee is also the designer of the distinctive red, green, and blue tricolour flag for Mars, inspired by Kim Stanley Robinson's Mars trilogy.

2000s

FMARS

When the Mars Society was founded, they declared their first major program would be to establish a number of "Mars Analogue Research Stations" (MARS), where simulated Mars missions would be conducted.

At a MARS, crew members role-play being astronauts on Mars. They live in a sealed habitat, and when they wish to conduct an EVA (extra-vehicular activity), i.e. go outside, they must don a realistic spacesuit and wait for a short period in an airlock to simulate pre- breathing. Communications between the habitat and mission support (located elsewhere, such as Denver, Colorado), are delayed by up to 20 minutes to simulate the communications lag astronauts on Mars will experience.

Haughton-Mars Project base camp on Devon Island.

The first MARS to be built was the Flashline Mars Arctic Research Station (FMARS), constructed by Robert Zubrin and other Mars Society members in 2000. It is on Devon Island just a few hundred metres east-south-east from the Haughton-Mars Project base camp.

From the perspective of FMARS, the HMP base camp is behind a ridge and not visible. This was done deliberately to add to the feeling of being in an isolated habitat on Mars.

Devon Island is a reasonably inaccessible site, and missions are conducted only during the summer. So far, 15 crews have been to FMARS.

Mars Gravity Biosatellite

In 2001, the entrepreneur Elon Musk, with $180 million in his pocket from the sale of PayPal and eager to contribute to the Mars program, approached

Dr Zubrin with the idea of investing up to $10 million in a Mars mission that would advance the cause. The “Mars Gravity Biosatellite” was born, a mission to send 15 mice to Earth orbit, subject them to Mars-level gravity by spinning the spacecraft, collect data, and return the mice safely back to Earth. They were to land at Woomera Test Range, a historic weapons testing area in South Australia. The intention of the mission was to learn more about the effect of Mars gravity on humans by studying the mice as a mammalian analogue.

The mission was subsequently developed by a consortium of universities, including the University of Washington, MIT, and the University of Queensland (UQ).

Unfortunately, hampered by ITAR (International Traffic in Arms Regulations) restrictions, funding issues, and an ever-shifting population of grad students, the mission was cancelled in 2009.

MDRS

The second MARS was the Mars Desert Research Station (MDRS), constructed in late 2001 near Hanksville, Utah.

The location is also Mars-like in appearance and geology. Although remote, it’s much more accessible than Devon Island, and the climate permits year-round missions. At the time of writing, more than 200 missions have been conducted to MDRS, involving researchers from all over the world.

FMARS flying the Mars flag.

The MDRS design included a number of improvements over the FMARS design, such as stairs, interior windows, ducted heating, a greenhouse, and an observatory. However, the habitat is made of cheaper and more conventional building materials, which are not as tough as the prefabricated fibreglass panels used to build FMARS. This, combined with the much larger number of missions, means MDRS is showing more wear-and-tear.

SpaceX

In 2002, after abandoning the idea of purchasing a Russian ICBM for conversion into a Mars rocket, Musk launched Space Exploration Technologies, also known as SpaceX, with the goal of extending human civilisation to Mars. Although many people did not initially predict success, the SpaceX team have proven themselves time and again, despite some early setbacks.

The first rocket developed by SpaceX was the Falcon 1. The first three launches failed, but on 28 September, 2008, the fourth Falcon 1 successfully reached orbit, making it the first privately built vehicle to do so.

An astronaut on EVA at FMARS

Musk and SpaceX had nearly run out of funds by the end of 2008. At the last minute, on 23 December, 2008, NASA offered SpaceX a $1.6 billion contract for 12 resupply flights to the ISS, saving the company. Since then, SpaceX has gone from strength to strength.

2010s

This decade has seen a noticeable increase in interest in human exploration and settlement of Mars.

By 2010, a growing torrent of websites, discussion forums, articles, and blogs had begun to flow from the worldwide community of enthusiasts, an increasing number of which were about human missions and settlement. However, the topic was still fairly niche and the movement had not yet fully penetrated mainstream consciousness. But things were about to change.

Mars 500

Mars 500 was a psychosocial isolation experiment conducted by Roscosmos, ESA, and CNSA, intended to study how astronauts would handle living and working together during a mission to Mars, including effects on relationships, stress, health, work capability, and other factors.

From 2007 to 2011, three crews of volunteers lived in a simulated environment at the Institute for Biomedical Problems in Moscow, Russia, which included a Mars Transfer Vehicle (MTV), a Mars landing module (ascent/descent vehicle), and the Martian surface. The three crews spent 15, 105, and 520 days in the simulation respectively. The first two missions tested the equipment and protocols, while the final and primary mission (June 2010-November 2011), with a crew of six male astronauts (three Russian, two European, and one Chinese), simulated a full Mars mission, including the outbound trip to Mars in the MTV, descent to Mars, four EVAs, ascent to the MTV, and return to Earth.

The simulation included a communications lag of up to 25 minutes, resource rationing, a hermetically sealed environment, and crew activities similar to those likely to be required from astronauts on a Mars mission. The simulated MTV included six crew cabins, a kitchen/dining room, living room, main control room, medical berths, equipment for medical examinations, food storage, an experimental greenhouse, a bathroom, toilets, a sauna, and a gym. The Mars landing module simulator, used for only 30 days, contained three bunk beds, two workstations, a toilet, and subsystems for communications, science, life support, and environment control.

The astronauts emerged from the simulation in optimal physical and psychological health, despite minor problems experienced during the simulation, including difficulty sleeping, skipping exercise, and withdrawal from the rest of the crew. Cultural and language differences (for, although all spoke some English, not all spoke Russian) did not present any major problems, communications remained friendly and constructive throughout the mission, and the crew were able to work together to solve complicated challenges.

Although the Mars 500 experiment could not simulate all aspects of a Mars mission, such as the physiological stresses produced by radiation and hypogravity, or the psychological stresses that would be caused by genuine isolation and danger, it nonetheless successfully demonstrated an international crew can work together effectively in a situation and environment, and over a period of time, analogous to a Mars mission.

The Martian

Another author who has attained recent prominence is Andy Weir. With his breakthrough novel The Martian (2011), Weir crafted a realistic and compelling narrative about survival on Mars, including precise calculations of orbits and resource requirements, and detailed problem solving. A film adaptation of the novel, directed by Ridley Scott, was released in 2015.

Both the book and the movie have given a huge boost to the Mars revolution by transporting everyday people to Mars and showing them a realistic vision of human missions.

Mars One

On 31 May, 2012, Dutch entrepreneur Bas Lansdorp announced the Mars One mission, a private effort to send multiple crews of astronauts on a one-way mission to colonise Mars, starting in 2023.

The announcement of an audacious plan to send as many as 40 astronauts on a one-way mission to Mars to spend the rest of their lives as the subjects of an interplanetary reality TV show, seemed, to many, like an absurd and incredible concept. The sentiments of space journalists evolved from mockery to cautious interest, and even enthusiasm, before devolving to derision and accusations of fraud once the plan's flaws were more fully revealed.

Mars One triggered discussion and debate among scientists, engineers, enthusiasts, students, its eager astronaut candidates, the organisers, and media. It inspired numerous presentations, scientific papers, debates, interviews, and articles. The process of recruiting potential civilian astronauts commenced in 2013; their plan was to send the first robots to Mars in 2018 and the first crew of four in 2025.

Mars One failed to gain much traction due to lack of credibility and money. The plan they originally revealed lacked sufficient details, and was implausible. Although Bas has said they always expected their plans to evolve and become more detailed over time as they raised money and became able to invest more in engineering, unfortunately it was never credible enough from the outset to raise that money.

Mars One became labelled a scam due to their acceptance of money from applicants and candidate astronauts despite the probability of success being very low. Although Mars One was created with sincere intentions, they made some unfortunate mistakes, causing many people to perceive it negatively.

In spite of this, Mars One garnered a lot of supporters, and their efforts achieved several important things:

1. They shifted the idea of Mars settlement into mainstream consciousness. Prior to Mars One, it was mainly only space professionals and enthusiasts thinking about sending humans to Mars. Mars One stimulated considerable discussion and research worldwide, positive and negative, and this ultimately benefitted the whole Mars settlement movement.
2. They helped to demonstrate there is genuine interest in Mars settlement in the global community. More than 200,000 people indicated their willingness to leave Earth and their families, partners, friends, jobs, businesses, and all the comforts and conveniences of their home planet, in order to participate in the grandest adventure in modern history, even if it involves great danger.
3. They stimulated considerable thinking and discussion in the community about how settlement of Mars could really be achieved. Mars One's proposal has highlighted some of the major engineering and financial challenges associated with the settlement of Mars:
    - A Mars settlement will need a much higher degree of self-sufficiency than anticipated.
    - The financial requirement will likely need to be much larger than their estimates.
    - The business case for a Mars settlement will probably not be based on television or advertising.

Mars One captured the attention and imagination of the world, inspiring the global public to think about Mars settlement more than ever before. Along with NASA, SpaceX, and others, they have helped elevate Mars in the global consciousness.

Over 100 countries now have a connection to Mars in the form of their astronaut candidates, many of whom have become local celebrities and are regularly giving presentations, inspiring students and others to get involved in STEM and space. This outcome should not be trivialised, having helped create a positive and exciting vision for the future of Mars in the minds of those most likely to go.

HI-SEAS

NASA established the Hawaii Space Exploration Analog and Simulation (HI-SEAS) another Mars analogue research station, on the slopes of Muana Loa volcano in 2013. This location is rocky, isolated, and very Mars-like. Missions to HI-SEAS are generally much longer than those conducted at FMARS or MDRS, lasting from 4–12 months.

So far, five missions have been conducted to HI-SEAS. The primary focus of these studies has included food and cooking; simulated EVAs and field research, including exploration, geology, and biology; physical and mental health; and crew isolation, group dynamics, problem-solving, conflict resolution, and other human factors. These studies have added greater insight into the various challenges likely to be faced by human crews on Mars.

Mars Settlement Design Competitions

In 2015, visionary architect and filmmaker Vera Mulyani founded Mars City Design, who subsequently launched its annual International Design Competition. This competition has inspired over 100 teams of students, designers, and architects from all over the world to submit Mars settlement concepts. These designs and ideas are further contributing to the dream of an inhabited Mars, and some are bound to influence the designs of real settlements.

The intention is to construct one or more of the successful design entries in the Mojave Desert, as a demonstration Mars settlement.

Also in 2015, NASA launched the 3D-Printed Habitat Challenge, which invited participants to design habitation solutions for the Moon, Mars, and beyond. Most entries have focused on Mars. Phase 1 (Design) was completed in 2015, phase 2 (structural members) was completed in 2017, and phase 3 (on site habitat), in which finalists fabricate sub-scale habitats, is underway in 2019.

In addition, the Mars Society held their first Mars Colony Prize Competition in 2019, selecting 10 finalists out of 100 entries.

SpaceX continued

The Falcon 1 was replaced by the larger Falcon 9, which was first successfully launched in 2010. As of late 2019 the Falcon 9 has been launched 75 times, with 73 successes, one partial failure, and one total loss of spacecraft. With many successful payload deliveries under their belt, and making groundbreaking progress with reusable launch vehicle technology, SpaceX has converted many disbelievers and positioned itself to be a key player in the space settlement movement. Their intention is to transport thousands or even millions of people to Mars and establish a self-sustaining city.

On 25 May 2012, the SpaceX Dragon capsule, launched atop a Falcon 9, became the first commercial spacecraft ever to dock with the International Space Station. Dragon capsules have since flown 18 successful missions to the ISS at the time of writing, with some capsules having been used for multiple missions. A crewed version of the Dragon capsule called Dragon 2 has been developed for transporting crew to and from the ISS, which is expected to commence in 2020.

SpaceX have also developed the Falcon Heavy, which is essentially a Falcon 9 plus two additional boosters, one on each side, equivalent to the Falcon 9 first stage. The partially reusable heavy-lift vehicle, which can deliver 64 tonnes to LEO or 17 tonnes to Mars, was first flown was in 2018, and has flown 3 times in total at the time of writing.

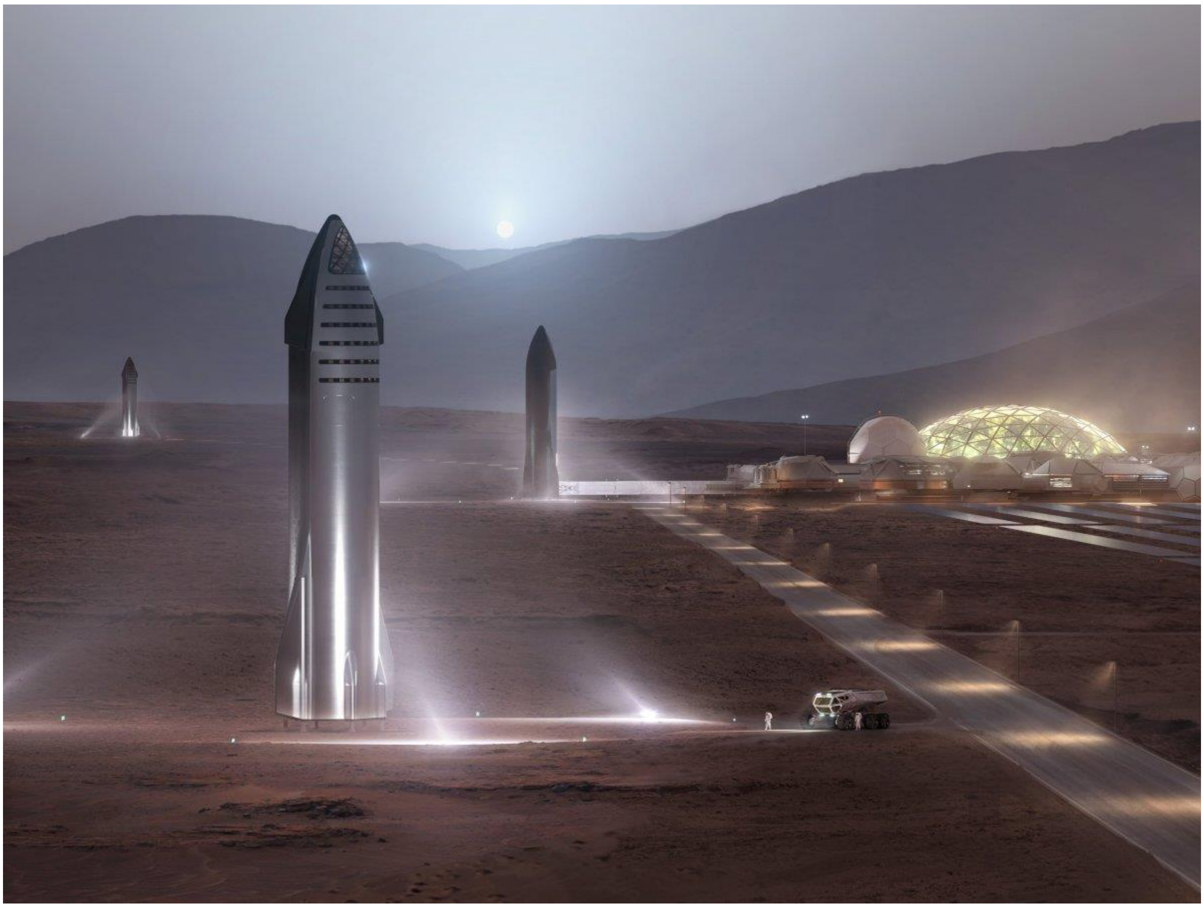
SpaceX’s Mars transportation architecture has gone through several iterations since the beginning of the decade. The original series of launch vehicles SpaceX planned to develop included the Falcon 9, Falcon Heavy, Falcon X, Falcon X Heavy, and Falcon XX. The Falcon X series of rockets, which were much larger than the Falcon 9 and Falcon Heavy, were originally conceived as vehicles to transport crew and cargo to Mars. However, they were never developed; instead, SpaceX announced in 2012 they were developing a new vehicle named the Mars Colonial Transporter.

The Mars Colonial Transporter was renamed the Interplanetary Transport System (ITS) in 2016, reflecting the vehicle’s ability to reach destinations other than Mars. The ITS comprised two primary elements, code named Big Falcon Rocket (BFR) and Big Falcon Spaceship (BFS), which function as the first stage and second stage of a super-heavy launch vehicle. Both are fully reusable, which significantly reduces the cost per flight and per kilogram.

In 2017, SpaceX announced a modified version of the ITS with a smaller booster and spaceship, called Super Heavy and Starship respectively. The system is designed for flights to Earth orbit, the Moon, and Mars, as well as between destinations on Earth, which will increase the utility of the system and make it more economical. The Starship will come in three primary configurations: passenger and cargo transport, satellite delivery, and fuel tanker.

Both the Super Heavy and Starship utilise cryogenic methalox (methane and oxygen) as propellant. Although methane is unusual as a rocket fuel; most liquid-fuel rockets use kerosene or hydrogen. However, methane offers some important advantages, including that it can be produced on the surface of Mars from carbon dioxide and water, both of which are readily available and ubiquitous on Mars. This is similar to the process of propellant production described in the Mars Direct architecture, except that it uses water obtained from ice on Mars instead of hydrogen brought from Earth.

The process for transporting passengers and/or cargo to Mars is as follows:



SpaceX Mars base

- Super Heavy boosts the Starship to orbit, then returns to Earth for refuelling. The Starship parks on orbit.
- One or more Super Heavy vehicles are used to launch several full Starship fuel tankers to the orbit where the Mars-bound Starship is parked. Each fuel transfer is docked with the spaceship, tail-to-tail, for fuel transfer; once this is complete, the empty tanker returns to Earth for reuse.
- The fully fuelled spaceship flies to Mars, where it lands on the surface and crew/cargo is unloaded.

SpaceX are planning to send two Starships to Mars in 2022 carrying cargo including an automated propellant factory, solar panels, mining equipment, surface vehicles, food, and life support equipment. In 2024, the plan is to send four additional Starships: two with cargo, and two with crew. The crew will live in their Starships while setting up the solar array, habitats, life support systems, water and air mining equipment, greenhouses, propellant production systems, and landing and launch pads.

The cargo Starships will be refuelled when possible and sent back to Earth for reuse. Due to Mars' lower gravity, no Super Heavy is needed to boost a Starship to Mars orbit. Once Mars surface habitats and life support systems are operational, crew Starships can also be sent back to Earth, and any crew members who want to will be able to return with them if they wish.

In 2019, a prototype vehicle called Starhopper was built and tested. Several prototype Starships are also currently under construction and sub-orbital test flights should begin in 2020, with the goal of commencing commercial flights the following year.

SpaceX are planning to replace the Falcon 9, Falcon Heavy, and Dragon spacecraft with the Super Heavy and Starship in order to reduce costs by optimising their operations around a single system.

Where are we now?

Several space agencies have claimed to be developing plans for Mars bases, including NASA, Roscosmos, CNSA, ESA, and JAXA. However, such bases are likely to be visited only by elite astronauts. Luminaries like Musk, Tomlinson and Mulyani, have tapped into a grander dream: the settlement of Mars by "regular" people.

Initiatives by The Mars Society, NASA, the Mars Foundation, Four Frontiers, SpaceX, Mars One, Mars City Design, and others, have stimulated a variety of settlement concepts, fuelled the idea of the settlement of Mars by private enterprise and individuals, and driven a global conversation about how a city could potentially be financed and built. The success of NASA's Mars rovers Sojourner, Spirit, Opportunity, and Curiosity, and the novel and movie The Martian, have additionally fuelled public enthusiasm for Mars.

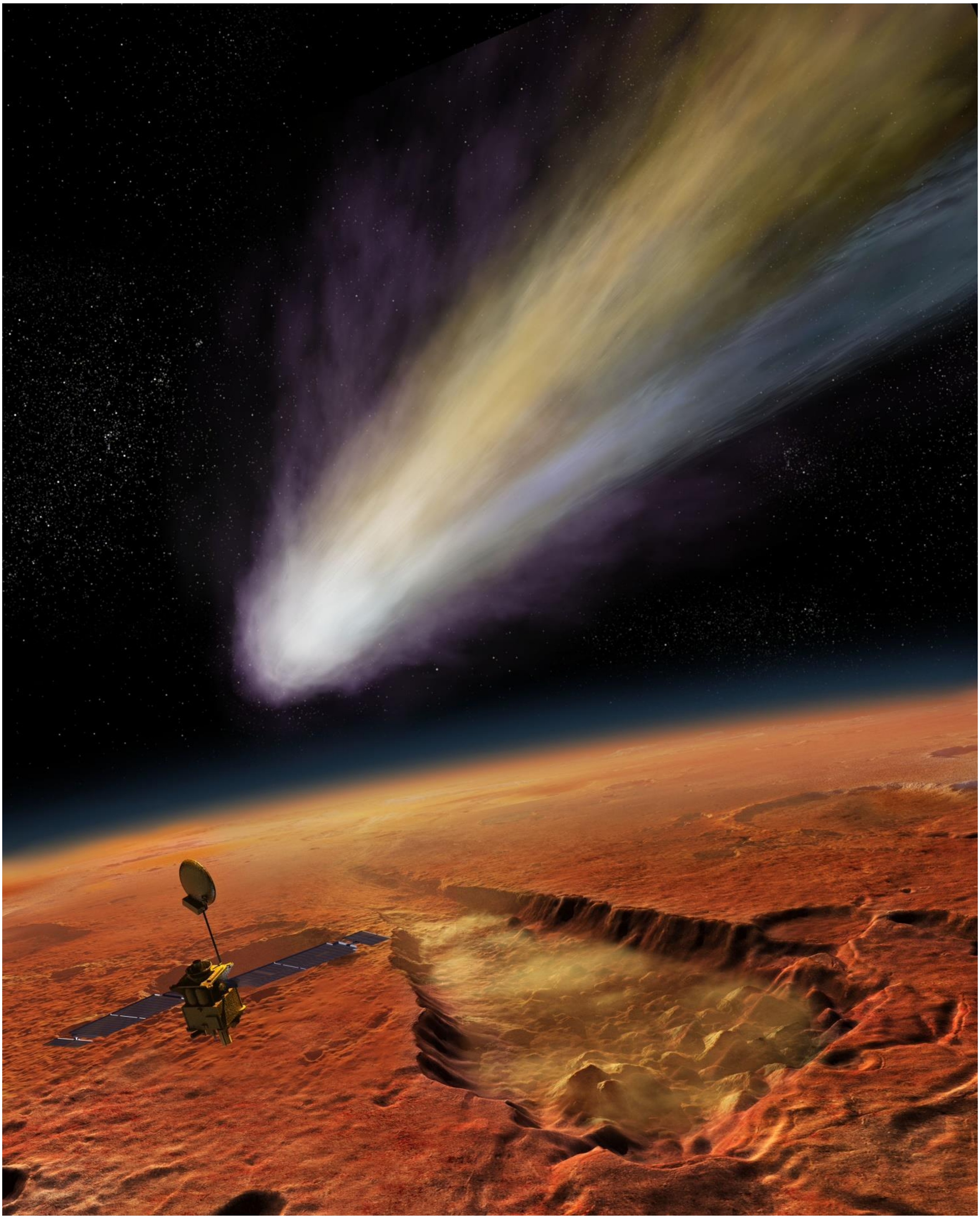
We're now truly on the verge of becoming a multiplanetary species. Students are designing cities for Mars, and enrolling in university courses with the intention to join Mars missions. Others are thinking and writing about the technologies, equipment, and systems necessary to survive on Mars.

More recent signs indicating humanity is getting seriously excited about the settlement of Mars include:

- Dozens of new Mars-themed computer and board games.
- Three rovers heading to Mars in 2020, including the Mars 2020 rover developed by NASA, the Rosalind Franklin developed by ESA and Roscosmos, and the Huoxing-1 developed by CNSA.
- India and Europe placing spacecraft in Mars orbit.
- Exploration and settlement of Mars being seriously discussed at almost every space conference.

The energy and enthusiasm is building. Almost everyone now acknowledges, whether via NASA, SpaceX, or some other organisation, humanity is going to Mars. The vision of human exploration of Mars is now firmly implanted in the global consciousness. Mars is no longer just a dream for science fiction enthusiasts. It has become a collective dream of humanity.

Phobos station (Digital art by Steven Hobbs)



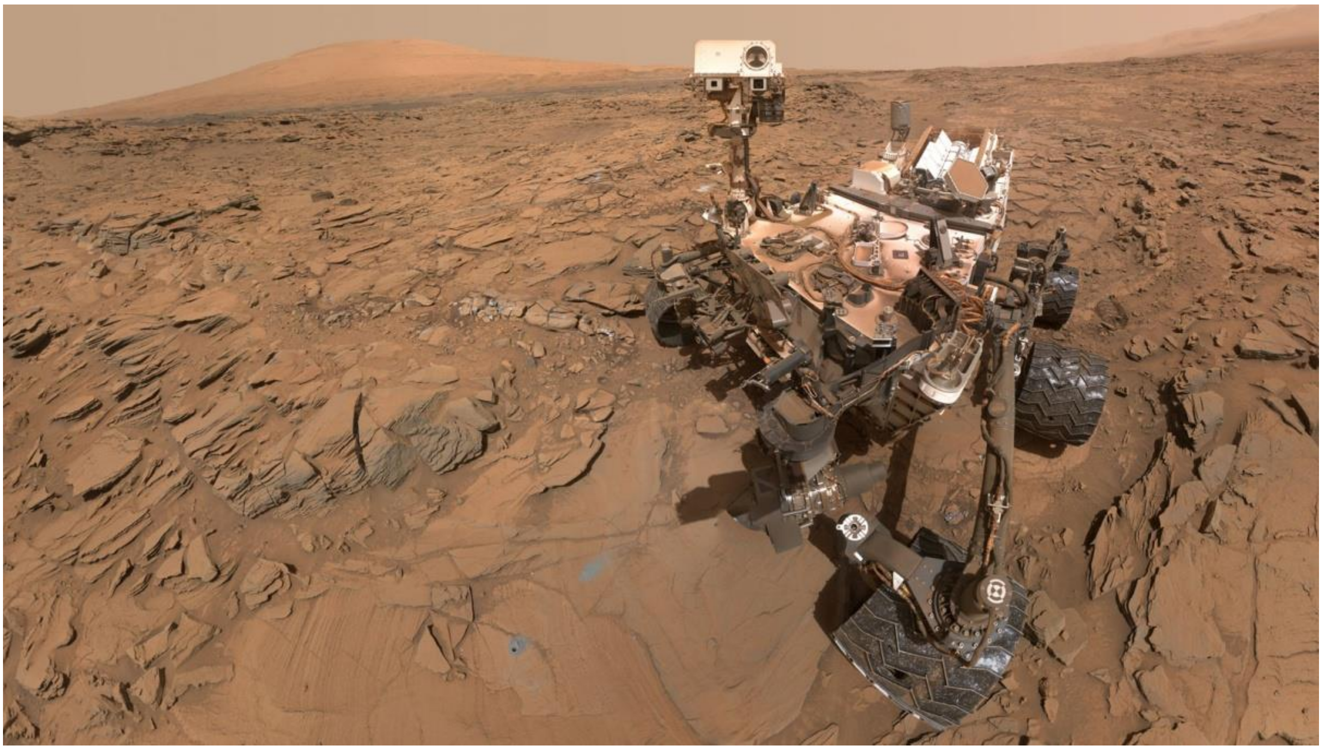
Mars comet (Digital art by Steven Hobbs)

What Might it be like to Live and Work on Mars?

Jonathan Clarke

Mars beckons us, like a giant orange in the sky. Over the centuries of human imagination it has been many things – place of imagination, a source of wisdom, a commentary on the human condition, a threat, a promise of escape, a new beginning, a frontier to conquer, a new world to explore, an opportunity for wealth, a place to create a new society, and many more. As the real Mars has begun to be revealed by telescopes and more by recently unmanned missions, the imaginary Mars of the past has been preserved like fossils in amber while the reality takes on a more immediate shape.

The real Mars is both beautiful and forbidding, a place of stunning landscapes and soft sunlight, but also a place with a tenuous and hostile atmosphere, characterised by extreme temperatures (from warm to cold enough to freeze the atmosphere), problematic dust, and high levels of cosmic radiation. This is a hostile frontier, more akin to Antarctica, the sea floor, or Earth orbit, than it is to the European settlement of the Americas or Australia that some draw parallels with. The technology to live on Mars will be a combination of advanced technology, some of which may not yet exist, and technology that dates back to the gaslight era of the industrial revolution and even to the earliest urban civilisations.



Curiosity rover in Gale Crater. NASA/JPL image.

Learning How to Live on Mars

We can approach the challenge of living on Mars in many ways. One is through designing the systems for living on Mars from first principles. More than 60 years of spacefaring has taught many lessons about what is needed in terms of structures, power supply, life support, logistic requirements, radiation protection, and all the other systems needed for a Mars mission and permanent Mars station. Most of this experience has been garnered in Earth orbit, and will need to be extrapolated to the surface on Mars with great care, with its new challenges of gravity, dust, isolation, and the need to live off the land for essential consumables such as propellant, breathing gases, power, and water.

Lessons from Mars missions

We have also learned much from decades of robotic operations in Mars orbit and on the planet's surface, at the time of writing more than two decades of continuous operations in Mars orbit starting with the *Mars Surveyor* spacecraft in 1996 and 14 years of continuous operation starting with the *Spirit* rover in 2004. These missions and others during this period have revolutionised our understanding of Mars, showing to it be much more diverse, complex, rich, and interesting place and had been thought before. New hazards, such as perchlorate salts, have been discovered, and old ones, such as radiation, have been laid to rest, at least partly. Some key questions have been answered, while others, especially whether Mars has – or ever had – life, have still not been answered. These data have great assisted people designing future missions and focussed the operations and goals of future crewed missions and stations.

Concordia Station, Dome C, Antarctica. ESA photo.

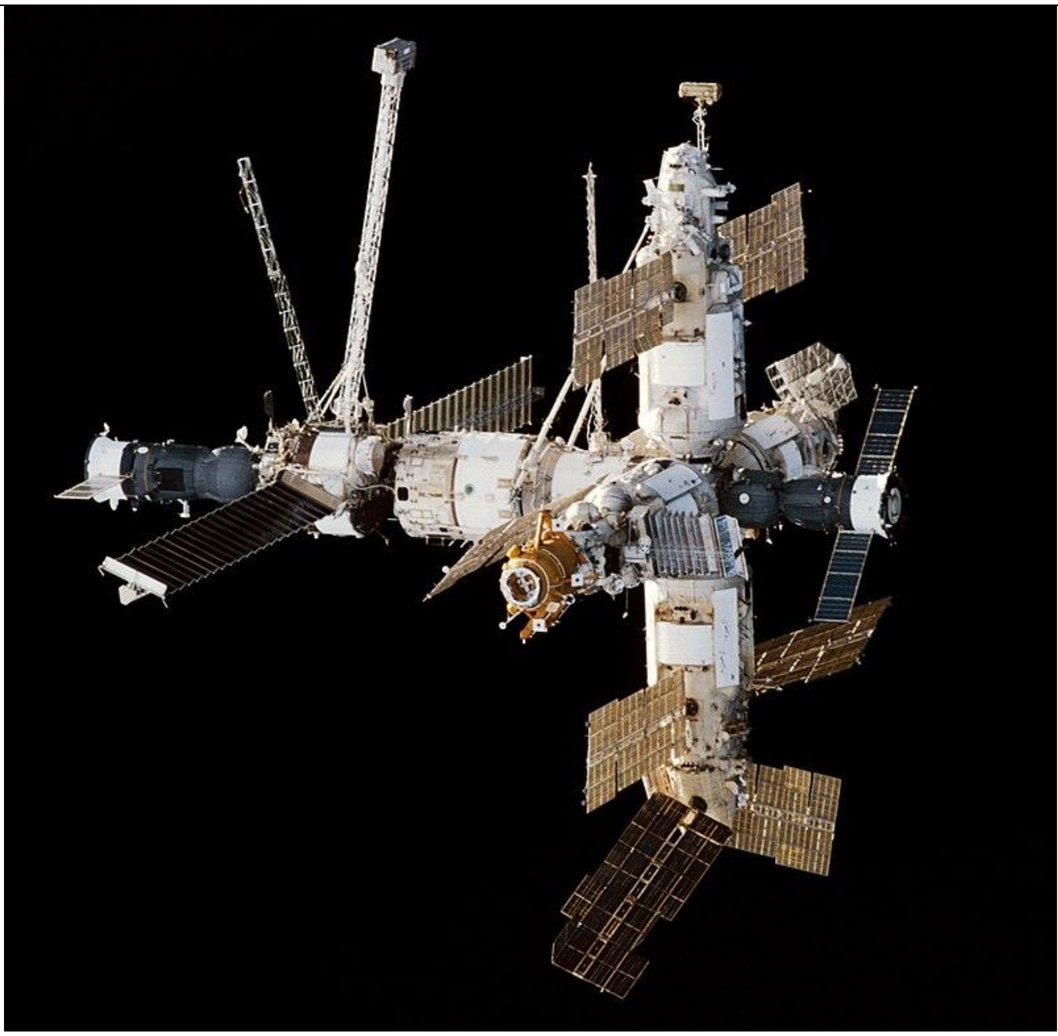
Isolated environments

A third way is through applying lessons learned in through operations and facilities in environments that offer similar challenges through their hostility and isolation. Some of the most significant examples have been polar stations, space stations in Earth orbit, nuclear submarines, and under-water habitats. Crews wintering over in Antarctica experience physical isolation, limited communications, a hostile outer environment of extreme cold, wind, dryness, darkness and, for inland stations, high altitude. Crew sizes are in the range of 10-50 people, similar to that which might be found in a permanent Mars station. The European Space Agency (ESA) has been a partner in the French-Italian Concordia station at Dome C in Antarctica since 2002, with crews carrying out research into biomedical and psycho-social questions related to long duration space flight and stations on the Moon and Mars since 2005.

Long duration missions to Earth orbiting space stations, starting with Salyut 1 in 1971 are now routine. Although there are significant differences between the physical and operational environments in low Earth orbit (LEO) and Mars, and the external environment even harsher, space stations are very helpful pointers to what is required. Life on a space station will be very similar to that on an interplanetary ferry between Mars and Earth. Many of the systems and structures will be similar, with allowances for the presence of gravity on Mars and the very different thermal and dust environments. Crews on space stations have ranged between two and six, similar to what might occur on a Mars mission, and people selected to go Mars will be very similar in skills, experience, qualifications, and personalities to those selected for missions to space stations. Mission durations to Mir and the ISS have typically been about six months, but flights as long as 14 months have been planned. The Aquarius underwater laboratory at a depth of 20 m off Key Largo in Florida is run by Florida International University and has been used since 2001 for the NASA Extreme Environment Mission Operations (NEEMO) program. Twenty two missions have been completed to date; they typically have crews of four aquanauts and last for seven to 14 days. Many of the aquanauts are astronauts. Additional support is sometimes provide by submersible crews or tele-operated equipment from the surface Crews investigate operation issues associated with EVAs on space stations, asteroids and, with appropriate ballasting, on the Moon and Mars.

Enclosure experiments

Enclosure experiments are yet another way to investigate issues relevant to Mars missions. These are generally run out of large research facilities which can provide the necessary support. They are ideal for testing key technologies such as closed life support systems. Enclosure experiments are often combined with studying the effect of long term enclosure of crew performance. Well known examples include the Biosphere 2 experiment, which featured a large glass house which supported a crew



Mir space station in its final configuration. NASA image.

Aquanauts returning to the Aquarius station after a simulated EVA during a NEEMO mission. NASA photo.

of eight for two years in 1991-93. They crew faced many challenges and many lessons were learned in what is still the longest such experiment run to date. The international Mars 500 expedition was run by the Institute for Biomedical Problems (IBMP) in Moscow and ran for 520 days in 2010-2011. IBMP are probably the world's leading centre for human factors in space light research, and have been conducting such research since the 1960s.

Biosphere 2, Arizona. Author's collection.

Hi-SEAS Mars analogue station. NASA photo.

Field analogue stations

Mars analogue research stations serve as platforms for diverse Mars related activities including engineering, systems, and operations research, astrogeology, and biology, and human factors studies. They are also effective tools for education and outreach activities.

Such stations were first conceived by Pascal Lee of the Mars Institute, who proposed to the US Mars Society that the first Mars analogue research station be constructed at the Institute's Haughton Mars Project on the rim of Haughton impact crater on Devon Island in the Canadian Arctic. This was constructed in 2000 and became the Flashline Mars Arctic research Station (FMARS). The US Mars Society subsequently constructed the Mars Desert Research Station (MDRS) in Utah in 2001. Other Mars analogue research stations have subsequently been built, most notably the Hi-SEAS station on the slopes on Mauna Loa volcano on Hawaii, operated by the University of Hawaii. Unlike MDRS and FMARS, HiSEAS is mostly used for remote location isolation and enclosure research. The crew generally go outside on simulated EVA once a week.

My own experience at these stations has consisted of four weeks at MDRS in 2003 (Expedition 1), two weeks each during 2010 and 2011 (crews 92 and 104), and 12 weeks in 2016 (Mars 160). I spent

Shared meal in the wardroom of the Mars 500 facility. IBMP photograph Mars Desert Research Station.

another five weeks at FMARS in 2017, also as part of the Mars 160 project. Through this experience I have been able to contribute both to Mars analogue research appreciate of what issues might face crews living and working on Mars. Perhaps most important of all I have gained a sense of what it might feel like to be part of a martian expedition.

Mars Desert Research Station

The MDRS is on the San Rafael Swell of southern Utah, approximately 12 km by road from the small town of Hanksville, east of Capitol Reef National Park. The area was chosen for its barren aspect, Mars-like red brown colouration, and diverse geology.

Upper deck of MDRS, Expedition One/Crew 11, 2003. Mars Society photo.

The station is built round a central module, known as the "Hab". This approximates the size and shape of a habitat module in a number of crewed Mars mission studies, such as "Mars Direct" and the early NASA Mars Reference Mission. The Hab is 8 m in diameter and 8 m high, including the domed roof. There are two decks, plus a half deck loft. The lower deck originally contained two airlocks, and EVA preparation room, toilet, shower, laboratory space and workshop. The laboratory and workshop were removed in 2016, converting the space into a multi-purpose area. Stairs connect the lover and upper decks. The upper deck is half taken by six individual cabins for the crew, and half by a combined galley and wardroom. This too was renovated in 2016 with removal of table round the periphery and their replacement with comfortable lunge furniture. Ladders connect the upper deck with the loft, which provide a seventh crew cabin, storage space, and an internal water tank. Gas provides heating and cooking, there is also a reverse cycle air conditioner for use in summer.

Park of lower deck, MDRS Expedition 1/Crew 11, in 2003. Mars Society photo.

The water comes from a bore in Hanksville and is transported onsite by trailer. Water consumption is typically about 30 litres per day per person. A range of toilet options have been tried over the 18 years of operation, including "Incinolet" incinerating toilets, "Biolet" composing toilets, and a standard flush toilet system. Grey water has been experimentally recycled through a "Living machine" purification system in the past. Currently however the toilet is a standard flush system to a septic tank. Power has been supplied in the past by diesel generators. Currently there is a solar array with a large battery system to provide much of the power, with a diesel boost and backup system.

The MDRS initially consisted of the Hab and a small greenhouse. Over the years this was added to and modified. The current greenhouse is the third version, replacing structures destroyed by storms and fire. New facilities include several observatories, a science dome, and a Remote Assembly Module that acts as an external storage area and workspace. Many of these facilities are connected by covered walkways, simulating pressurised tunnels. There is a resident onsite manager who lives in facilities close to the station, but hidden from view.

Simulated space suits are usually worn outside the station to simulate extra-vehicular activity (EVA) conditions. Under these conditions crews spend five minutes in the airlocks to "depressurise" and "repressurise". Simulation rules are, however abandoned in emergencies, where carrying out specific tasks are outside safe simulation constraints. Lights vehicles, typically quad bikes and electric 4WD utility vehicles, are provided to extend the surface range of the EVAs. Communications between the EVA team members and the Hab is provided by UFH. There is a satellite internet link for emails to and from the Hab.

View of the MDRS campus just prior to the start of the Mars 160 expedition 2016. Mars Society photo.

The current (April 2018) season is the 18th at the station. Seasons cover the autumn and spring months, summers being too hot for field activities under simulation conditions. Other programs have been run most summers, including the University Rover Challenge since 2007.

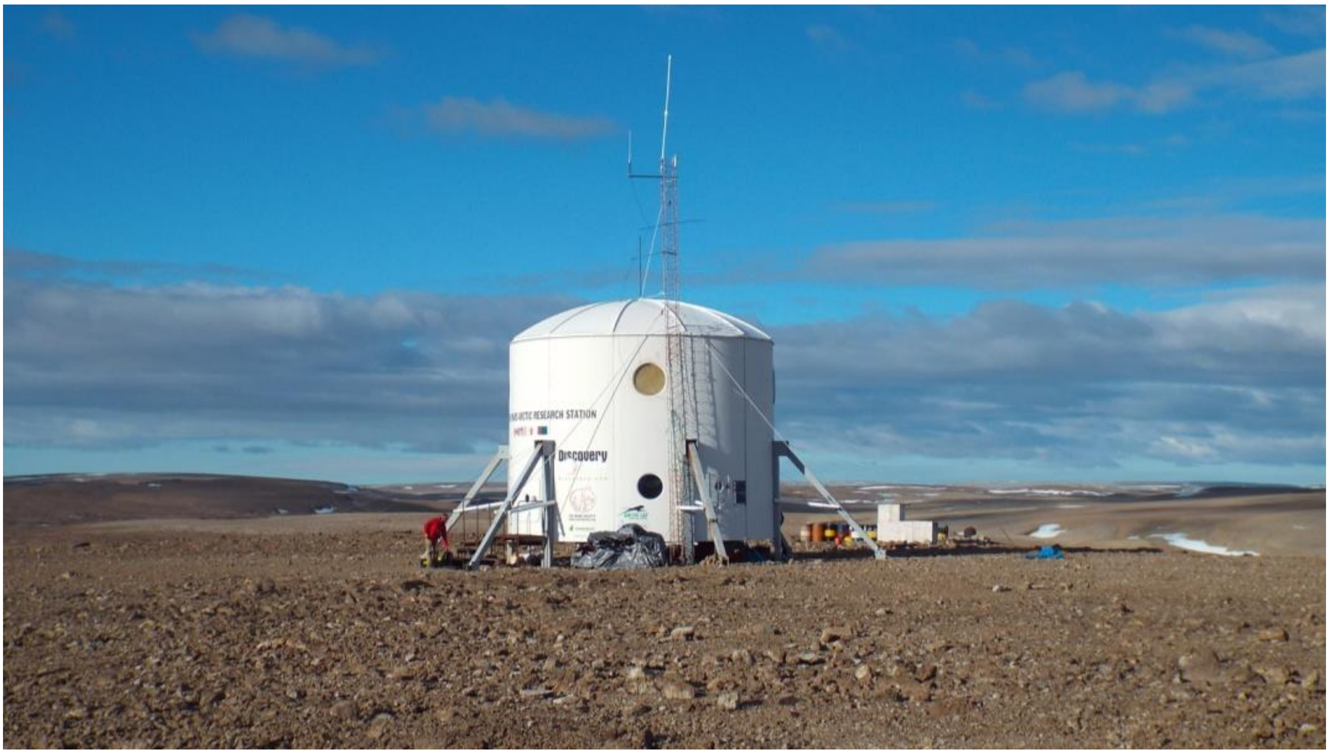
Crews typically consist of five to seven, although occasionally crews have consisted of as few as four and as many as twelve. A typical rotation lasts for two weeks. A few crews have stayed longer, most notably the one month "Expedition One" in 2003 and the "Mars 160" crew in 2016, who were on site for over 80 days.

External work at the station can be carried out "in sim" or "out of sim". In-sim work means that operations are carried out end to end, safety concerns permitting, simulating how they would be carried out on Mars. All external activities are performed whilst wearing simulated space suits, egress and entry are performed via airlocks with a simulated depressurisation-repressurisation cycle. Out of sim work means that people can come and go from the station in normal clothing whilst carrying out various research activities.

Since 2006 MDRS has been the site of the annual University Rover Challenge, a robotics competition for university level students that requires building of field robotics to meet science and engineering tasks of the type that would be required to support early crewed missions to Mars.

Flashline Mars Arctic Research Station

Devon Island in the Canadian Arctic is one of the prime sites for Mars analogue research. The island has a small ice cap, the 20 kilometre diameter Haughton impact structure, and extensive periglacial features associated with the shallow permafrost and frost activity. The Mars Institute began the Haughton Mars Project (HMP) in 1996 at the Haughton crater, initially setting up in the interior of



FMARS station on Devon Island at start of the Mars 160 expedition, 2017. Author's collection.

the crater and later moving to a more favourable site outside the crater of the northwest. The HMP has carried out diverse instigation into the Haughton impact structure environment, Mars analogue geology, astrobiology, EVA operation methodologies for the Moon and Mars, vehicle, robot and space suit design, and running automated greenhouses in extreme environments.

Upper deck of FMARS, crew writing reports. Mars 160, 2017. Mars Society photo

FMARS was the first analogue field station constructed. The site on the northwest rim of the crater was selected to be close to HMP with which it was originally associated. Work commenced in 2000 with the first crew occupying it that year. There have been a further 14 crews occupying the station up to the time of writing, six short rotations in 2001, and month long rotations in 2002, 2003, 2004,and 2005. There was a four month rotation in 2007, the longest field analogue mission to that time. A month long mission followed in 2009 and a short servicing mission in 2013. In 2017 a crew occupied the station for a month as part of the Mars 160 expedition. The station as currently fitted out can be used only during the short summer, which typically runs between June and August. Outside this window the area is usually snow covered, precluding most field science activities and restricting operations.

The station consists of a habitat module and a few minor support structures. It is very similar in exterior and interior to the later MDRS, although the construction is different. FMARS is 8 m in diameter and 8 m high, including the domed roof. There are two decks, plus a half deck loft. The roof is slightly higher than at MDRS, resulting in more headroom for the loft. The lower deck contains two airlocks, an EVA preparation room, toilet, shower, laboratory space and workshop, and a tool storage area. One airlock is mainly used for EVAs and the other to store waste for later disposal. The EVA preparation room also has water tanks connected to the upper pressure tank in the loft. The laboratory and workshop were removed in 2016, converting the space into a multi-purpose area. Stairs connect the lower and upper decks. The upper deck is half taken by six individual cabins for the crew, and half by a combined galley and wardroom. The position of the galley and stairs on the upper deck are reversed compared to MDRS. The upper deck contains a seventh cabin, water pressure tank, water pump and general stores. The galley is all electric, as are the heaters. Dehumidifers reduce the moisture content of the atmosphere, which would otherwise be close to saturation.

Externally there are parking bays for the quad bikes and trailers, a small hutment for the generator (in theory there are three), and a fan-forced incinerator. There is also a fuel dump of 200L drums and a storage area for urine, also in 200L drums.

Devon Island is the largest uninhabited island in the world, almost as large as Tasmania. At 75ºN, it experiences several months of darkness in winter and constant daylight in summer. Access to FMARS is by air from Resolute, a settlement on Cornwallis Island to the west and the nearest place with a scheduled air service. Charter air services and private aircraft provide the only link between Resolute and Devon Island. Flights to and from FMARS use a number of relatively smooth and level areas near the station as landing strips. Landing is not guaranteed because of weather conditions and can occur only when the ground is either completely snow covered (using aircraft fitted with skis) or has dried out sufficiently so that wheeled aircraft will not become bogged.

Station operations are much more self-sufficient than at MDRS because of this isolation. Water is fetched in jerry cans from a nearby stream; crews typically use about 12 L per person per day. The much lower usage compared to MDRS (less than half) is because of the absence of a flush toilet. Crew members usually shower about once a week. Urine is passed via collection devices into 200 litre drums. These are stored onsite and will eventually have to be flown out. Solid waste from the toilet is incinerated along with food scraps, paper, boxes, and any other combustible material. Non-combustible rubbish and washes from the incinerator are flown out at the end of the rotation for disposal at Resolute. Waste water is collected in a drum and dumped in a drainage pit about 15 m from the station.

Power is limited at FMARS, and tripping of overload switches is common place when more than two of three appliances are running. To save fuel the generators may be run for only four to six hours a day. This is less of a problem than might be first thought because of the continuous daylight during the period when the crews are at the station. Internet access via a satellite link is also very limited. Satellite phone calls are possible, but only in emergencies or to arrange flights.

Polar bears are a hazard for any operations in the Arctic. The risk of attack is low because FMARS is more than 20km from the coast, although bear tracks have been seen in the area. Consequently there is always a guard armed with a 12 gauge shotgun or high powered rifle whenever people are working outside away from the station. This includes on the simulated EVAs, which are otherwise carried in the same manner as those at MDRS. Some crews have dealt with the issue of having such a significant workload of tasks that cannot be performed "in sim" by having a dedicated person to do these, allowing the rest of the crew to adhere more closely to simulation procedures. Other crews have rotated the tasks for a more equitable distribution of workload.

Lower deck of FMARS during Mars 160 (2017). One crew member uses the exercise bike while three others prepare for EVA. The orange-suited crew member will be bear guard. Mars Society photo.

Research

Many fields of research have been carried out at both MDRS and FMARS across such disciplines of geology, biology, robotics, operations research, human factors, psychology, sociology, horticulture, and astronomy. I will focus on the research projects I have been engaged on at these stations.

Geology

As a geologist it is the rocks and landforms of these two locations that I find particularly interesting. The area surrounding MDRS is dominated by benches, mesas, and buttes composed of nearly flat-lying sandstones and shales of Jurassic and Cretaceous age. Fossil wood and dinosaur bones are common, thin coal seams and traces of plant roots and fossil insects can also be found. These sediments were deposited in fluvial to shallow marine conditions. Erosion has exhumed and inverted ancient river channels, a process and landforms that occur in many places on Mars, while weathering has produced a Mars-like suite of clay and sulphate minerals. The sediments themselves include shales formed by the weathering of volcanic ash and beds of sulphate evaporites. The environment is a hot desert, with low precipitation (less than 150 mm) and temperatures reach almost 40 degrees in summer. However winters can be very cold, with frosts for several months of the year and night time temperatures falling below -10 degrees. These factors give rise to very sparse variation except in the few permanent river valleys, and characteristic desert landforms. Small sand dunes are present near the station and there are extensive partially stabilised sand dunes. My own geological research has focussed on the evaporitic and fluvial sediments, regolith processes, and the formation of the inverted channels.

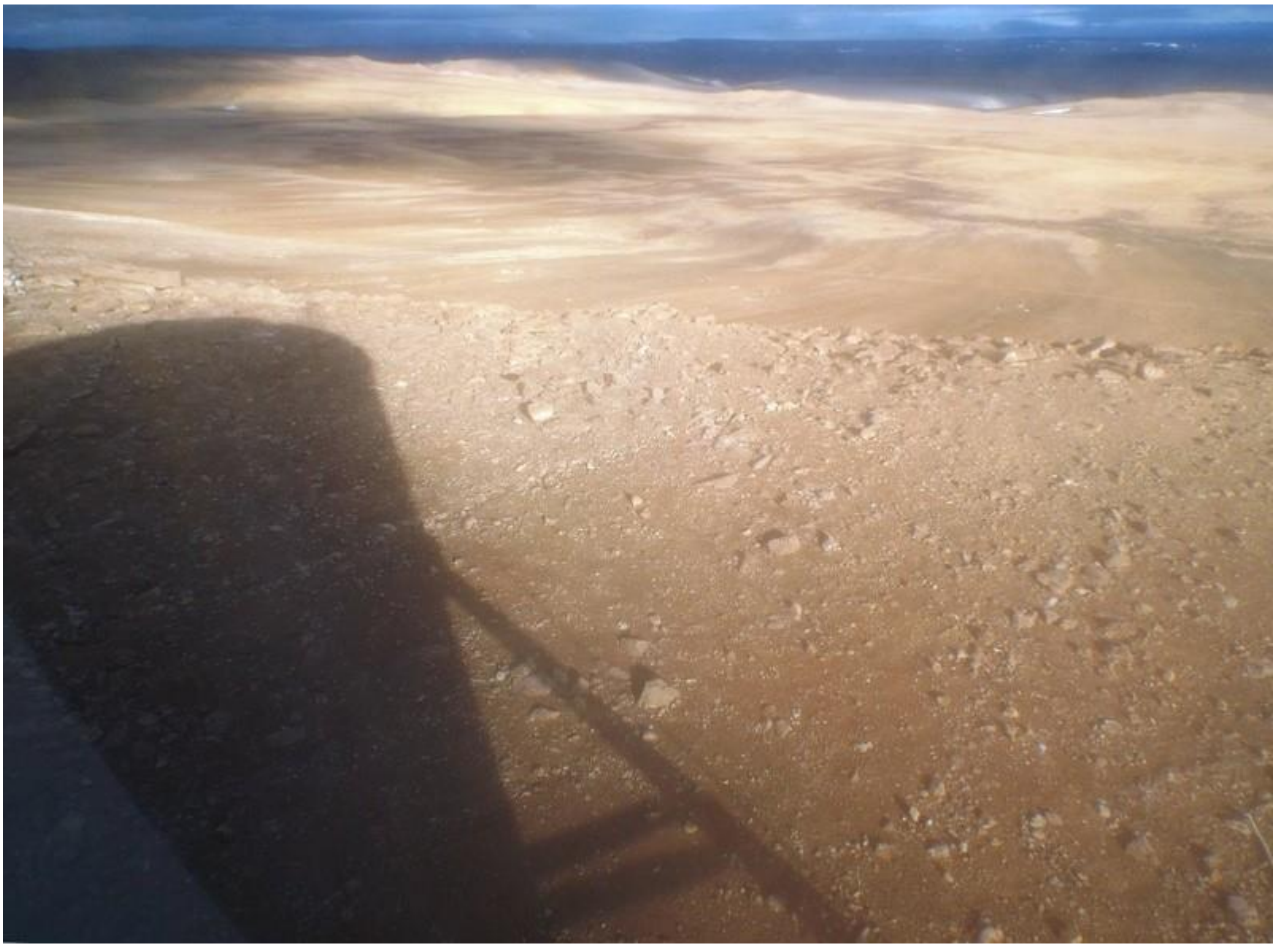
Layer cake geology near MDRS. Red layered Jurassic shales of the Morrison Formation are overlain by interbedded grey shales and yellow sandstones of the Cretaceous Mancos Formation. Taken during the Mars 160 project, 2016. Author's collection.

By contrast FMARS is in a cold desert. No climate averages are available for Devon Island, but at Resolute ~160 km to the southwest of FMARS, temperatures do not exceed 10 degrees in summer and in winter can fall below -30 degrees. Average temperatures go above freezing for only two to three months of the year. Average precipitation is about 90 mm per year. Grise Fiord, 220 km to the northeast of FMARS, receives less than 160 mm per year. As a result the ground is permanently frozen below a depth of about 60 cm. Snow cover is relatively thin except in hollows, but melts for only three to four months of the year. As a result the active layer of the soil above the permafrost is often completely saturated and runoff is active. Snow patch erosion, runoff and frost activity has shaped the bedrock, and expansion and contraction of the soil during freeze-thaw cycles has formed extensive fields of polygonal ground. The bedrock consists of Ordovician dolostones, limestones, gypsum rich evaporites, and Siluro-Devonian dolostones and limestones. Stromatolites andfossils of solitary and colonial corals, molluscs, brachiopods, sponges, and nautiloids are common. The dominant feature of the geology at FMARS is the Haughton impact crater. The HMP was initiated because of this feature and the analogues to martian craters it resembles. Haughton impact crater is about 23 km in diameter, although current rim structure is 16 km across. When formed 39 million years ago the crater was 500-700 m deep.

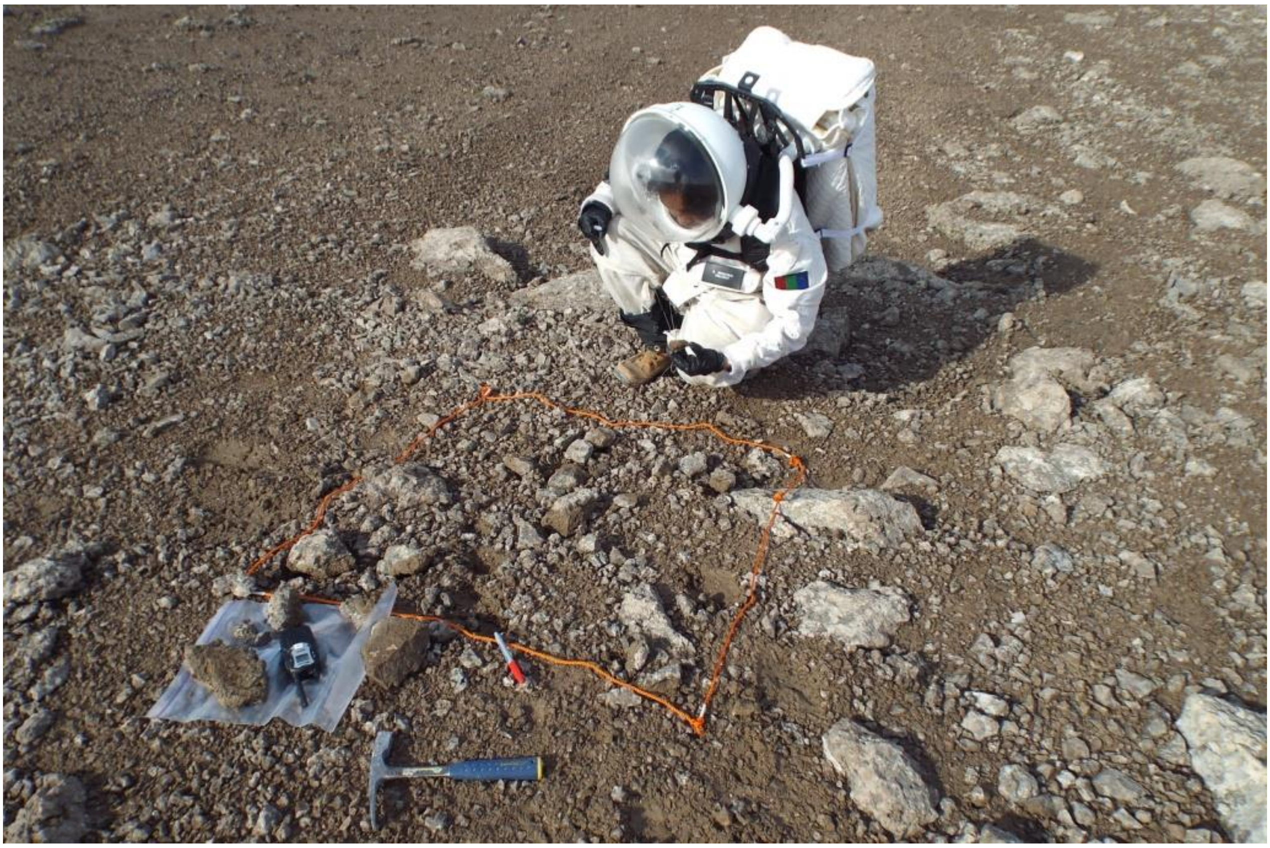
This has been reduced by several hundred metres of erosion and a similar amount of infill by impact breccia, melt rocks and crater lake sediments to about 300 m. A good martian counterpart is Endeavour crater, where the Opportunity rover mission has spent the last seven years exploring the rim. Haughton crater has been extensively studied, so my own researches have concentrated on the stromatolites, because they represent the kind of microbial constructs that might one day be found on Mars, and the nature of the regolith and landforms.

Biology

Biological research during my times at both these stations has been varied. At MDRS my biological colleagues have studied microbial niches associated with rock overhangs and water seeps (Expedition 1), and the identification of native and introduced microbial taxa through PCR analysis of DNA in soils, cores, and rock surfaces (Crews 92 and 104). The Mars 160 expedition biologists studied lichens and distribution of hypoliths at both locations and collected arctic plants at Devon Island. The microbial studies provide analogues for potential habitats for martian life where conditions are hospitable and protected from threats such as extreme temperatures, radiation and desiccation.



View across Haughton crater from FMARS window. Further rim is 16 km away. Taken during the Mars 160 project, 2017. Author's collection.



Crew biologist working on Hypolith quadrat in Haughton crater. Mars 160 project 2017. Author's collection.

Space suits

To perform these studies on Mars astronauts will need to explore the surface, which requires carrying out field science while burdened with stiff heavy suits, clumsy boots, and inflexible gloves. Apollo suits weighed 16 kg on the Moon, but massed 96 kg. The early MDRS suits and those at FMARS weighed 12 kg, the latest MDRS suits 17 kg, although do not replicate the stiffness. Even so EVAs are physically demanding and the suits limit what can be done in any amount of time. Despite these limits people in the simulation can walk many kilometres, climb steep slopes, collect samples, deploy equipment, and assemble structures while wearing them. Mars Society Australia members have also used MDRS to test iterations of the MarsSkin suit, a design intended to simulate mechanical counter pressure suits, which are much lighter and more flexible than conventional gas pressure suits.

Assembling a dome during the Mars 160 project, 2016. Author's collection

MarsSkin suits being tested by the Leonardo Crew (Crew 92). Mars Society photo.

Vehicles

Because both real and analogue suits are so heavy and clumsy, exploration at distances beyond a few kilometres of the landing site will require vehicles. On the Moon this was achieved by the Lunar Roving Vehicle (LRV) that allowed the crews of Apollos 15, 16, and 17 to cover traverses of 10 km and more during each of their three day stays on the Moon. The most effective vehicles for exploration is a question that has been studied at MDRS and elsewhere. A range of vehicles have been used at MDRS to provide mobility beyond the immediate hab environs. Most common have been single-person quad bikes. These are cheap, effective, and easy to use. However they are not particularly good analogues for what might be used on Mars because they can carry only a single person, whereas for work any distance from a real Mars station they will need to be able to carry two in emergencies. More recently electric two seater utility vehicles have been used at MDRS. These resemble the LRVs and are excellent analogues for what might be used to allow exploration well beyond walking distance from the station. At FMARS vehicle use has been confined to quad bikes and their trailers, although larger vehicles have been tested at HMP.

Pressurised vehicles will be needed for very long range exploration on Mars. These will support exploration at distances of 100 km from the station and traverses lasting from several days to more than a week. Such vehicles will be large and mass several tonnes. Their interiors will be fitted out like medium campervans to provide living and working spaces for crews of two to three. Two such vehicles towing trailers with extra consumables could travel even greater distances and stay out for longer periods. One such vehicle was the *Ares*, built by the University of Michigan and tested during Expedition 1/Crew 11 in 2003. MSA member Dr Graham Mann of Murdoch University in Western Australia carried out extensive comparisons between this and other vehicles, evaluating their utility and design.

Drilling

Scientists can sample the martian surface readily with hand tools. To go deeper to collect samples for geological or biological research that have not been affected by weathering or cosmic radiation they will often need to drill. A number of different drills have been tested at MDRS. These include simple hand held drills, backpack drills, and drills mounted on trailers. A full robotic drill, MARTE, developed by NASA Ames Research Centre and Honeybee Robotics, has also been tested, following previous trials at Rio Tinto in Spain. Most of these drill projects have returned cores, which are the most useful type of sample that can be returned, although also the most technically challenging.

Two seater electric utility vehicle (foreground with quad bikes parked in background. Mars 160 expedition 2016. Author's collection

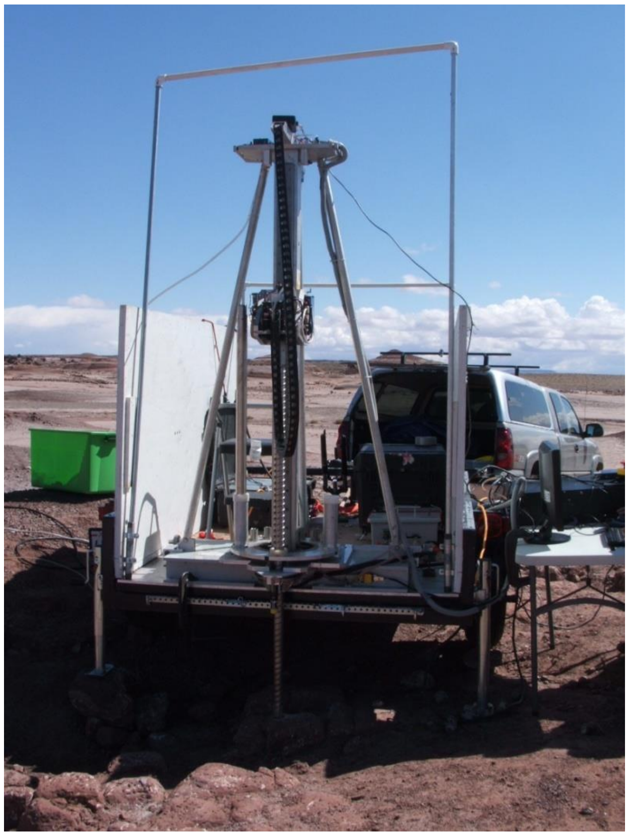
Most drilling projects have been executed in both simulation and non-simulation modes, depending on the research goals. The MARTE drilling however was always carried out autonomously, although commanded from on site. Drilling on Mars has, however, its issues. On Earth water is used to remove cuttings from round the drill bit and to keep the bit cool. Water is not as readily available on Mars and the low temperatures and pressures render its use impractical, so this option will not be available. Alternatively drilling rates can be much slower to keep temperatures at acceptable levels. This will greatly slow the drilling rate in hard rocks. Cuttings can be removed by auger flutes on the outside of the drill stem or perhaps by compressed air. Perhaps autonomous drilling rigs such as MARTE can be set up by astronauts and revisited when the drilling is complete. Or perhaps drilling will mostly be done in unconsolidated material, as it was on the Moon during the Apollo era. Alternatively, geologists may well seek out cliff exposures to sample less weathered material, as they do on Earth.

Graham Mann doing maintenance checks on the University of Michigan Ares Rover. Mars Society photo.

Personal Experience

Media reports constantly spout headlines like “Mars colonists will definitely go crazy”, “Mars astronauts could go mad”, or even “Astronauts on deep space Mars missions might go mad before reaching the red planet”. Then of course there is “Mission to Mars could bore you to death!” That’s just the psychological issues of course. Other headlines warn “If a Trip to Mars Doesn't Kill You It Might Cause Massive Brain Damage” or, more bluntly: “How You'll Die On Mars”. This is reinforced by many movies and TV shows about Mars. Almost every mission to Mars is beset by dramas technical, physical, and human, it not supernatural or fantastic. Viruses turning crew into zombies or sex maniacs, deadly fireflies and killer robots, spies and saboteurs, implausibly malicious corporations and governments, aliens with their pesky gateways, or even unrealistic dust storms are the norm.

Carol Stoker (left) and author (right) using the Backpack drill near MDRS for full sim drilling. Mars society photo.



The MARTE drill on Crew 104 (Author’s collection).

Even the supposedly well researched National Geographic mini-series *Mars* was quite egregious in this respect. As a result when people learn about my time in analogue stations the questions come out:

> "Aren't you bored locked inside all that time? No – we worked 12 hours a day six days a week, we didn't have time to be bored!
>
> "Don't you fight all the time?" Only with mission control and then only occasionally! My crew was composed of sensible people who were like family more than friends and friends more than colleagues.
>
> "You must have been glad to leave!" No way! I loved my time there; it's such a beautiful environment. There is so much more that could be done and I miss my crew mates who are like second family.
>
> "Wasn't it stressful?" Actually, I slept like a baby most nights and had great fun during the expedition, lots of laughs and wonderful memories.
>
> "Did you end up hating everyone and everything?" In fact I loved my time there and would do it again with the same people without question.
>
> "Didn't the station seem cramped?" Plenty of room for our crews, when people were out it was even spacious. Besides, we went out on EVA every few days.

The scenery really was extraordinary. MDRS is on the edge of the San Rafael swell, classic "western" scenery of buttes and mesas. To the south of MDRS lie the peaks of the Henry Mountains, almost always snow covered in winter. Perhaps the most intriguing feature of the FMARS landscape on Devon Island was the light. The low sun angle and permanent daylight of the Arctic provides a constantly shifting light show across Haughton crater.

Perhaps the biggest handicap was washing. At both MDRS and FMARS showers were restricted to one a week to save water, in between times we used flannel and wet wipes. Burning each other's toilet waste at FMARS was a bonding experience, although not quite as unpleasant as it sounds! However cleaning out the mess left in the incinerator – partially burned saturated leftovers - was not quite the most disgusting job I have ever had, but it was up there!

Other issues arise from the nature of the stations. They are each approaching 20 years old, built and maintained by volunteers. Some things therefore are not quite as finished and are rather more rickety than they could be. Wiring sometimes shows a rather creative approach to layout, ladders and stairs are not always as safe as they could be, and not everything is connected. Odd corners are unfinished and unpainted. MDRS in particular rattles and shakes in a strong wind. However, Mars stations will also show their age after 20 years on the surface of the planet and nothing will be pristine after a few years use.

Celebrations like birthdays are great occasions for crews to relax and bond. Mars 160 project, 2016. Mars Society photo.

MDRS after dark. Mars Society photo.

Burning waste at FMARS. Mars 160 project, 2017. Author's collection.

Living at FMARS during the second phase of the Mars 160 project was a constant battle with mould. This is due to the constant near saturation of the atmosphere in the station. Condensation was often trickling down the walls and dripping from the ceiling. There was mould everywhere when we arrived, in cupboards and stored food, down the walls and over the carpet. It took several days to clean up the worst, and it was a constant battle after that. We felt a bond with astronauts of space stations who have also had to battle mould.

Long term waste management is not something that is well addressed in any concept of a Mars station that I have read. Despite recycling, incineration, and other means to reduce waste, there are always leftovers. These include broken down equipment that cannot be repaired or cannibalised for their parts and Structural elements too damaged to be reused. Some materials such as glass are too refractory to be recycled with the means to hand. Even after incineration there is residual material. This is a problem on Earth as well. Arctic communities have huge rubbish dumps, Antarctic stations used to have the same. Alternatively they placed the rubbish on ice flows or dumped it through holes in the ice. Now they ship it back to the country of origin. Space stations load their rubbish on to cargo spacecraft that burn up in the atmosphere with residuals landing in the Pacific. These options will not be available on Mars.

Returning to civilisation is always an experience. After almost three months at MDRS in the first part of the Mars 160 project I was struck by the speed of the traffic, crowds of people, and such wasteful use of food, water, and space. The exquisite taste of fresh fruit and vegetables, and a juicy steak! The presence of animals, especially of course cats, of which I am exceptionally fond, was very noticeable. Also noticeable was high speed internet, something we had done without and has such an impact on our lives. Coming back from the Arctic was less of a transition, perhaps because we staged first through the little settlement of Resolute then the larger town of Yellowknife. However I remember looking out of the window of the plane as I flew south from Yellowknife and being struck by the enormous grain fields of the Canadian prairie, and how humanity has transformed the landscape on such a large scale.

Final lessons

What lessons do experiences of Mars analogue missions impart? I can only speak from my own experience but I think the following are noteworthy:

Like real Mars missions and unlike enclosure and isolation experiments, crews will be busy and productive exploring and studying Mars as well as running the mission. This imparts a much greater sense of purpose, both individually and as a crew, to what is being done.

Because of this, people on Mars are unlikely to be bored but stimulated and challenged. They will work for 12 hours a day, six days a week. Being in a new and extraordinary environment will be a positive, enjoyable, even exhilarating experience. It may be even transformative, an experience reported by many astronauts and cosmonauts from their space missions.

Well-chosen crews of compatible people who know each other before hand are not likely to quarrel, but will be drawn together by the experience. They will be mutually supportive of each other’s needs in difficult times, and the inevitable disagreements will be overcome as in any good family or circle of friends.

Isolation can be a positive experience, as it removes external distractions and allows you to focus on the tasks to hand. People will find rewards in their unique mission, the reality of the outside world they are exploring, and in their recreation activities, be it group activities such as meals, movies, celebrations, and games, or individual activities like reading and personal projects. This is not only my experience, but that of well-planned polar expeditions and long duration flights to space stations.

The Future

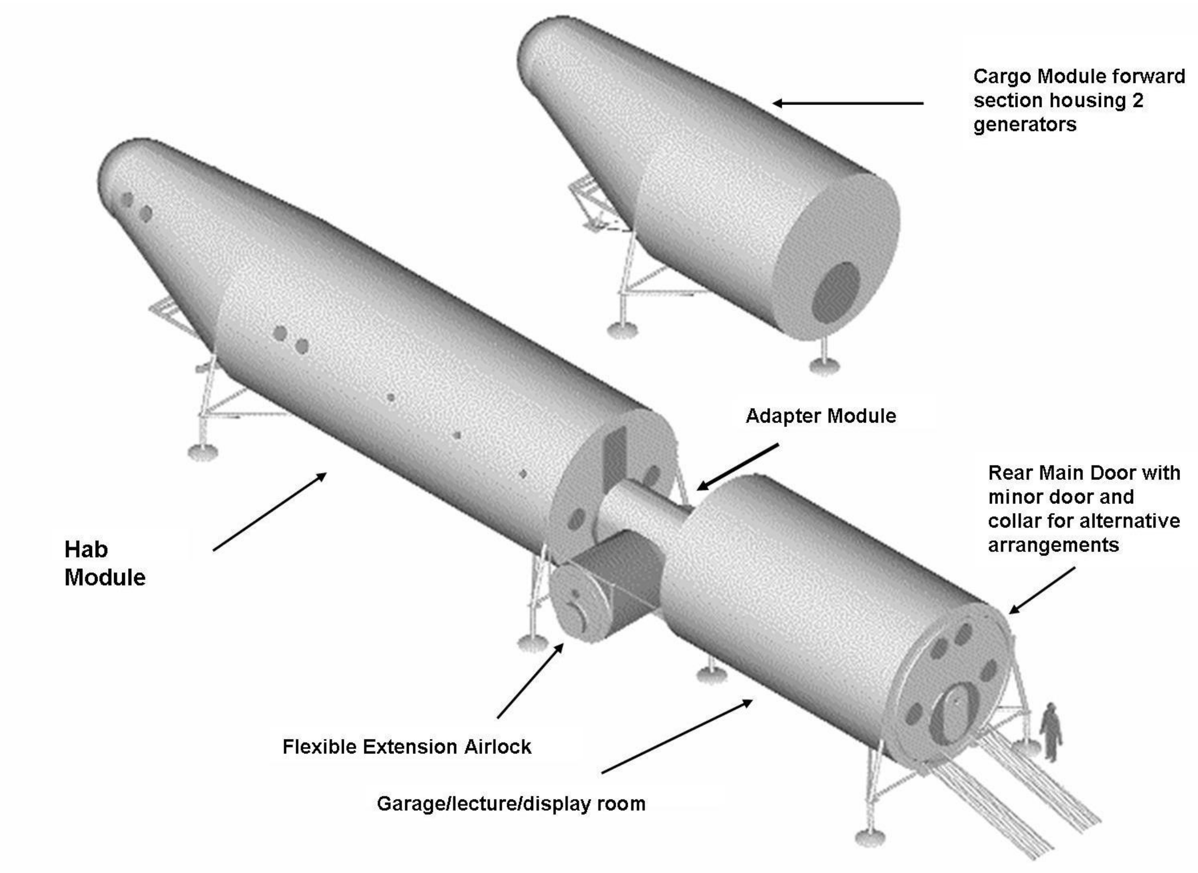
About a dozen Mars Society Australia members have taken part in expeditions to MDRS and FMARS and since the Society’s inception in 2000 it has planned to eventually set up its own station, to be known as Mars Oz. So far the plans have not progressed beyond the design phase, although many avenues have been explored. The project has proved useful for students, which have worked collaboratively on designing detailed aspects of the station system.

Mars Oz is intended to fulfil the same role as MDRS and FMARS but has a different configuration. Both MDRS and FMARS present a “tuna can” design, where the habitat would land vertically on the martian surface. Mars Oz represents a horizontal lander. Each approach has its advantages and disadvantages. The advantages of the horizontal lander configuration include the possibility of lower G entry and more accurate landing on Mars, a more efficient use of interior space, and easier egress and entry to the station, especially for heavy items. Mars Oz would consist of two modules, each 4.7 m in diameter and 18 m in length. They would be trucked to the research sites as a unit, from than assembled there. One module is the hab, and has two decks. The other comes apart into two sections. The nose section contains batteries for a solar power system and also facilities such as incinerators. The rear section is a garage and workshop, which would be docked to the rear of the hab.

Mars Society Australia would like to set up Mars Oz at Arkaroola in the northern Flinders Ranges. The Society has used this area for many Mars analogue expeditions in the past because of its diverse geology, geomorphology, palaeontology, and the presence of extremophliles. The Arkaroola Village is also available for logistic support, there is an all-weather day and night airstrip for emergency evacuation, and the village has several thousand visitors a year, offering considerable education and outreach potential.

The Mars 160 crew at Devon Island. Mars Society photo.

Possible location for the Mars Oz station at Arkaroola.



Conceptual design of the Mars Oz station. Mars Society Australia image.

Structural mockup of a segment of the upper deck of the Mars Oz habitat module with the designer Willson at NASA Ames Research Center. Mars Society Australia image.

Eye to the Sky: An Overview of Culture and Imagination in the Human Engagement with Space

Trevor Rodwell

In every age and in every place where humans have left records, we see evidence of a marvellous instinct. As soon as societies obtain by their labours even a little product beyond the needs of bare survival, they begin to create arts, to invent gods, to wonder and theorize about the universe. (Burke 2008)

We know from structures, artefacts and writing left behind from bygone eras that humans have studied the sky for millennia. In many cultures there are examples of myths and legends concerning the cosmos. For ancient people there appears to be several reasons for studying the sky:

- To identify markers that would indicate seasonal changes. This knowledge would help with agricultural practices and aid awareness of forthcoming changes in their environment.
- To have prior warning of cosmic events that were associated with superstitions. Examples of these were found on Babylonian clay tablets called Enuma Anu Enlil which are thought to be several thousand years old. These tablets detail omens associated with Moon phases, eclipses and the rising and setting of planets.
- For what could be termed scientific enquiry, a search to understand our solar system and the cosmos.

Some of the earliest remains that appear to show observations of the Moon are over 30,000 years old. A bone of a baboon found in a cave in the Lebombo Mountains in Swaziland and dated at around 37,000 years old is carved with notches that appear to reference the phases of the Moon. Another bone, dated at over 30,000 years old, was found in a cave in the Dordogne Valley in France inscribed with a series of dots that also appear to describe the phases of the Moon.

It is often reported that ancient structures incorporate astronomical alignments or were used as observatories. The oldest known of such monuments is at Goseck in Germany which is claimed to be nearly 7,000 years old. From archaeological excavations it appears to consist of two concentric circles of wooden palisades surrounded by an outer narrow ditch that was around 70 metres in diameter. Within the palisade circles were three openings, or gates, facing south east, south west and north. Adjacent to these gates were earthen walkways across the ditch.

An observer standing in the centre of the inner circle would see the sun through the two southern gates indicating the start of the summer and winter solstices. This phenomenon has prompted the henge to be described as ‘possibly the world’s oldest solar observatory’, however, no astrological reason for the north gate has been found. Although the main function of the henge at Goseck is still open to debate, it is now accepted that, in part at least, solar and possibly lunar observations were integral to its use.

It should not be surprising that prehistoric people would feel a connection to the Sun, Moon and night sky; the Sun and Moon cycles were useful indicators of seasons and, at a time when terrestrial light pollution was unheard of, the night sky would have been awe-inspiring, especially for people who often slept under the stars.

In Europe and the UK especially there are many ancient large stone structures that appear to contain astronomical alignments. One well known example is Stonehenge in Wiltshire, UK. Alignments appear to have been built into the final construction because the midsummer sunrise and midwinter moonrise could be observed within the horseshoe configuration of the inner stones. Whether there were also intentional star alignments we will probably never know, however it would not be inconceivable that the night sky of 4,000 years ago may have inspired something in their design. As if to connect this enigmatic structure with the technological space age, USA astronaut Story Musgrave flew a small piece of Stonehenge into space. This could be seen as an interesting example of how an engagement with a new environment, in this case outer space, can create cultural meaning even for a small piece of stone.

Australian Aboriginals have been described as ‘probably the world’s first astronomers’. This statement is based on assessments that Aboriginal people probably inhabited the Australian continent for at least 40,000 years and, during this time, they built up a system of social cultural astronomy.

There is clear evidence from recorded accounts as well as Aboriginals living today that the sky was regarded as part of their environment as much as the land that they walked upon.

Stonehenge with starry night sky. Composite image. Image credit: Trevor Rodwell.

The night sky, full of stars, would serve as a giant storyboard for the many and varied stories associated with individual groups. In other parts of the world people relied on mnemonic devices to inform them of important information that could be gleaned from the Moon and Stars.

A visually impressive ancient astronomical mnemonic device was found in 1999 at the summit of Mittelberg Hill, near the town of Nebra in Germany. Now known as the Sky Disc of Nebra, it is a 32 centimetre diameter bronze disc with features of the Moon and Stars highlighted in gold. According to forensic investigation the patina of the bronze disc would have originally been a deep violet colour, making the gold stand out almost like the real objects in the sky.

Nebra Sky Disc. Image credit: Patrik Tschudin, www.flickr.com

The disc has been dated at around 3,600 years old although some sections, namely the two lateral arcs and the lower pinnate arc, were added at a later date. A detailed investigation of how the disc was used was undertaken utilising assigned references to the markings as relevant to its found position on Mittelberg Hill. These appear to coincide with the beginning and end of the agricultural season in that area. The Sky Disc of Nebra is just one of many prehistoric devices that give a tantalising glimpse of the relevance of astrological observation to these people.

The methods of recording astrological events so that future predictions could be made reached remarkable levels of sophistication, as revealed in the Antikythera mechanism. The device was found in 1900 by sponge divers who had been blown off course by a gale in the Aegean Sea. Finding themselves near an islet called Antikythera they resumed their diving but, instead of sponges, they found an ancient shipwreck. The ship was identified as Roman carrying looted Greek treasures back to Rome when it sank sometime between 70 and 60 BC. Among the many treasures recovered from the wreck was a corroded bronze mechanism that contained many gearwheels.

Although large scale gears were developed at least two centuries earlier, with probably the most well-known devices credited to Archimedes, such small fine clockwork gears were not known to have existed around this time. Although there were many attempts to understand the purpose of the mechanism, none was conclusive until recent times when a more scientific diagnosis could be implemented. The device was originally housed in a wooden box estimated to have been 32 centimetres high by 17 centimetres wide. On the side of this box was a small rotating handle that activated the complex gear mechanism which operated revolving pointers on the front and back of the box. It has been established that these pointers revolved around inscribed dials that had accompanying text describing how to interpret the readings.

It is now recognised that the Antikythera mechanism is a device that could chart the changing positions of the Sun, Moon and planets. It showed the phases of the Moon and could determine eclipses to a high degree of accuracy. Other dials showed a repeating 19 year calendar which reflected the 235 lunar months that fit almost exactly into 19 solar years. Inscriptions also detailed the movement of stars for any given time that was dialled into the device. Turning the handle allowed the viewer to see cosmic events in the past and well into the future with a precision unheard of before the discovery of this device.

Careful observations of the sky probably prompted people in ancient times to build structures and devices that utilised what they saw. With varying degrees of accuracy, cultures around the world devised means of predicting or using cosmic events for reasons including the foretelling of omens and the sowing and harvesting of crops. Many eyes, across many continents, over thousands of years, surveyed and recorded the environment above them. The Sun, Moon, the planets and stars were a reality that could be constantly seen; they reacted in certain ways and had observable consequences which, if predicted, could be advantageous. However, for some astronomers this was not enough and so began a quest to discover not only what cosmic events would happen in the future but why they would happen. They wanted to know how the observable universe worked.

One of the first recorded documents that details a theory based on years of continual observation and calculation came from the Greek mathematician Aristarchus. Living around 310 to 250 BC his work *On the sizes and distances of the Sun and Moon* involved 18 propositions, from which his most well-known results concerned the distance of the Earth to the Sun as well as an estimate of the size of the Sun. Using geometry, he calculated the distance to the Sun in measurements of Earth to Moon distance. The result he arrived at was that the Sun was 19 times further away from the Earth than the distance from the Earth to the Moon (this figure is actually around 390). He also calculated that the Sun was seven times larger than the Earth. This figure is also wrong as the diameter of the Sun is around 109 times that of Earth.

Even though Aristarchus was inaccurate with his calculations, his conclusion that it was more likely that the Earth, as the smaller body, went around the Sun was correct. This is the first known recording of what was to be later termed the heliocentric model of the universe.

However, the accepted view at the time was for a model where the Earth was stationary at the centre of the universe, with the five observable planets (Mercury, Venus, Mars, Jupiter and Saturn), or wandering stars as they were known, plus the Sun and Moon revolving around it. The background of stars, it was thought, were attached to a hemisphere whose boundary was just beyond Saturn. This geocentric model of the universe could account for most of the observable cosmic events to the satisfaction of other sky observers, and was eminently acceptable to rulers who liked the idea that their gods created the earthly world at the centre of everything. The Aristarchus heliocentric idea would not be seriously revisited until early 1500 by Nicolaus Copernicus.

One of the main difficulties with the geocentric model of the solar system was the movement of the planets in the sky, which appeared to have a looped path. In the case of Mars, this phenomenon is particularly noticeable on its passage through the sky, with the effect showing as if the planet comes to a halt, then for several weeks reverses its direction, before resuming its original eastward motion. It is known today as retrograde motion, which happens when Earth passes Mars as they orbit the sun at different speeds. Claudius Ptolemy, an astronomer in Alexandria in the second century AD, developed an innovative cosmic model to account for this and other conflicting observations but his model had to be continually modified as more accurate observations revealed more inconsistencies.

The first concerted challenge to the geocentric theory came from the writings of Nicolaus Copernicus who finished his major work On the Revolutions of Heavenly Spheres in 1530. His thesis put the Sun at the centre of the universe and the Earth as another planetary sphere revolving around it. He correctly positioned Mercury and Venus as the inner two planets, Earth as the third from the Sun and also predicted the correct order for Mars, Jupiter and Saturn (still the only known planets at the time). In his writing On Revolutions he also calculated that the Earth had a slow gyration around its axis and that it turned on this axis once every day and revolved around the Sun once every year.

At this time Europe was very much under the influence of the church who subscribed to the geocentric model of the universe for the same reason as the Greek and Roman rulers. It was dangerous to promote other theories so Copernicus waited for 13 years after writing his major work and was, in fact, dying before he finally published it. He was probably wise in this regard as the Italian scientist, philosopher and friar Giordano Bruno, who agreed with the heliocentric model proposed by Copernicus and answered some of the problem areas of the model, fell foul of the Inquisition. Bruno's writings and lectures on this model, plus his views that there may be an infinite number of worlds in the universe, some of which may have intelligent life of a level that could possibly be superior to humans, resulted in his being put on trial. He was subsequently found guilty of heretical beliefs and, in 1600, he was burned at the stake. However, only a few years later in 1610 Galileo Galilei trained his telescope on Jupiter and made observations that would eventually end the geocentric model of the universe.

Observing Jupiter, he noticed at first three tiny stars alongside the planet. Over a period of time these stars moved, disappeared and seemingly reappeared on the other side of the planet to be joined by a fourth star. Galileo soon realised that these four points of light were moons revolving around the planet. Today, through images obtained from spacecraft we know of 79 moons orbiting the planet but Galileo's telescope was not strong enough to resolve more than the four largest.

The well theorised geocentric model of the universe stated that all heavenly bodies orbited the Earth exclusively. Four moons, orbiting a planet that was observed to be a world in its own right shattered this basic premise of the model.

Eventually, with confirmation from more telescopic observations, the heliocentric model of the solar system was accepted. As telescopes developed, more discoveries were made. The industry of making telescopes became so widespread that small cheap versions could also be purchased in fairgrounds, enabling those who bought them to at least see a few detailed features of the Moon. This appeared to start a cultural shift away from the astrological interpretations of the Moon, Planets and Stars

Drawings of the Moon, Jupiter's moons and sunspots by Thomas Harriot. Replica of a Galileo telescope. Replica of Isaac Newton's reflecting telescope. Galileo's book *Sidereus nuncius.* Image credit: Trevor Rodwell

towards more science-based cultural writings. Astrology did continue in most cultures and is still active today, however, there was an imagining of this newly-discovered space that would lead to much debate about how the solar system worked as well as the rise of what we call today 'science-fiction writing'.

The first stories of space travel in science fiction literature were primarily focused on ventures to the Moon. The Moon was a place that was observable as a destination with the naked eye and even early telescopes confirmed it had physical features, mountains and valleys similar to the Earth.

One of the first serious attempts to explore the idea of humans travelling to the Moon was written by Johannes Kepler who, in 1601, became the Imperial Mathematician in Prague and used his skill in mathematics to enhance his astronomical observations to underpin the heliocentric model of the solar system. It was while he was a student at Tübingen University in Germany that the idea for his story emerged. At this time he was wondering what the cosmic environment, and particularly Earth, would look like from the Moon. He reasoned that by observing Earth from the Moon he would see the planet rotating and changing its position, thus contradicting the theory that the Earth was stationery.

His story, entitled Somnium translated from the Latin as The Dream was worked on over the duration of his career and was published in 1634, four years after his death.

Like other storytellers who followed, Kepler had no scientific theory on how to get to the Moon. In his story he introduced a mythical race who lived on the Moon and had the power, during a lunar eclipse, to travel between the Moon and Earth. It was these strange creatures who were to transport the characters in the story to the Moon.

Despite the almost Alice in Wonderland theme, Kepler wrote the story as a way of working through some of his unresolved scientific questions. For instance, he understood that to leave the Earth would take a significant velocity, which was described by the main character as though being shot from a canon. He also speculated that during the journey in space it would be difficult to breathe. Subscribing to the heliocentric model he also understood that, because both the Earth and Moon are in motion, the shortest route to the Moon is not to aim directly at it but to a point ahead, where the Moon will be when the voyagers arrive after a period of time.

Although Kepler could not conceive of the technology needed to get to the Moon, he nevertheless believed it was theoretically possible. Today, we know that it is not only theoretically possible but humans have actually done it. Kepler's story and his belief in future space travel set him apart from many other astronomers of his time. There could be justification in claiming that Kepler's inclusion of scientific thought in his story, which he explained in his copious footnotes, set the benchmark for other science fiction writers to explore what may be feasible rather than revel in sheer fantasy. However, stories that followed, like Francis Godwin's The Man in the Moon, 1638, that had the hero carried to the Moon by a flock of geese showed that there was inevitably a divide between serious and what would today be called 'pulp' science fiction.

The advent of the balloon as a means of human flight in the late 1700s gave writers a proven technology for launching their characters into the sky – and beyond. Edgar Allan Poe utilised this method to transport his hero to the Moon in his book The Unparalleled Adventure of one Hans Pfaall.

In the many books written by Jules Verne, one entitled From the Earth to the Moon published in 1865 foretold with reasonable accuracy the Apollo 8 mission to the Moon in 1968. The Apollo 8 mission was a precursor to the later Apollo missions that made a Moon landing. In Verne's story, astronauts are launched from Florida in the USA, successfully flew around the Moon and returned to Earth to finally splash down in the Pacific Ocean.

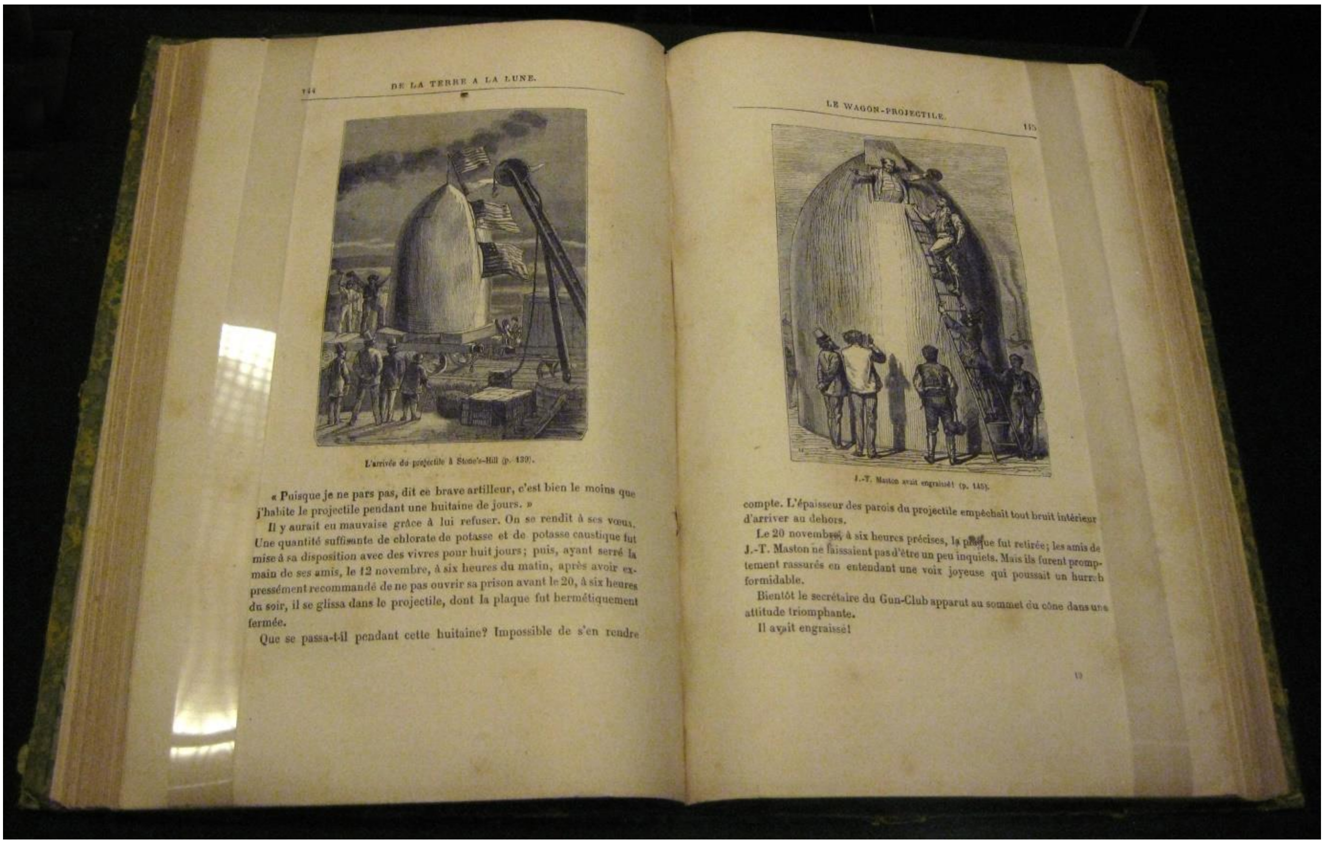
Jules Verne's stories were read by a wide general public and notes that he made while writing on subjects, such as the distance of Earth to astronomical points, indicate his intention to integrate facts in his stories. Because of the wide popularity of his writing, the European Space Agency named their first Automated Transfer Vehicle (ATV) the Jules Verne. This ATV was designed to supply cargo to the International Space Station (ISS). The Jules Verne spacecraft docked with the ISS on 3 April 2008 and, apart from vital supplies for the astronauts, it delivered two of Jules Verne's handwritten notes, a handwritten quote and two of his books – Round the Moon and From the Earth to the Moon that were published in his lifetime. Jean-François Clervoy, an ESA spokesperson for the mission, said:

> *We chose two of his [Jules Verne's] notes directly related to space travel, and selected also one of his own quotes that reflects well the vision of the European Space Agency; 'en avant ... ce doit être la devise de l'humanite!' ('go forward ... it should be the motto of humankind!')*

With more telescopic observations of the solar system planets, Mars began to feature in science fiction writing. From the 18th century when William Herschel described his observation of the Martian polar caps seemingly melting, suggesting that they were formed of ice or snow and that Mars may have an Earth-like environment, there was speculation that Mars may support alien life-forms.

At the beginning of the 19th century many, often ludicrous, ideas were put forward on how we might gain the attention of the Martians, for it was assumed that Martian technology would be at least comparable to our own or, some suggested, even superior. The fact that they would be observing Earth also appeared to be taken for granted. Ideas ranged from creating huge geometric forms from different coloured vegetation to prove we knew about mathematics, lighting a 24-mile-wide circular fire in the Sahara Desert, or constructing huge mirrors to focus the sun's rays and burn numbers onto the surface of Mars (hoping, we could presume, that no Martian was in the vicinity while this was in progress).

The debate about whether Mars was inhabited became more intense with the American, Percival Lowell, who built his own observatory in Flagstaff, Arizona, being the most prominent supporter of the theory, claiming he had seen canals on the Mars surface that could only have been built by intelligent beings. In 1895 he published his theories in a



Jules Verne's book *From the Earth to the Moon, 1865*, showing images of his spacecraft made from aluminium for lightness and launched from a cannon. Image credit: Trevor Rodwell.

book entitled Mars. However, many other astronomers disputed these claims and in 1909 observations from the Meuden Observatory, near Paris, and also Mount Wilson in California, USA, confirmed the canals did not exist.

Science fiction writers had many ideas on Martian life-forms. A book entitled A Parallel Unveiled: A Romance (1893) by Alice Jones and Ella Merchant depicted Mars as a site of a feminist utopia whereas the War of the Worlds (1898) by H G Wells portrayed the Martians as aggressive invaders. H G Wells book War of the Worlds was adapted and broadcast as a radio play in 1938. Read by Orson Welles as though it were a live newscast, it caused mild panic in New Jersey, USA, to those who missed the announcement that it was a work of radio theatre. Two film versions of the story were also produced.

Other authors such as Edgar Rice Burroughs were prolific in their output of Martian stories and Ray Bradbury's The Martian Chronicles became the most widely read science fiction book during the 1950s and, in 1980, was adapted for a three-part television series.

Many other film and television stories were produced such as the fifteen episode film version of Flash Gordon's Trip to Mars, produced in 1938 for children's Saturday morning cinema; in 1964 the film Robinson Crusoe on Mars came to the cinema and, in 2009, the very popular Doctor Who television series aired the episode Doctor Who: The Waters of Mars. In 2015 the film The Martian starring Matt Damon, based on the book by Andy Weir, became a blockbuster in the cinema. The story about an astronaut stranded on Mars and the subsequent rescue contained many features that were accurate except the initial storm that traps him; an event that would be impossible because of the low atmospheric pressure on Mars.

The visual arts has also been involved in popular representations of Mars, for example, artist Chesley Bonestell produced the book The Conquest of Space in 1949 that contained some of the finest illustrative depictions of Mars and the moons of Jupiter and Saturn of the time. It was said that the images were so realistic that they looked ‘like postcards from the future’.

Later, Bonestell teamed up with rocket scientist Wernher von Braun, who became the first director of the Marshall Space Flight Centre of NASA, USA to produce magazine articles on rockets and spaceflight and the book The Exploration of Mars in 1954. Like Jules Verne, von Braun was keen to show that spaceflight was not just imagination but actually achievable. Bonestell’s paintings, with their photographic quality, depicted the images that von Braun was writing about and contributed to raising public awareness of the possibility of human space exploration. By the time the USA government was deciding on allocating billions of dollars to a space program they found that they had the enthusiastic support of the taxpayers.

In relation to societal perceptions and popular culture it is easy to imagine that something as technical and complex as astronomy and spaceflight has an impact on ideas and society that is unidirectional. Certainly, new theories on space open up potential in the sphere of science fiction. When Percival Lowell claimed there were canals and probably intelligent life on Mars, Ray Bradbury built his Martian civilisation around this theory in his book The Martian Chronicles.

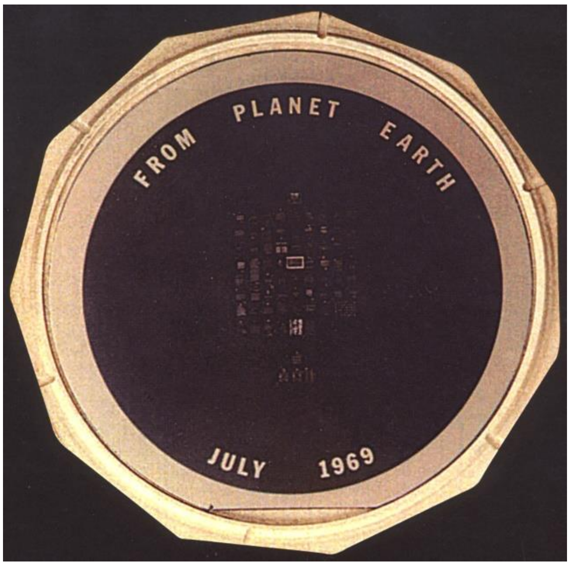
However, the cancellation of the Apollo Moon Program, in part because of waning public interest, would indicate that the mood of society can sometimes influence the actions of politicians in matters of space exploration.

The landing of the first two astronauts on to the surface of the moon as part of the Apollo Program was a triumph of technology and determination that captured the imagination of people around the world. As a gesture of cultural collaboration, heads of state around the world were invited to write a goodwill message for the astronauts to carry to the moon.

Just before leaving the Moon, the astronauts left a small etched silicon disc with goodwill messages from 74 heads of state. To fit the messages on the 38mm diameter disc the text was reduced to a size which meant that the lower case letters were only a quarter the width of a human hair. Nevertheless the messages are still legible through a low-powered microscope.

The message from Australia reads:

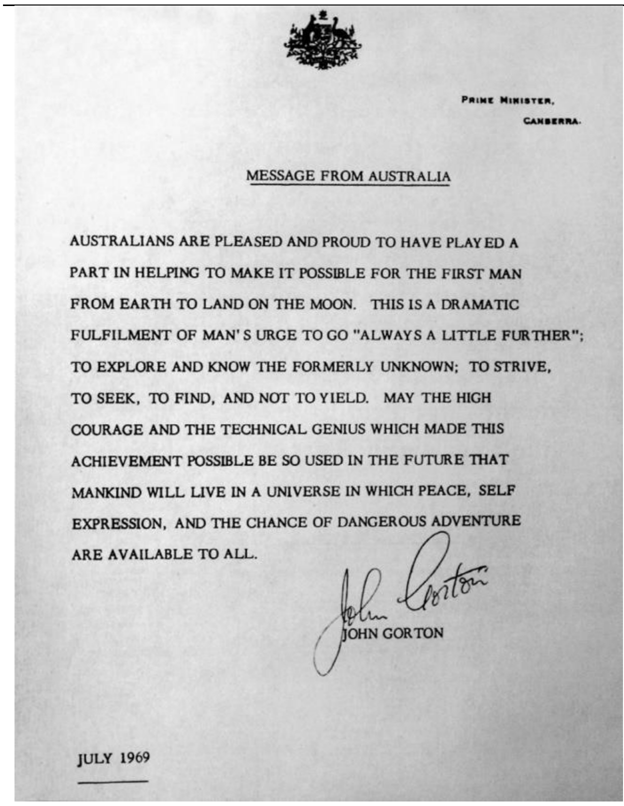
> *Australians are pleased and proud to have played a part in helping to make it possible for the first man from earth to land on the moon. This is a dramatic fulfillment of man’s urge to go ‘always a little further’; to explore and know the formerly unknown; to strive, to seek, and to find, and not to yield. May the high courage and the technical genius which made this achievement possible be so used in the future that mankind will live in a universe in which peace, self-expression, and the chance of dangerous adventure are available to all. John Gorton, Prime Minister.*



Silicon disc left on the Moon showing the minute size of each goodwill message. Image credit: NASA

In return for Australia’s goodwill message and help with the Apollo Missions through the Deep Space Radio Telescope network, the USA presented Australia with a commemorative plaque on which was mounted a fragment of Moon rock given as a ‘symbol of the unity of human endeavour’ and an Australian flag which was carried on the Apollo 17 Mission. The plaque reads:

> *This flag of your nation was carried to the Moon aboard Spacecraft America during the Apollo 17 Mission, December 7-19 1972. Presented to the people of the Commonwealth of Australia from the people of the United States of America. Richard Nixon, 1973.*



PRIME MINISTER,
CANBERRA.

MESSAGE FROM AUSTRALIA

AUSTRALIANS ARE PLEASED AND PROUD TO HAVE PLAYED A PART IN HELPING TO MAKE IT POSSIBLE FOR THE FIRST MAN FROM EARTH TO LAND ON THE MOON. THIS IS A DRAMATIC FULFILMENT OF MAN'S URGE TO GO "ALWAYS A LITTLE FURTHER"; TO EXPLORE AND KNOW THE FORMERLY UNKNOWN; TO STRIVE, TO SEEK, TO FIND, AND NOT TO YIELD. MAY THE HIGH COURAGE AND THE TECHNICAL GENIUS WHICH MADE THIS ACHIEVEMENT POSSIBLE BE SO USED IN THE FUTURE THAT MANKIND WILL LIVE IN A UNIVERSE IN WHICH PEACE, SELF EXPRESSION, AND THE CHANCE OF DANGEROUS ADVENTURE ARE AVAILABLE TO ALL.

John Gorton
JOHN GORTON

JULY 1969

The goodwill message from Australia that was etched on the Silicon Disc left on the Moon. Image Credit: NASA.

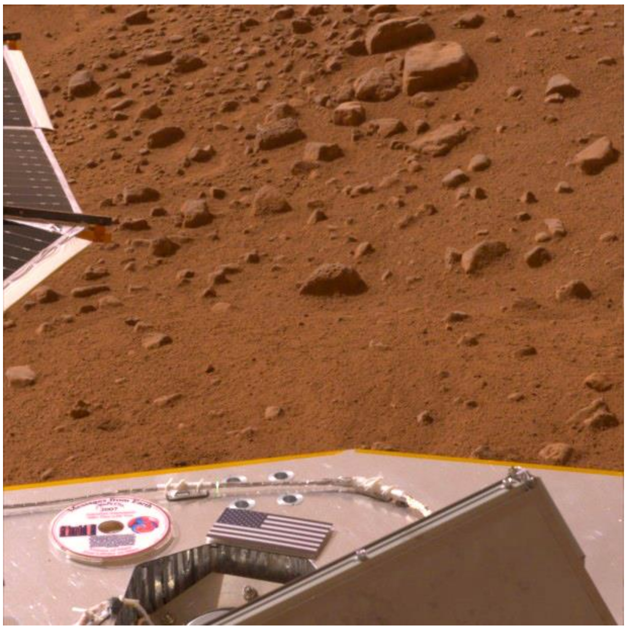
The first Moon landing created an enormous amount of interest, however, with space missions the amount of interest depends significantly on the way missions are communicated to the public. Public engagement and, where possible, participation is now seen as an important part of space activities by space agencies. Names and messages on spacecraft have recently become a popular form of participation and, because modern recording technology can produce large volumes of data on small devices, it is not usually a problem to install them on spacecraft.

These projects started flying on spacecraft in 1996 with the first being on the failed Russian Mars orbiter Mars 96; but the first successful mission was also in 1996 when 100,000 names flew on the NASA Mars Pathfinder spacecraft. In 1997 a mini-DVD containing 616,400 hand-written signatures was included on the Cassini-Huygens Saturn orbiter and Titan moon probe mission. The comet sample return spacecraft Stardust, launched in 1999, took with it a microscopically etched metal plate containing over 1,136,000 names.

In 2003 the Japanese space agency (JAXA) launched its Hayabusa asteroid sample return spacecraft. When it reached the asteroid Itokawa it fired two shiny target markers onto its surface to facilitate its optical navigation instruments in manoeuvring the spacecraft to the asteroid surface. Inside one of the markers was a thin aluminium foil etched with 877,490 names which are still travelling through space on the back of Itokawa.

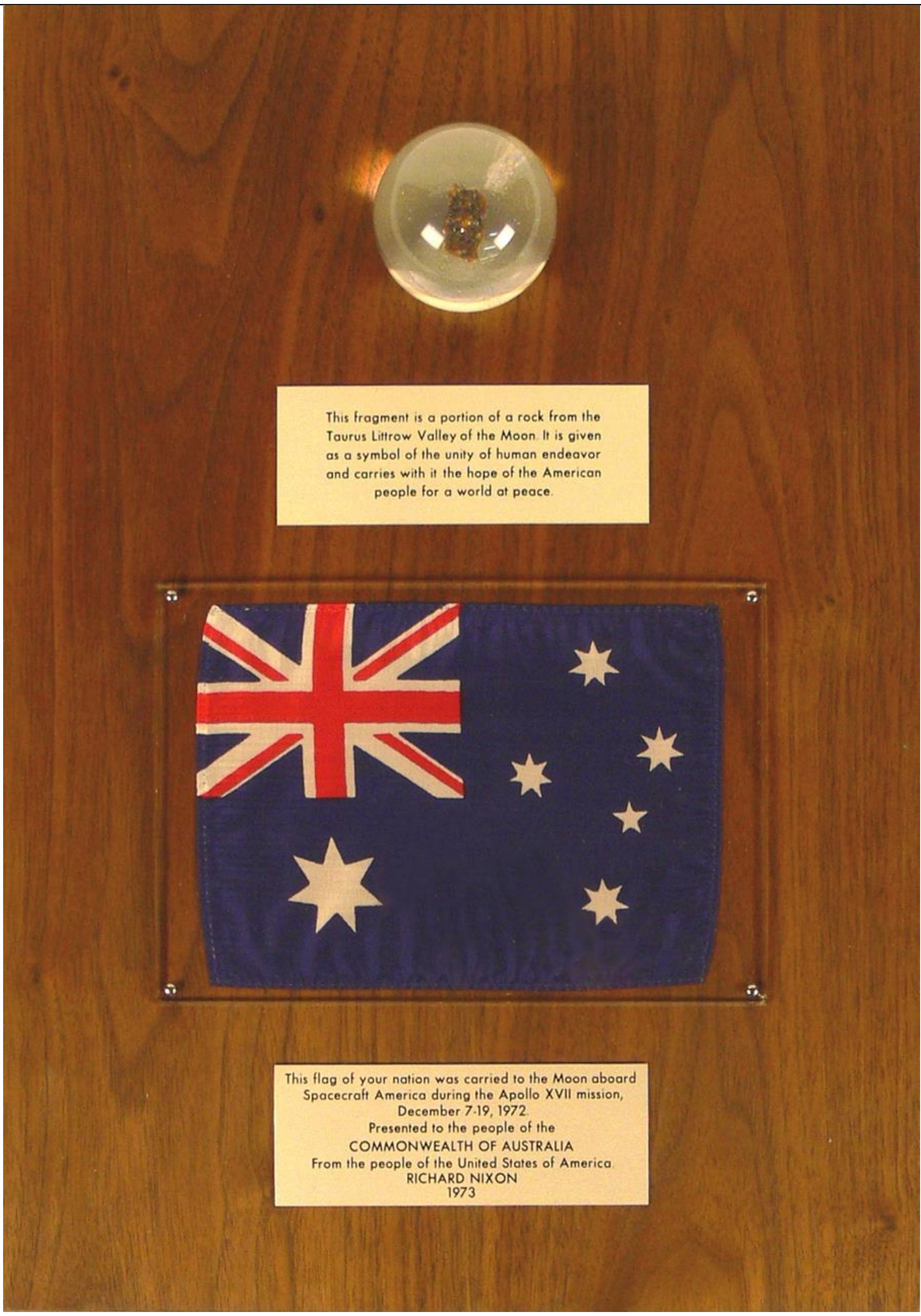
The landers that brought the twin rovers Spirit and Opportunity safely to the Martian surface in 2004 both had on board identical silica glass DVDs containing more than four million names. In 2007, when JAXA launched its lunar orbiter Selene it also marked the culmination of its Wish upon the Moon campaign which invited people to submit their name and a very short message, of 20 Japanese characters or 40 English letters, to be carried by the spacecraft. The number of people who responded was 412,627 and their messages were micro-written on metal foil and attached to the outside of the spacecraft.

Also in 2007, NASA launched its Phoenix Mars lander which excavated a small portion of the northern polar Martian surface and discovered ice. For this mission, a silica glass DVD titled the Visions of Mars was included. The DVD contained messages from Carl Sagan, Arthur C Clarke and others, books and stories of Mars by such authors as Isaac Asimov and Ray Bradbury, the Orson Welles' radio broadcast of the H G Wells' story War of the Worlds and a musical production of Bob Derkach's Winds of Mars. Also included on the disc were over 250,000 names from people around the world.



Phoenix Mars Lander showing *Visions of Mars* DVD. Image credit: NASA. The *Visions of Mars* DVD was produced by the Planetary Society.

NASA also collected names and included them on a microchip carried to Mars on the Science Laboratory Rover named Curiosity. The Mars Society Australia promoted this 'Send your name to Mars' initiative during the Science Alive! event in Adelaide during National Science Week, 2009 and there was an



Moon rock and Australian flag plaque. Image credit: Trevor Rodwell.

enthusiastic response from both adults and children. Curiosity was launched 26 November 2011 and landed successfully on Mars on 6 August 2012. More than 1.2 million names were included on the microchip from 246 nations.

These few examples of public engagement with space missions also indicate a level of popular interest in such missions, especially in the light of limited public media publicity about these missions and the opportunities for participation that are offered.

Another form of public engagement is that of competitions built around a particular project. These mostly take the form of 'name the spacecraft' type events, for example the two Mars exploration rovers launched in 2003 were named after a student contest during which 10,000 entries were received. The winner of this particular competition was nine-year-old Sofi Collis with her names of 'Spirit' and 'Opportunity'. A similar competition was launched to name the Mars Science Laboratory rover – this was won by twelve year-old Clara Ma with her essay entry 'Curiosity', 'an everlasting flame that burns in everyone's mind'. Ma was chosen from 9,000 essay entrants and, as the winner, was invited to sign her name on the rover before it was launched to Mars.

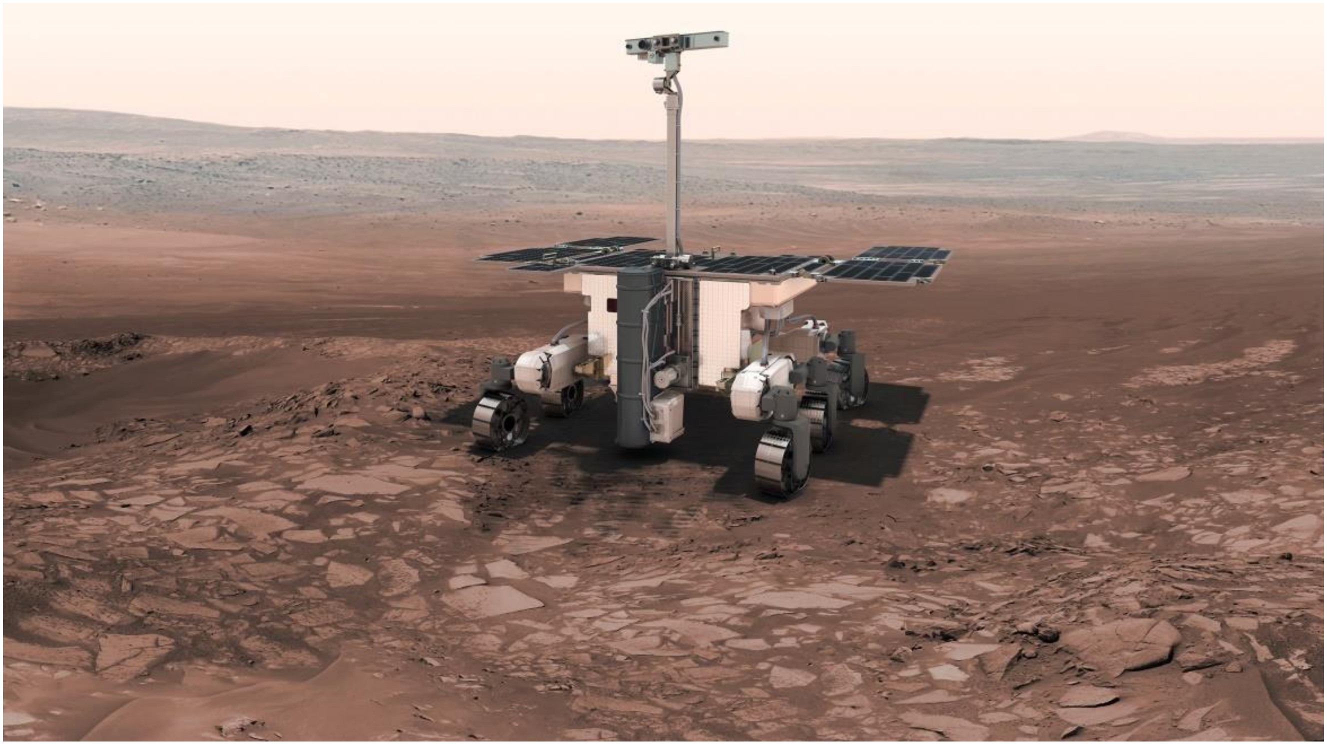
NASA certificate of participation. Image Credit: NASA design.

It is interesting to note that many space observatories and space probes are given the names of people who have made a major contribution in a number of related fields to the particular mission design. For example, the Hubble Space Telescope was named after Edwin Hubble who made many advances in astronomy in the early 1900s; the Kepler Space Telescope was named after Johannes Kepler. In 2009 the ESA launched the Herschel Infrared Space Observatory named after Sir William Herschel and his sister Caroline Herschel who were both pioneering and successful astronomers in the late 1700s. The Planck Microwave Observatory was named after the scientist Max Planck (1858-1947) who won the Nobel Prize for Physics in 1918.

Space agencies today are very aware of the history that they have built on, but they are also aware that relating their missions to human endeavours is more appealing to the general public. They are becoming more engaged with the public in an endeavour to show space as something exciting and worthy of observation.

As an example, the European Space Agency (ESA) ExoMars rover is due for launch in July 2020 and scheduled to land on Mars in March 2021 with the aim to search for the building blocks of life on Mars. A public participation competition to name the rover received 36,000 entries. The winning entry was 'Rosalind Franklin', named after a British chemist and X-ray crystallographer who contributed to unravelling the double helix structure of human DNA.

Link: Burke, J.D (2008). Why we explore – striving outward. Retrieved 7 December 2008, from http://planetary.org/explore/why.html



ExoMars rover. Image credit: ESA.

Why We Should Colonize Mars

Robert Zubrin

Mars is the decisive step in humanity's outward migration into space. The Red Planet is hundreds of times further away than the Moon, but it offers a much greater prize. Indeed, uniquely among the extraterrestrial bodies of our solar system, Mars is endowed with all the resources needed to support not only life but the development of a technological civilization. In contrast to the comparative desert of Earth's moon, Mars possesses oceans of water frozen into its soil as permafrost, as well as vast quantities of carbon, nitrogen, hydrogen, and oxygen, all in forms readily accessible to those clever enough to use them. Additionally, Mars has experienced the same sorts of volcanic and hydrologic processes that produced a multitude of mineral ores on Earth. Virtually every element of significant interest to industry is known to exist on the Red Planet. With its 24-hour day-night cycle and an atmosphere thick enough to shield its surface against solar flares, Mars is the only extraterrestrial planet that will readily allow large scale greenhouses lit by natural sunlight.

Mars can be settled. For our generation and many that will follow, Mars is the New World.

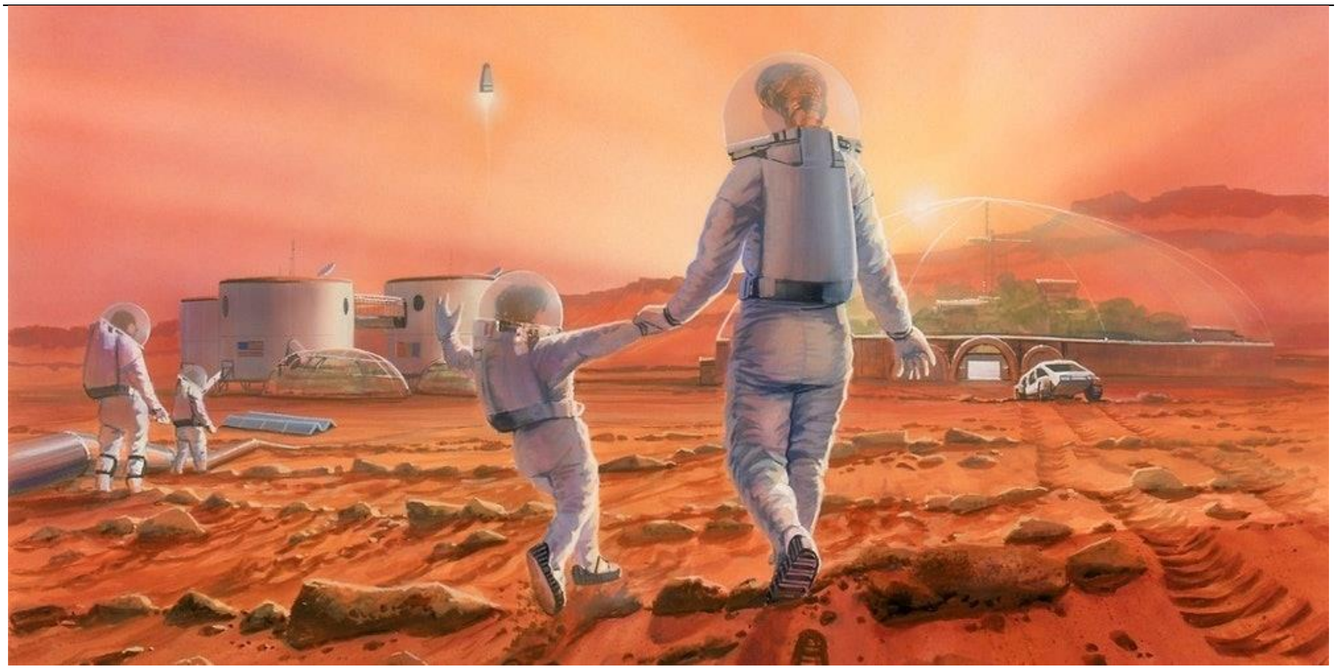
How We Can

"We hold it in our power to begin the world anew ..." Tom Paine, 1776.

The question of colonizing Mars is not fundamentally one of transportation. If we were to use a vehicle comparable to the SpaceX Starship now under development to launch habitats carrying settlers to Mars on one-way trips, firing them off at the same rate we launched the Space Shuttle when it was in its prime, we could populate Mars at a rate comparable to that which the British colonized North America in the 1600's, and at much lower expense relative to our resources. No, the problem of colonizing Mars is not that of moving large numbers to the Red Planet, but of the ability to use Martian resources to support an expanding population once they are there. The technologies required to do this will be developed at the first Mars base, which will thus act as the beachhead for the wave of immigrants to follow. It will develop techniques for extracting water out of the soil, for conducting increasingly large scale greenhouse agriculture, for making ceramics, metals, glasses and plastics out of local materials, and constructing large pressurized structures for human habitation and industrial and agricultural activity.

Over time, the base could transform itself into a small town. The high cost of transportation between Earth and Mars will put a strong financial incentive to find astronauts willing to extend their surface stay beyond the basic one-and-a-half-year tour of duty, to four years, six years, and more. Experiments have already been done showing that plants can be grown in greenhouses filled with CO2 at Martian pressures—the Martian settlers will thus be able to set up large inflatable greenhouses to provide the food required to feed an expanding resident population. Mobile microwave units will be used to extract water from Mars' abundant permafrost, supporting such agriculture and making possible the manufacture of large amounts of brick and concrete, the key materials required for building large, pressurized structures. While the base will start as an interconnected network of "tuna can" habitats, by its second decade, the settlers could live in brick and concrete pressurized domains the size of shopping malls. Not too long afterwards, the expanding local industrial activity will make possible a vast expansion in living space by manufacturing large supplies of high strength plastics like Kevlar and spectra that will allow the creation of inflatable domes encompassing Sun-lit pressurized areas up to 100 meters in diameter. Each new reactor landed will add to the power supply, as will locally-produced photovoltaic panels and solar thermal power systems. However, because Mars has been volcanically active in the geologically recent past, it is also highly probable that underground hydrothermal reservoirs exist on the Red Planet. Once such reservoirs are found, they can be used to supply the settlers with abundant supplies of both water and geothermal power. As more people steadily arrive and stay longer before they leave, the population of the town will increase. In the course of things, children will be born, and families raised on Mars, the first true colonists of a new branch of human civilization.

We don't need any fundamentally new or even cheaper forms of interplanetary transportation to send the first teams of human explorers to Mars. However, meeting the logistical demands of a Mars base will create a market that will bring into being low-cost, commercially developed systems for interplanetary transport. Combined with the base's own activities in developing the means to use Martian resources to allow humans to be self-sufficient on the Red Planet, such transportation systems will make it possible for the actual colonization and economic development of Mars to begin.



In the course of things, children will be born, and families raised on Mars, the first true colonists of a new branch of human civilization. (Credit: Robert Murray, Mars Society).

While the initial exploration and base building activities on Mars can be supported by government or corporate largess, a true colony must eventually become economically self-supporting. Mars has a tremendous advantage compared to the Moon and asteroids in this respect, because unlike these other destinations, the Red Planet contains all the necessary elements to support both life and technological civilization, making self-sufficiency possible in food and all basic, bulk, and simple manufactured goods.

That said, Mars is unlikely to become autarchic for a very long time, and even if it could, it would not be advantageous for it to do so. Just as nations on Earth need to trade with each other to prosper, so the planetary civilizations of the future will also need to engage in trade. In short, regardless of how self-reliant they may become, the Martians will always need, and certainly always want, cash. Where will they get it?

While it may be possible to export plentiful Martian deuterium (fusion power fuel) to Earth, or food to and other necessaries to miners in the asteroid belt, in my view the most likely export that Mars will be able to send to Earth will be patents. The Mars colonists will be a group of technologically adept people in a frontier environment where they will be free to innovate — indeed, forced to innovate — to meet their needs, making the Mars colony a pressure cooker for invention. For example, the Martians will need to grow all their food in greenhouses, strongly accentuating the need to maximize the output of every square meter of crop-growing area. They thus will have a powerful incentive to engage in genetic engineering to produce ultra-productive crops, and will have little patience for those who would restrict such inventive activity with fear-mongering or red tape.

Similarly, there will be nothing in shorter supply in a Mars colony than human labor time, and so just as the labor shortage in nineteenth-century America led Yankee ingenuity to a series of labor-saving inventions, the labor shortage on Mars will serve as an imperative driving Martian ingenuity in such areas as robotics and artificial intelligence. Recycling technology to recapture valuable materials otherwise lost as wastes will also be strongly advanced. Such inventions, created to meet the needs of the Martians, will prove invaluable on Earth, and the relevant patents, licensed on Earth, could produce an unending stream of income for the Red Planet. Indeed, if the settlement of Mars is to be contemplated as a private venture, the creation of such an inventor's colony — a Martian Menlo Park — could conceivably provide the basis for a fundable business plan.

Martian civilization will become rich because its people will be smart. It will benefit the Earth not only as a fountain of invention, but as an example of what human beings can do when they rise above their animal instincts and invoke their creative powers. It will show all that infinite possibilities exist, not to be taken from others, but to be made.

Terraforming Mars

Currently available scientific evidence shows that Mars was once a warm and wet planet, a place friendly to life. Atmospheric resources in the form of vast reserves of carbon-dioxide and water adsorbed or frozen into the soil still exist. Once sufficient human industrial potential is developed on Mars, human colonists might begin to employ it to return the planet to the warm-wet climate of its distant past. By producing fluorocarbon (“CF”) super-greenhouse gases on Mars at a rate similar to what we are now doing on Earth, and willfully dumping these climate-altering substances into the atmosphere, Mars colonists could, over a period of several decades, warm the planet by as much as 10 degrees centigrade. This warming would have the effect of causing massive quantities of carbon-dioxide to outgas from the soil. Since CO2 is a greenhouse gas, this would raise the temperature of the planet still more. As the temperature rises, the vapor pressure of water in the Martian atmosphere would also rise, and since water vapor is also a very strong greenhouse gas, this would raise the temperature of the planet still more, forcing even more CO2 out of the soil, etc. As a result of these positive feedback mechanisms, a runaway greenhouse effect could be created on a planet-wide scale on Mars, with the net result being to raise the average temperature on the planet by over 50° C within half a century. At the same time, the atmospheric pressure would rise from its current level of about 1 percent that of Earth to about 35 percent (i.e. 5 psi pressure.) As a result, the large frozen water reserves of Mars would melt, and the planet’s dry rivers would flow once more, filling its lakes and seas. With the hydrosphere mobilized, there would be rain, and it would be possible to spread green plants across the planet. Over a period of a thousand years – or perhaps much less if genetic engineering technology continues to advance – these plants could put enough oxygen in Mars’ atmosphere to make it breathable by humans and higher animals. Eventually, the day would come when breathing gear and city domes would no longer be necessary.

This feat, the “terraforming” of Mars from its current lifeless or near-lifeless state to a living, breathing, world supporting multitudes of diverse and novel life forms and ecologies, will be one of the greatest and noblest enterprises of the human spirit. No one will be able to contemplate it and not feel prouder to be human.

Life in the initial Mars settlements will be harder than life on Earth for most people, but life in the first North American colonies was much harder than life in Europe as well. People will go to Mars for many of the same reasons they went to colonial America: Because they want to make a mark, or to make a new start, or because they are members of groups who are persecuted on Earth, or because they are members of groups who want to create a society according to their own principles. Many kinds of people will go, with many kinds of skills, but all who go will be people willing to take a chance to do something important with their lives. Out of such people are great projects made and great causes won. Aided by ever-advancing technology, such people can transform a planet and bring a dead world to life.

Some people consider the idea of terraforming other planets heretical—humanity playing God. Others would see in such an accomplishment the most profound vindication of the divine nature of the human spirit—dominion over nature, exercised in its highest form to bring dead worlds to life. Personally, I prefer not to consider such issues in their theological form, but if I had to, my sympathies would definitely be with the latter group. Indeed, I would go farther. I would say that failure to terraform constitutes failure to live up to our human nature, and a betrayal of our responsibility as members of the community of life itself.

These may seem like extreme statements, but they are based in history, about 4 billion years of history. The chronicle of life on Earth is one of terraforming—that’s why our beautiful blue planet is as nice as it is. When the Earth was born, it had no oxygen in its atmosphere, only carbon-dioxide and nitrogen, and the land was composed of barren rock. It was fortunate that the Sun was only about 70 percent as bright then as it is now, because if the present-day Sun had shined down on that Earth, the thick layer of CO2 in the atmosphere would have provided enough of a greenhouse effect to turn the planet into a boiling Venus-like hell. Fortunately, however, photosynthetic organisms evolved that transformed the CO2 in Earth’s atmosphere into oxygen, in the process completely changing the surface chemistry of the planet. As a result of this activity not only was a runaway greenhouse effect on Earth avoided, but the evolution of aerobic organisms which use oxygen-based respiration to provide themselves with energetic life styles was enabled (though a primeval EPA dedicated to preserving the status quo on the early Earth might have regarded this as a catastrophic act of environmental destruction). This new crowd of critters, known today as animals and plants, then proceeded to modify the Earth still more, colonizing the land, creating soil, and drastically modifying global climate. Life is selfish, so it’s not surprising that all the modifications that life has made to the Earth have contributed to enhancing life’s prospects, expanding the biosphere, and accelerating its rate of developing new capabilities to improve the Earth as a home for Life still more.

Humans are the most recent practitioners of this art. Starting with our earliest civilizations, we used irrigation, crop seeding, weeding, domestication of animals and protection of our herds to enhance the activity of those parts of the biosphere most efficient in supporting human life. In so doing, we have expanded the biospheric basis for human population, which has expanded our numbers and thereby our power to change nature in our interest in a continued cycle of exponential growth. As a result, we have literally remade the Earth into a place that can support billions of people, a substantial fraction of whom have been sufficiently liberated from the need to toil for daily survival that they can now look out into the night sky for new worlds to conquer.

It is fashionable today to bemoan this transformation as destruction of nature. Indeed, there is a tragic dimension to it. Yet it is nothing more than the continuation and acceleration of the process by which nature was created in the first place. Life is the creator of nature

Today, the living biosphere has the potential to expand its reach to encompass a whole new world, on Mars, and the interplanetary civilization that develops as a result will have the capability of reaching much further. Humans, with their intelligence and technology, are the unique means that the biosphere has evolved to allow it to blossom across interplanetary and then interstellar space. Countless beings have lived and died to transform the Earth into a place that could give birth to a species with such capabilities. Now it's our turn to do our part.

It's a part that 4 billion years of evolution has prepared us to play. Humans are the stewards and carriers of terrestrial life, and as we spread out, first to Mars, and then to the nearby stars, we must and shall bring life to many worlds, and many worlds to life.

It would be unnatural for us not to.

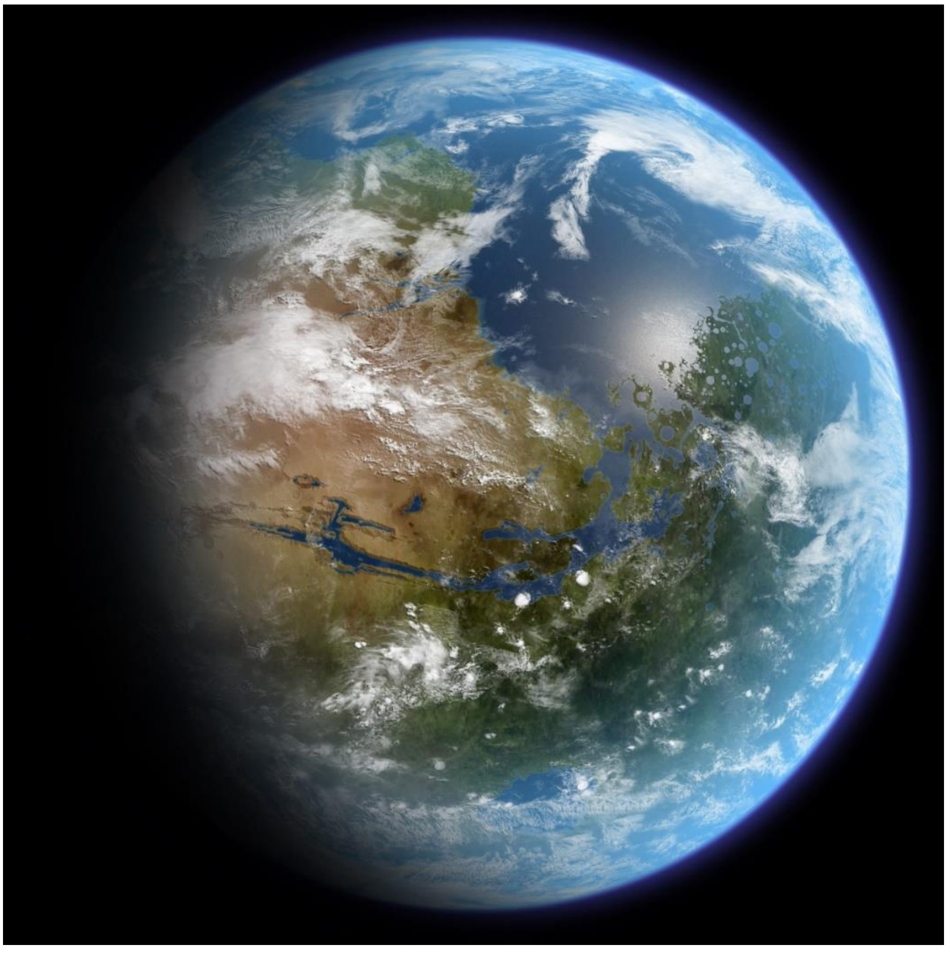
Why We Must

The law of existence prescribes uninterrupted killing, so that the better may live (Adolf Hitler, 1941).

Human civilization currently faces many serious dangers. The most immediate catastrophic threat, however, does not come from environmental degradation, resource depletion, or even asteroidal impact. It comes from bad ideas.

Ideas have consequences. Bad ideas can have really bad consequences.

The worst idea that has ever been is that the total amount of potential resources is fixed. It is a catastrophic idea, because it sets all against all.



The Mars of the future? Mars was once a warm and wet planet and could be made so again through human engineering efforts. But this time it would be seeded with life. We can create a living world. Would it be ethical to do it? Would it be ethical not to? (Credit Daein Ballard)

Currently, such limited-resource views are quite fashionable not only among futurists, but much of the body politic. But if they prevail, then human freedoms must be curtailed. Furthermore, world war and genocide would be inevitable, for if the belief persists that there is only so much to go around, then the haves and the want-to-haves are going to have to duke it out, the only question being when.

This is not an academic question. The twentieth century was one of unprecedented plenty. Yet it saw tens of millions of people slaughtered in the name of struggle for existence that was entirely fictitious. The results of similar thinking in the twenty-first could be far worse.

The logic of the limited resource concept leads down an ever more infernal path to the worst evils imaginable. Basically it goes as follows:

1. Resources are limited. Therefore:
2. Human aspirations must be crushed.
3. So, some authority must be empowered to do the crushing.
4. Since some people must be crushed, we should join with that authority to make sure that it is those we despise, rather than us.
5. By getting rid of such inferior people, we can preserve scarce resources and advance human social evolution, thereby helping to make the world a better place.

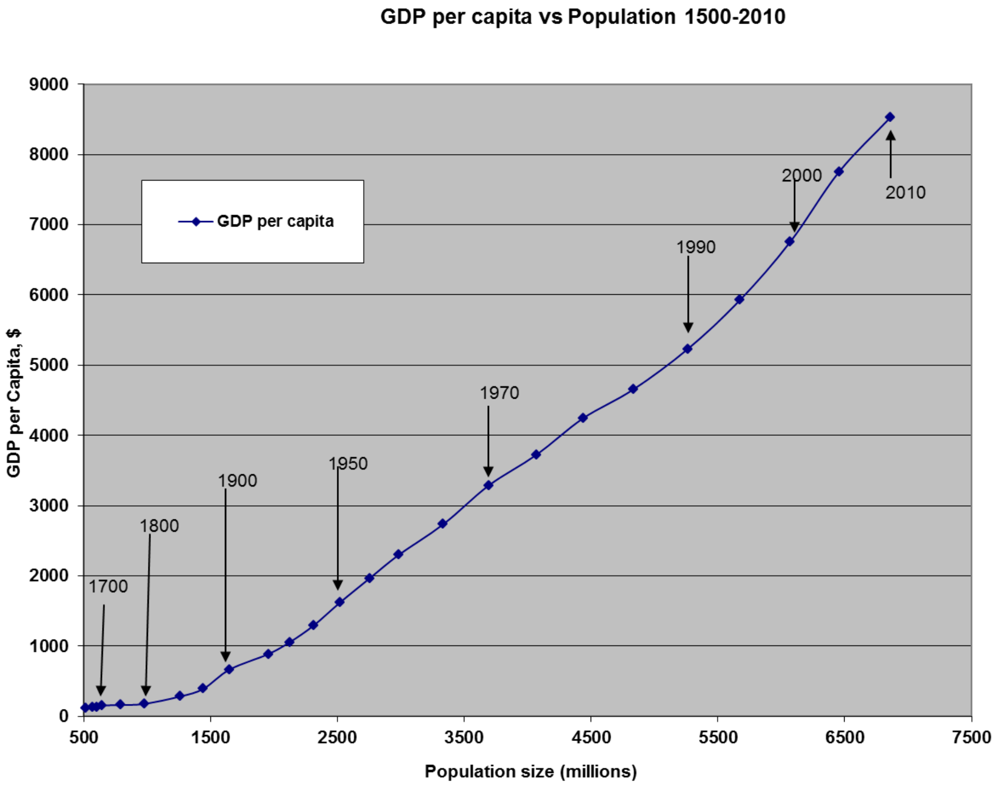
The fact that this case for oppression, tyranny, war and genocide is entirely false has made it no less devastating. Indeed, it has been responsible for most of the worst human-caused disasters of the past 200 years. So let's take it apart.

Two hundred years ago, the English economist Thomas Malthus set forth the proposition that population growth must always outrun production as a fundamental law of nature. This theory provided the basis for the cruel British response to famines in Ireland and India during the mid through the late 19th Century, denying food aid or even taxation, rent, or regulatory relief to millions of starving people on the pseudoscientific grounds that their doom was inevitable.

Yet the data show that the Malthusian theory is entirely counterfactual. In fact, over the two centuries since Malthus wrote, world population has risen sevenfold while inflation-adjusted global gross domestic product per capita has increased by a factor of fifty, and absolute total GDP by a factor of 350.

Indeed, it is clear that the Malthusian argument is fundamentally nonsense, because resources are a function of technology, and the more people there are, and the higher their living standard, the more inventors, and thus inventions, there will be, and the faster the resource base will expand.

Our resources are growing, not shrinking, because resources are defined by human creativity. In fact, there is no such thing as "natural resources." There are only natural raw materials. It is human ingenuity that turns natural raw materials into resources.



Contrary to Malthus's theory, human global well-being has increased with population size, and at an accelerating rate. (Credit: Author)

Land was not a resource until people invented agriculture, and it is human ingenuity, manifested in continuous improvements in agricultural technology, that has multiplied the size of that resource many times over.

Petroleum was not originally a resource. It was always here, but it was nothing useful. It was just some stinky black stuff that sometimes oozed out of the ground and ruined good cropland or pasture. We turned it into a resource by inventing oil drilling and refining, and by showing how oil could be used to replace whale oil for indoor lighting, and then, later, liberating humanity with unprecedented personal mobility.

There are things around today that clearly could become major resources, but are not yet. Uranium and thorium were not resources at all until we invented nuclear power, but we are going to have to do a bit more inventing to get all the bugs out so as to unleash their truly vast potential. The same thing is true for solar energy, which needs to be made cheaper if it is to become practical. But this is happening, year by year, through innumerable inventions, great and small. Other enormous resources, more distantly in view, await the invention of ways to use them; for example, there is deuterium in sea water that could provide fusion power; there are methane hydrates and stratospheric winds. Today, the revolutionary new resource is shale. Twenty years ago shale was not a resource. Today, as a result of the invention of new techniques of horizontal drilling and fracking, it's an enormous resource. In the past ten years, we've used it to increase our oil production 50 percent. In the past twenty years, America's gas reserves have tripled, and we can and will do that and more for the world at large.

So the fact of the matter is that humanity is not running out of resources. We are exponentially expanding our resources. We can do this because the true source of all resources is not the earth, the ocean, or the sky. It is human creativity. It is people, who are resourceful.

It is for this reason that, contrary to Malthus and all his followers, the global standard of living has continuously gone up as the world's population has increased, not down. The more people - especially free and educated people - the more inventors, and inventions are cumulative.

Furthermore, the idea that nations are in a struggle for existence is completely wrong. Darwinian natural selection is a useful theory for understanding the evolution of organisms in nature, but it is completely false as an explanation of human social development. This is so because, unlike animals or plants, humans can inherit acquired characteristics – for example new technologies – and do so not only from parents but from those to which they are entirely unrelated. Thus inventions made anywhere ultimately benefit people everywhere. Human progress does not occur by the mechanism of militarily-superior nations eliminating inferior nations. Rather inventions made in one nation are transferred all over the world, where newly combined with other technologies and different mind sets, they blossom in radical new ways. Paper and printing were invented in China, but they needed to be combined with the Phoenician-derived Latin alphabet, German metal-casting technology, and European outlooks concerning freedom of conscience, speech, and inquiry to create a global culture of mass literacy. The same pattern of multiple sourcing of inventions holds true for virtually every important human technology today, from domesticated plants and animals to telescopes, rockets, and interplanetary travel.

Based on its inventiveness and its ability to bring together people and ideas from everywhere, America has become extremely rich, inciting envy elsewhere. But other countries would not be richer if America did not exist, or was less wealthy or less free. On the contrary, they would be immeasurably poorer.

Similarly America would not benefit by keeping the rest of the world underdeveloped. We can take pride in our creativity, but in fact we would be much better off if other people can have a chance to live, and thus contribute to progress, as we do.

Nevertheless, so long as humanity is limited to one planet, the arguments of the Malthusians have the appearance of self-evident truth, and their triumph can only have the most catastrophic results.

Indeed, one has only to look at the history of the 20th Century, and the Malthusian/national social Darwinist rationale that provided the drive to war of both Imperial and especially Nazi Germany to see the horrendous consequences resulting from the widespread acceptance of such myths.

As the German General Staff's leading intellectual General Friedrich von Bernhardi put in in his 1912 bestseller Germany and the Next War;

> *"Strong, healthy, and flourishing nations increase in numbers. From a given moment they require a continual expansion of their frontiers, they require new territory for the accommodation of their surplus population. Since almost every part of the globe is inhabited, new territory must, as a rule, be obtained at the cost of its possessors—that is to say, by conquest, which thus becomes a law of necessity."*

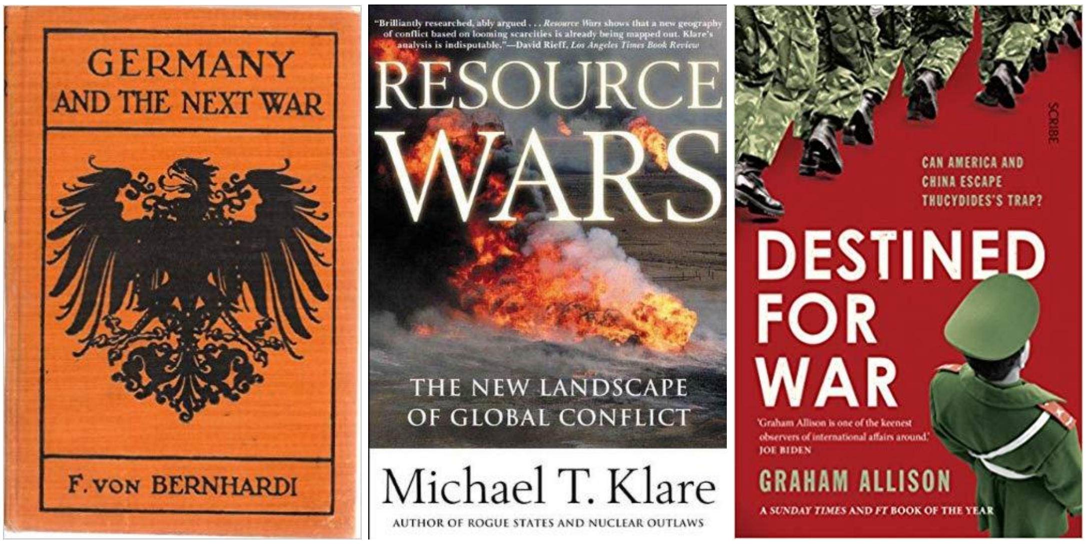
Having accepted that war was inevitable, the only issue for the Kaiser's generals was when to start it, and they chose sooner rather than later so as not to give Russian industry a chance to develop.

Thus in 1914, the unprecedently prosperous European civilization was thrown into a completely unnecessary and nearly suicidal general war. A quarter century later, the same logic led the Nazis to do it again, with not merely conquest, but systematic genocide as their insane goal.

Hitler was quite aware of the central importance of such an ideological foundation for his program of genocide. As noted holocaust historian Timothy Snyder wrote in in a September 2015 New York Times op ed; "*The pursuit of peace and plenty through science, he claimed in 'Mein Kampf,' was a Jewish plot to distract Germans from the necessity of war*."

Once again, to be clear, the issue is not whether space resources will be made available to Earth in the proximate future. Rather it is how we, in the present, conceive the nature of our situation in the future. Nazi Germany had no need for expanded living space. Germany today is a much smaller country than the Third Reich, with a significantly higher population, yet Germans today live much better than they did when Hitler took power. So in fact, the Nazi attempt to depopulate Eastern Europe was completely insane, from not only a moral, but also a practical standpoint. Yet driven on by their false zero-sum beliefs, they tried anyway.

If it is allowed to prevail in the twenty-first century, zero-sum ideology will have even more horrific consequences. For example, there are those who point to the fact that Americans are 4% of the world's population, yet use 25% of the world's oil. If you were a member of the Chinese leadership and you believed in the limited resource view (as many do—witness their brutal one-child policy), what does this imply you should attempt to do to the United States?



Self-fulfilling prophesies. In 1912 the theoreticians of the German General Staff said it was inevitable that Germany would have to wage war for living space. In 2001, American geostrategists proclaimed we would need to fight for oil. Both were wrong. Both set the stage for disaster. Much worse could be on the way if such zero sum ideology is not discredited.

On the other hand, there are those in the US national security establishment who cry with alarm at the rising economy and concomitant growing resource consumption of China. They project of future of "resource wars," requiring American military deployments to secure essential raw materials, notably oil.

There were no valid reasons for the first two World Wars, and there is no valid reason for a third. But there could well be one if zero-sum ideology prevails. Despite the bounty that human creativity is producing, there are those in America's national security establishment who today are planning for resource wars against peoples who could and should be our partners in abolishing scarcity. Their equivalents abroad are similarly sharpening their knives against us. This ideology threatens catastrophe.

Do we really face the threat of general war? There seems to be no reason for it, and in fact, there isn't. People all over the world today are actually living much better than they ever did before, at any time in human history. But the same was true in 1914.

If it is accepted that the future will be one of resource wars, there are men of action who are prepared to act accordingly.

There is no scientific foundation supporting these motives for conflict. On the contrary, it is precisely because of the freedom and affluence of the United

States that American citizens have been able to invent most of the technologies that have allowed China, Russia, and so many other countries to lift themselves out of poverty. And should China (with a population five times ours) develop to the point where its per-capita rate of invention mirrors that of the United States—with 4 percent of the world's population producing 50 percent of the world's inventions—the entire human race would benefit enormously. Yet, that is not how people see it, or are being led to see it by those who should know better.

"The Earth has cancer and the cancer is man," proclaims the elite Club of Rome in one of its manifestos. This mode of thinking has clear implications. One does not provide liberty to vermin. One does not seek to advance the cause of a cancer.

The real lesson of the last century's genocides is this: We are not endangered by a lack of resources. We are endangered by those who believe there is a shortage of resources. We are not threatened by the existence of too many people. We are threatened by people who think there are too many people.

If the twenty-first century is to be one of peace, prosperity, hope, and freedom, a definitive and massively convincing refutation of these pernicious ideas is called for—one that will forever tear down the walls of the mental prison these ideas would create for humanity.

A Question of Faith

Science, reason, morality based on individual conscience, human rights; this is the Western humanist heritage. Whether expressed in Hellenistic, Christian, Deist, or purely Naturalistic forms, it all drives toward the assertion of the fundamental dignity of man. As such, it rejects human sacrifice and is ultimately incompatible with slavery, tyranny, ignorance, superstition, perpetual misery, and all other forms of oppression and degradation. It asserts that humanity is capable and worthy of progress.

This last idea – progress – is the youngest and proudest child of Western humanism. Born in the Renaissance, it has been the central motivating idea of our society for the past four centuries. As a civilizational project to better the world for posterity, its results have been spectacular, advancing the human condition in the material, medical, legal, social, moral, and intellectual realms to an extent that has exceeded the wildest dreams of its early utopian champions.

Yet now it is under attack. It is being said that the whole episode has been nothing but an enormous mistake, that in liberating ourselves we have destroyed the Earth. As influential Malthusians Paul Ehrlich and John Holdren put it in their 1971 book Global Ecology:

> *"When a population of organisms grows in a finite environment, sooner or later it will encounter a resource limit. This phenomenon, described by ecologists as reaching the 'carrying capacity' of the environment, applies to bacteria on a culture dish, to fruit flies in a jar of agar, and to buffalo on a prairie. It must also apply to man on this finite planet."*

Note the last sentence: *It must also apply to man on this finite planet.* Case closed. The only thing left to decide is who gets death and who gets jail.

We need to refute this. The issue before the court is the fundamental nature of humankind. Are we destroyers or creators? Are we the enemies of life or the vanguard of life? Do we deserve to be free?

Ideas have consequences. Humanity today faces a choice between two very different sets of ideas, based on two very different visions of the future. On the one side stands the antihuman view, which, with complete disregard for its repeated prior refutations, continues to postulate a world of limited supplies, whose fixed constraints demand ever-tighter controls upon human aspirations. On the other side stand those who believe in the power of unfettered creativity to invent unbounded resources and so, rather than regret human freedom, demand it as our birth right. The contest between these two outlooks will determine our fate.

If the idea is accepted that the world's resources are fixed with only so much to go around, then each new life is unwelcome, each unregulated act or thought is a menace, every person is fundamentally the enemy of every other person, and each race or nation is the enemy of every other race or nation. The ultimate outcome of such a worldview can only be enforced stagnation, tyranny, war, and genocide. Only in a world of unlimited resources can all men be brothers.

On the other hand, if it is understood that unfettered creativity can open unbounded resources, then each new life is a gift, every race or nation is fundamentally the friend of every other race or nation, and the central purpose of government must not be to restrict human freedom, but to defend and enhance it at all costs.

And that is why we must take on the challenge of space. For in doing so, we make the most forceful statement possible that we are living not at the end of history, but at the beginning of history; that we believe in freedom and not regimentation, in progress and not stasis, in love rather than hate, in peace rather than war, in life rather than death, and in hope rather than despair.

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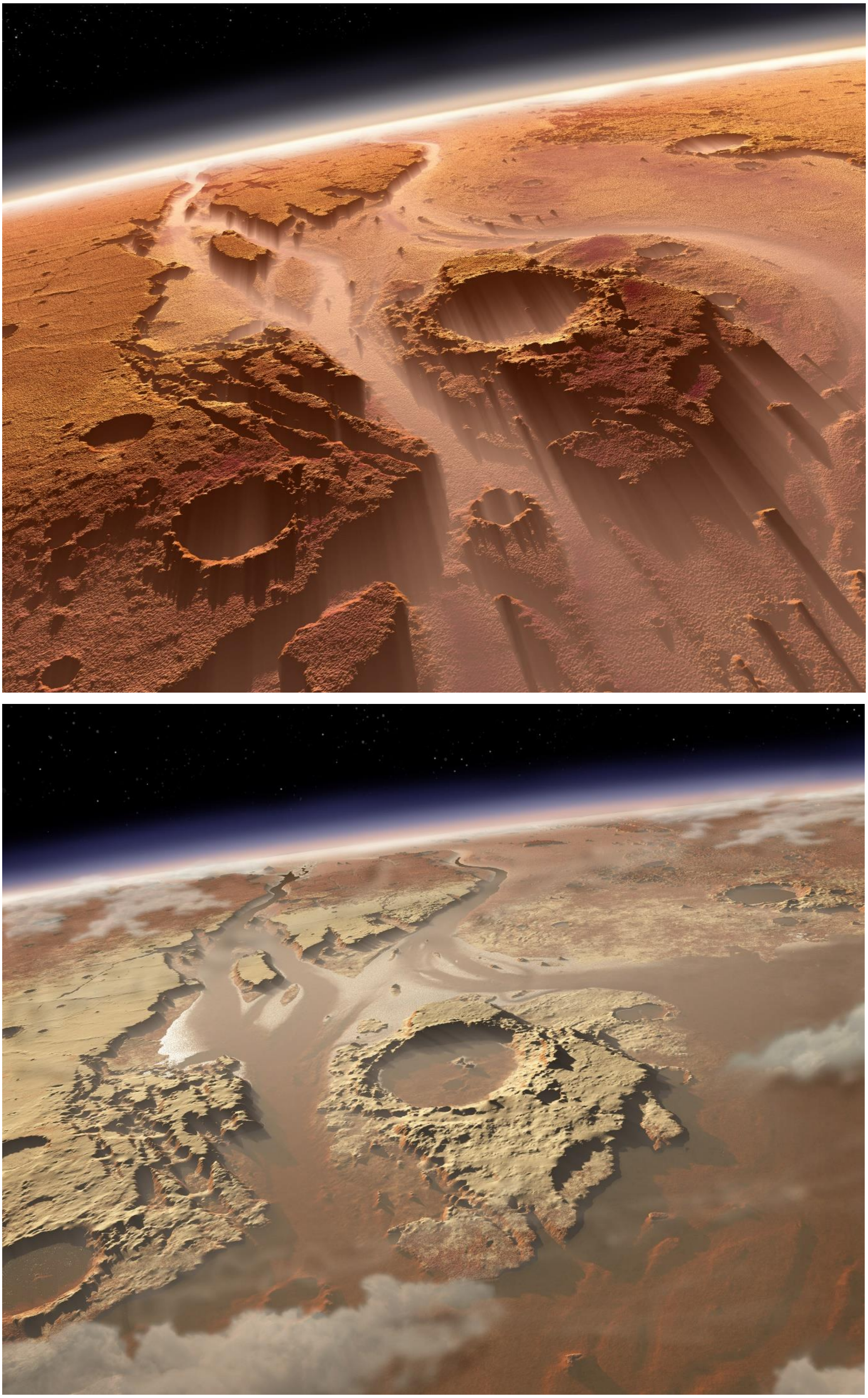

Kasei Valles: Top – dry as it is now. Bottom – filled with water.