Charles J. Byrne

TRAVELS WITH CURIOSITY

EXPLORING MARS BY ROVER

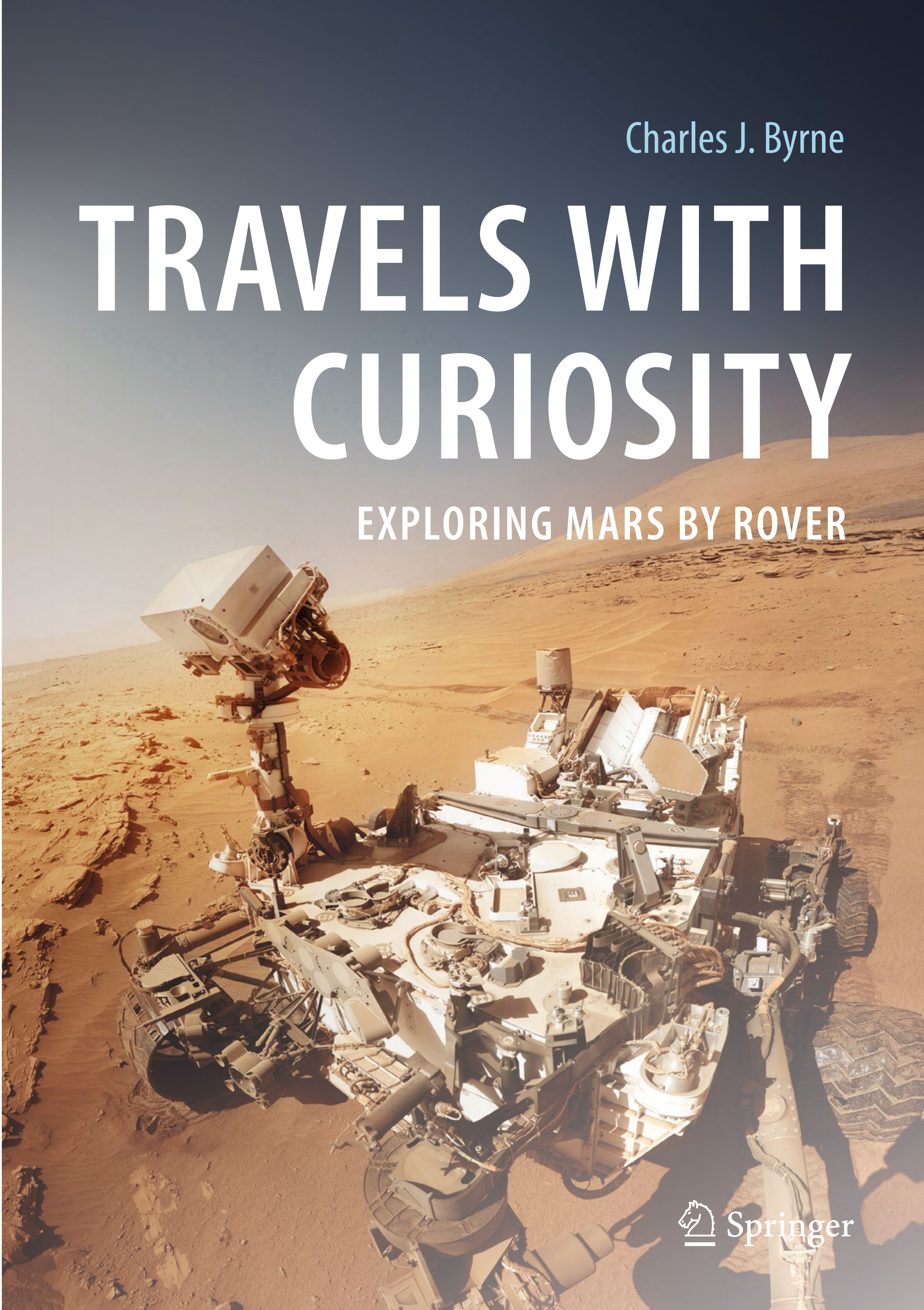

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Image Again
Middletown, NJ, USA

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Cover image: In this image, Curiosity is parked at the foot of Mount Remarkable in the Kimberly site; her MastCam is examining a rock that has tumbled from the hill. The surface of Mars is covered with fine red dust that also floats in the atmosphere. The color images are often filtered like this to show contrast in the rocks for the geologists. That turns the dusty sky to light blue. Credit: NASA

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Preface

The Mars Science Laboratory and the Curiosity Rover

The project Mars Science Laboratory (MSL) was so named to emphasize its objective to land a large mobile array of instruments on the surface of Mars. These instruments were to be designed by scientists in diverse disciplines to gather information not only about the surface as it is today but also how it came to be that way in the course of its history.

The centerpiece of the MSL project is the rover, large enough and strong enough to carry an entire laboratory of instruments and support equipment as well as travel over a diversity of terrain conditions while gathering data for scientific investigation of Mars.

Scientific Curiosity

The winner: Clara Ma

Clara Ma was a 12-year-old student at the Sunflower Elementary School in Lenexa, Kansas when she won NASA's name contest. Asked why she entered the contest, she replied:

"I was really interested in space. But I thought space was something I could only read about in books and look at during the night from so far away. I thought that I would never be able to get close to it, so for me, naming the Mars rover would at least be one step closer."

Scientists, of course, are as diverse in their characters as any other groups of people. But there is one common bond that draws them together in the activity of science. That is a desire to learn more about nature—the Earth, the biosphere, the Solar System, and the universe. In short, how things work. A word for this common bond is CURIOSITY. And that is the name Clara Ma chose as the title for her winning essay submitted to NASA's rover name contest.

Clara signed her name on the rover while it was in test; the rover passed through space on its way to Mars and has been on the surface there for seven years now. A line from Clara's essay is:

> We have become explorers and scientists with our need to ask questions and to wonder.

Some of the questions that the MSL Science Team ponders are: Since life is so pervasive on Earth, how come there is so little evidence of life on Mars? Is there any evidence that there once was life on Mars? Could there have been? To address these questions, the Curiosity rover has instruments that can investigate the habitability of Mars. By examining the current geology of Mars, the nature of the past environments that formed them can be inferred, as can be the habitability of those environments. Curiosity's instruments are discussed in Chap. 2.

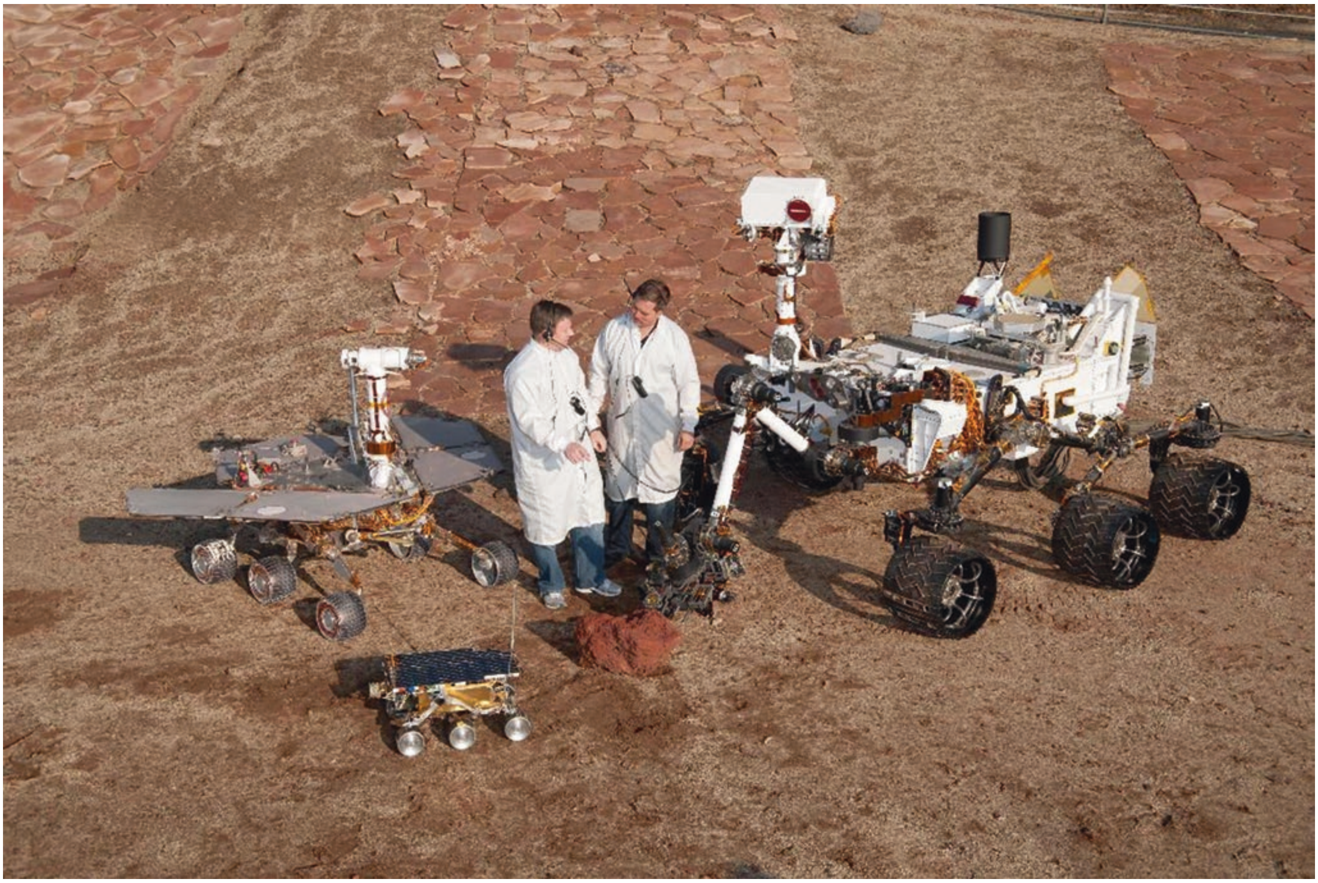

Fig. 1 Test models of three JPL designs of Mars rovers are shown with two JPL engineers. Sojourner (bottom left) was landed in 1997, and Spirit and Opportunity (above Sojourner) landed in 2004. Curiosity (right) was landed in 2012. (Image courtesy of NASA, JPL-Caltech.)

The MSL Science Team: Each of the 10 science instruments was proposed by principal investigators. These senior planetary scientists also appointed members of their staff, to be members of the MSL Science Team, a group of about 160 scientists who are responsible, along with their collaborators, for the tactical decisions of Curiosity's activities.

These scientists, about 400 in total, are listed in Appendix A. The management, performance, and productivity of this group of scientists, representing several relevant disciplines and many academic institutions, are discussed in Chap. 11.

Curiosity is the heaviest rover that has ever been landed on any planet but Earth, weighing in at about 2 tons (see Fig. 1). The Apollo Lunar Modules, which landed humans on the Moon, had a dry weight of about 6 tons.

In addition to the construction of the Curiosity rover, the MSL project included figuring out the means of delivering such a heavy load safely to Mars, using a soft landing near a designated site. Landing from space to the surface of Mars is actually more of a challenge than landing on Earth or the Moon. Its thin atmosphere is both a help in dissipating the vehicle's energy and a hindrance because of high winds.

Other parts of the MSL are the communications, propulsion, and support systems used in the transfer trajectory from Earth. The aeroshell (see Fig. 2) contains the ablative shield used in early entry to the Mars atmosphere and a parachute to further reduce the speed. Retro rockets and a radar system maneuver Curiosity to hover over the landing site after it deploys its wheels. Finally, a sky crane gently lowers

Fig. 2 The MSL, assembled for testing. Curiosity is inside the aeroshell (above the black heat shield). (Image courtesy of NASA, JPL-Caltech.)

Curiosity to a landing, ready to roll. The MSL components that support the entry, descent, and landing are discussed in Chap. 3. Someday, similar components scaled by payload weight, may bring astronauts, scientists, and (who knows?) tourists safely to the surface of Mars.

The Tour

What would it be like to travel on Mars? For starters, it would be different from anything you could experience on Earth. First, you would be conscious of not only the spacesuit you are wearing to protect you from the low-density Mars atmosphere but also the equipment in your backpack that would provide the air you breathe. Yet, although heavy on Earth (it would weigh 50 pounds), it only would weigh a sixth of that on Mars.

The environment of Mars itself would be disturbing. First, the sky is red (if the Sun is shining) because of the pervasive fine dust in the atmosphere. Here on Earth, the moisture in the atmosphere scatters sunlight and makes the color of the sky blue if there are no clouds. On Mars, the tiny particles of red dust (iron oxide) do something similar. The red light also causes the color of everything you see to be tinted reddish, so your suit, if white, would appear to be pink.

Many of the images in this book came from the navigation cameras, which are grayscale, but there are many color pictures as well from the science cameras. Some of these are in the natural reddish tints of Mars, but others are color-shifted so that minerals that are similar to those on Earth look familiar. You can tell that these images have been color-shifted because the sky is blue!

Time does not fly, it crawls on Mars!

Your timepiece would be similar to one for Earth, but the duration of a day would be a little different. Because Mars rotates slower than Earth, about 40 minutes each Earth day, the time between sunrise and sunrise would be longer than a day. To avoid confusion, we do not use “day” for this important interval: the term on Mars is “sol.” For planning, you would divide a sol into 24 hours and each hour into 60 minutes, but you would be aware that each Mars interval would be slightly longer than a corresponding Earth interval. You should remind yourself of the difference by saying yestersol and tosol and tomorrowsol for yesterday and today and tomorrow, especially when talking to a person on Earth. Actually, you would probably be texting, because of the long minutes (about seven each way) of delay time:

“How are you?”……(fourteen minutes later)……“Fine!”

As you look around you, there would be familiar landforms such as sand, rocks, hills, valleys, but no vegetation whatever. Even though you are high on a hill or ridge with the horizon many kilometers away, there is not a trace of a green tint or water, either! Few places on Earth are so barren.

Still, as we follow the Curiosity rover’s trail of exploration together, we would see many signs of powerful flows of water in ancient times having eroded the landscape much as it does on Earth. Such ancient flows have been a determinant of mineral composition of the rocks because the presence of water influences how atoms combine to form molecules and crystals of rocks.

The Curiosity rover will be your guide as she explores the floor of Gale Crater and ascends Mount Sharp. Its many cameras will provide the views as we progress, including the deployment of its instruments. We will provide comments on what has been planned on the ground for Curiosity to perform. Also, we will summarize the interpretation of the data on minerals and structural formations by the diverse scientists as they publish their results. You will be able to join this exciting, ongoing exploration not merely by a robot but also by scores of scientists paving the way back on Earth.

Background of the Mars Science Laboratory

The Jet Propulsion Laboratory, a division of Caltech, came to NASA from the DOD when NASA was founded. Its early history was focused on the Moon (Ranger, Surveyor) but later, as rocket science matured, managed larger, more ambitious projects: Viking landed on Mars, Voyager 1 and 2 visited several planets in fly-bys before they left the Solar System. Mariner flew by Mars. NASA and JPL missions explored Venus, Mercury, Saturn, and Jupiter.

A new NASA administrator, Daniel Goldin, was appointed in 1992. He introduced a new initiative, FBC, standing for “Faster, Better, Cheaper.” He was responding to a period when NASA’s programs were overrunning their budget and running late. In some ways, there were successes in this new management style, but in others there were failures.

In the particular case of JPL, an early success after NASA endorsed the FBC policy was the Pathfinder Program, which landed the first roving vehicle, Sojourner, on Mars at Ares Vallis on December 4, 1996. Pathfinder, managed by Tony Spear, was often seen as a validation of the FBC policy. Sojourner, managed by Donna Shirley, included an X-ray diffraction instrument similar to one carried by Curiosity. Together, Pathfinder and Sojourner were light enough for an airbag landing. After their safe landing and deployment, a number of rocks and soil samples were analyzed, finding both similarities and differences to Earth rocks. Power was supplied by solar panels to supplement a battery. Sojourner managed by Donna Shirley operated for 3 months and drove a total of 100 meters on its six wheels, a configuration that was successfully used for Spirit, Opportunity, and Curiosity. It also will be used for Mars 2020.

Sojourner's success as an FBC project can be attributed to limited and well-chosen objectives, taking advantage of previously established technologies, yet also taking focused development risks. Unfortunately, the next two JPL missions, Mars Polar Lander, launched January 3, 1999, and Mars Climate Orbiter, launched December 11, 1998, were unsuccessful.

Was JPL trying to do too much? Or were the faster and cheaper rules getting in the way of success? NASA and JPL changed strategy after reviewing the success and failures of the FBC policy.

NASA asked the Academy of Sciences to survey the national and global community of planetary scientists on which of their goals was most important in the decade of 2003–2013. This was a successful step toward producing missions that would be individually productive, mutually supportive, and affordable. It was the first planetary decadal survey, published in 1999. The second decadal survey, published in 2013, was for the years 2013–2022.

This first decadal survey was entitled "New Frontiers in the Solar System. An Integrated Exploration Strategy." The duration of the study period was chosen to be 10 years to allow for a reasonable time to develop proposals, engineer, develop, and test the spacecraft and obtain the launch vehicles.

The First Decadal Survey

New Frontiers in the Solar System: An Integrated Exploration Strategy

National Research Council 2003. Washington, DC: The National Academies Press.

https://doi.org/10.17226/10432. Springer, 1999.

Chapter 3 of the document on Mars objectives is entitled "The Evolution of an Earth-like Planet." Exploration of Mars was given a high priority: over 90% of the responses put it as one of their top five targets for the period of the study. The next two were the Moon (65%) and Europa (62%). The discussion points out its similarity to Earth as a rocky planet of similar size, having an atmosphere, and apparently once having had liquid water on its surface. Was it ever habitable? If so, did it have life? Does it have life now, perhaps below the surface?

NASA and JPL would adopt a long-range, ambitious goal "to look for signs of life on Mars." That goal was given credence by evidence, provided by Sojourner and other missions, of an early Mars climate that would allow liquid water on the surface. The new strategy was to pursue that ambitious goal with a series of missions, each with limited subordinate goals, and also to limit risks through redundancy. Two orbiters and two rovers were planned. The rovers were about the same mass as the Pathfinder and Sojourner together, small and light enough for an airbag landing.

In this new strategy, an added goal was to support future human landings on Mars. For this purpose, one of the orbiters was named Mars Reconnaissance Orbiter and would have a high-resolution camera, to play a similar role that Lunar Orbiter played for the Apollo Program—landing site selection and certification. These steps gained support for the new robotic program as did the prospect of increased longevity and mobility on the Mars surface.

The experiences of the FBC era were settled for JPL with the new goals. JPL now felt that it could take on the challenge of searching for signs of early life on Mars. An important subordinate task would be to mobilize the scientific community to rise to the challenge. How do you determine what is or is not a sign of life? This was found to be too difficult a task in the first decadal period. Instead, the goal would be to first try to determine if the Mars environment was ever habitable in the first place.

The new project was named the Mars Science Laboratory (MSL). While mobility was essential in its mission, as learned in the Apollo Program when it added a roving vehicle (for two astronauts!), it would be a laboratory on wheels, not just a vehicle with instruments.

Other requirements, not only supportive of the science mission but also supportive of a manned mission, would be extended lifetime and range (relative to Sojourner's 3 months and 100 meters) and improved landing precision. Payload weight had to increase. Airbags would not scale to that problem (and explorers would not miss bouncing and rolling to a stop), so a new plan for entry, descent, and landing would be needed.

The landing site selection could be influenced, in the course of development, by information gathered from the fleet of two orbiters, 2001 Mars Odyssey and Mars Reconnaissance Orbiter, and two mobile landers, Spirit and Opportunity. Such flexibility required additional navigational capability, especially in latitude and its attendant thermal range.

A particularly difficult challenge was to develop a new technology to take samples of rocks and analyze them for not only their element composition but also their molecular and mineral structure, in order to determine environmental conditions during the rock's formation and modification. The specific goals for the Mars Science Laboratory would not be the detection of life (or past life) on Mars but rather to try to answer the questions: Was there ever an environment on Mars that could support life (as we know it)? How long could that environment have existed?

As the proposal for the MSL was being developed, the launch window was set for 2009. However, as the implications of the requirements were realized, the delivery of instruments and the heat shield were late for testing. Engineering changes needed as tests failed caused further delays. A much more detailed discussion of the problems of this period can be found in *The Design and Engineering of Curiosity* by Emily Lakdawalla, Springer, 2018.

The result of these problems and others was that the launch window had to be delayed to 2011, at a large hit to the NASA budget. The cost was absorbed in the unmanned program's budget, generating some hard feelings in other programs. The two-year slip on such a large project put JPL management and workers on a lot of pressure to survive in a very difficult mission.

Fortunately, the four JPL Mars missions that were planned for the prelude to the Mars Science Laboratory were successful. 2001 Mars Odyssey launched on April 7, 2001 and entered orbit on October 24, 2001. Mars Reconnaissance Orbiter launched on August 12, 2005 and entered orbit on March 10, 2006. Spirit launched on June 10, 2003 and landed on January 4, 2004, operating for six years before becoming stuck in deep sand. Opportunity launched on July 7, 2003 and landed on January 25, 2004. It was still in operation, exploring Endeavor crater, when MSL rover Curiosity landed and continued for a record of 5,250 Earth days for rover endurance on Mars! Meanwhile, the orbiters are still acting as high-speed data relays and tactical camera support for Curiosity.

Middletown, NJ, USA — Charles J. Byrne

Acknowledgements

My interest was diverted from the Moon to Mars (that is quite a distance) by my son, Daniel Joseph (DJ) Byrne. DJ has had a long career at JPL; he wrote and tested the radar pre-processing program for the powered descent phase of the Mars Science Laboratory. Guided by the radar, the sky crane dropped Curiosity well inside its target ellipse. He is now working on Mars 2020. He contributed the last chapter of this book, describing the exciting improvements in engineering and science capability of this next NASA mission to Mars. Mars 2020 is scheduled to launch in July 2020 and land in Jezero crater on February 18, 2021, at 20:30 GMT.

In the course of writing this work, I am indebted first to NASA for their policy of rapid release of raw data and timely news releases. The images from the engineering cameras and the science cameras are posted on web pages within days, sustaining your interest (what did Curiosity see today).

Then there are the journalists, especially the regular bloggers like Emily Lakdawalla, of the Planetary Society. In addition to her blogs, her book "The Design and Engineering of Curiosity," was very helpful. I am aware of how much research Emily has done because I prepared a talk on the topic for my local astronomy group in the summer of 2018, before her book was available, and had to plunge into the diverse engineering sources to find out how the rover worked. My work got much easier when I got a copy of her book and then harder again when the book's coverage of the early surface operations ended in March of 2017.

Two other journalists, Phil Stooke of the Planetary Society and Robert Burnham of Arizona State University have been a very useful resource. Phil provides overlays for the track maps regularly, annotating the stops of Curiosity every time it moves, labeling the stop names. Robert edited "The Red Planet Report" for ASU's Mars Space Flight Facility until recently, providing reports from members of the nearly daily Curiosity operations meetings.

I am deeply indebted to my patient proofreaders, first my diligent, loved, and loving wife, Mary R. Byrne, who corrected the early drafts. DJ Byrne brought his JPL and Mars experience to bear. Then the Springer editor, Maury Solomon now retired, and her successor, Hannah Kaufman, who have now brought my fifth book toward publication.

Finally, I honor the many people all over the world, including those from Caltech, JPL, and the many Science Team Members, engineers, and technicians from many other academic institutions and corporations as we enter the shadow of the coronavirus pandemic. Stay safe and carry on teleworking and following safe practices in essential activities: learning is an essential activity.

Operations of the rovers, Curiosity now at Mars and Perseverance near the launch site, are or will be carried on by teleworking, with the exception of final assembly in a clean room and Earth-based testing of work-arounds for unexpected events, which will be done, as all kinds of collective activities, following safe practices.

Specific information for each project is in Chaps. 11 and 12. The status of each of these missions can be followed by going to mars.nasa.gov or searching for Mars Exploration Program.

Contents

1 The Mars Science Laboratory Mission

The Mars Science Laboratory mission is derived from NASA's strategic vision for Mars, called the Mars Exploration Program. It is the product of the consultation by NASA scientists with American and international scientists who are active in the analysis and design of observational instruments that supplement the results of previous missions.

Program Goals

The Mars Exploration Program set forth four goals:

Goal I: *Determine If Mars Ever Supported Life*
Goal II: *Understand the Processes and History of Climate on Mars*
Goal III: *Understand the Origin and Evolution of Mars as a Geological System*
Goal IV: *Prepare for Human Exploration*

(From MEPAG, 2018, Mars Scientific Goals, Objectives, Investigations, and Priorities. D. Banfield, ed., 81 pp. white paper posted October 2018 by the Mars Exploration Program.)

NASA chose the name "Mars Science Laboratory" to emphasize that the previous spacecraft (landers, rovers, fly-bys, and orbiters) were directed toward relatively specific goals. Earlier missions have gathered a considerable understanding of Mars and that planet's relation to Earth, but many new questions have arisen.

Sets of overlapping disciplines are needed to come to an understanding of not only what is the nature of the surface and atmosphere today but how did it come about? What processes produced the geologic formations we see now? Dr. John Grotzinger, now Chief of the Division of Geological and Planetary Sciences, Caltech, was the first Chief Scientist, who led teams of about 400 researchers working in many institutions. Later Dr. Aswin Vasavada, initially MSL Project Scientist, JPL, replaced Dr. Grotzinger.

A difficult question is whether conditions were ever favorable for life, and if so was it a long enough time to allow life to emerge and leave evidence we could find today. Since Mars is a rocky planet much like Earth (but with important differences), it is a promising place to search for life. On Earth, the time interval between the emergence of life and its evolution to the stage when it left evidence of its existence extends from when the surface had cooled sufficiently for water to be liquid to the time when generations of bacteria could form the massive stromatolites (organized mats of bacteria), the earliest fossils found so far. The interval between these two times is estimated to be about 700 million years. Of course, that period is a single data point, neither a maximum nor a minimum period for life to begin and also to leave evidence to be detected in our time.

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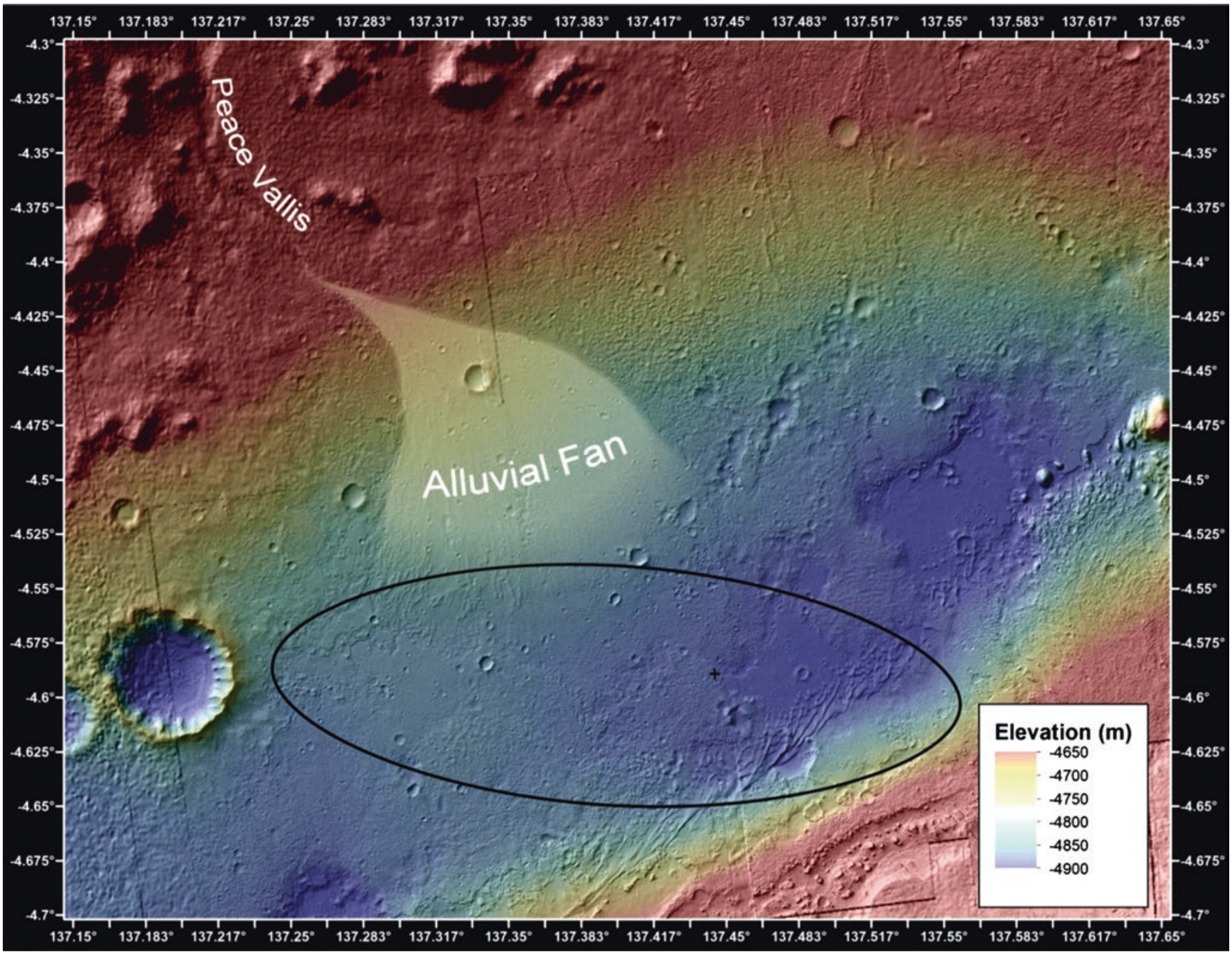

Fig. 1.1 This false-color topographic map displays elevation, derived from orbital observations. It shows the northern edge of Gale crater and Peace Valley (officially Peace Vallis). The ellipse is the landing target, and a small black **+** marks the landing site of Curiosity. Water from the surrounding region ran down Peace Vallis, spreading out into channels in the alluvial fan. (Image courtesy of NASA/JPL-Caltech)

Since life as we know it is dependent on water, the history of water on Mars is critical to the search for evidence of life there. So the role of water in the geology and geochemistry of Mars are critical fields of study. This strategy is sometimes called "Follow the water." One of many examples of erosion by fluid flow is shown in Fig. 1.1. Curiosity has been able to confirm that the fluid that eroded Peace Valley was water.

Goals II and III make it clear that investigation of the atmosphere and geology of Mars are objectives in themselves. They not only increase our knowledge of Mars and Earth but also (by inference) of the other rocky planets of the Solar System and exoplanets. In relation to Goal III there is a small volcanic area near the top of Mount Sharp. Instruments can sense data up to a few centimeters below the surface as well as from cliffs and other features presented by the terrain. Examples of geological formations are shown in Fig. 1.2. These formations, which come together in this single image, are typical of those seen by Curiosity throughout its travels on lower Mount Sharp.

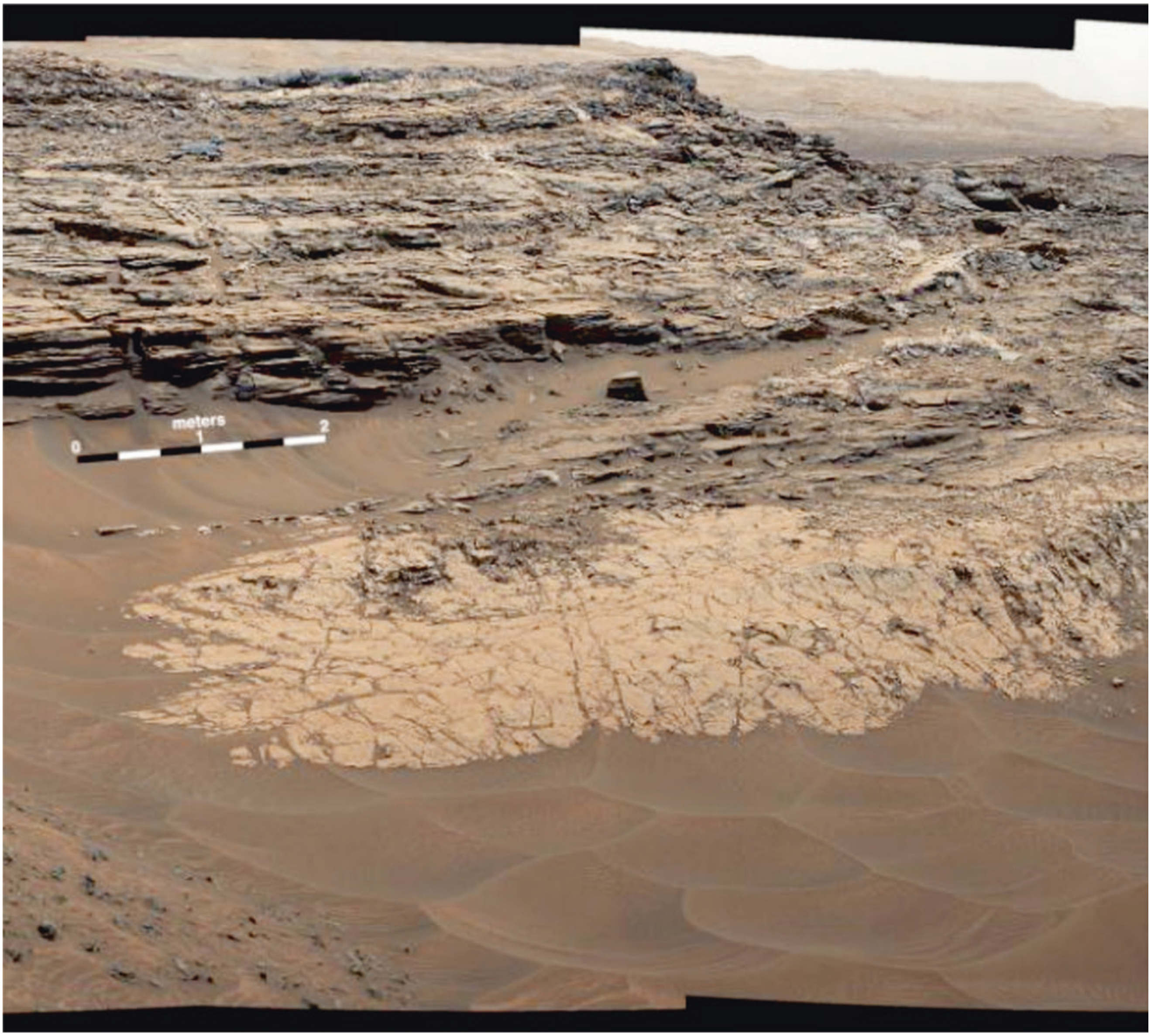

Fig. 1.2 Murray formation (center) and Stimson formation (upper left), with windblown sand. (Image courtesy of NASA/JPL-Caltech/MSSS, from a panorama cropped by the author)

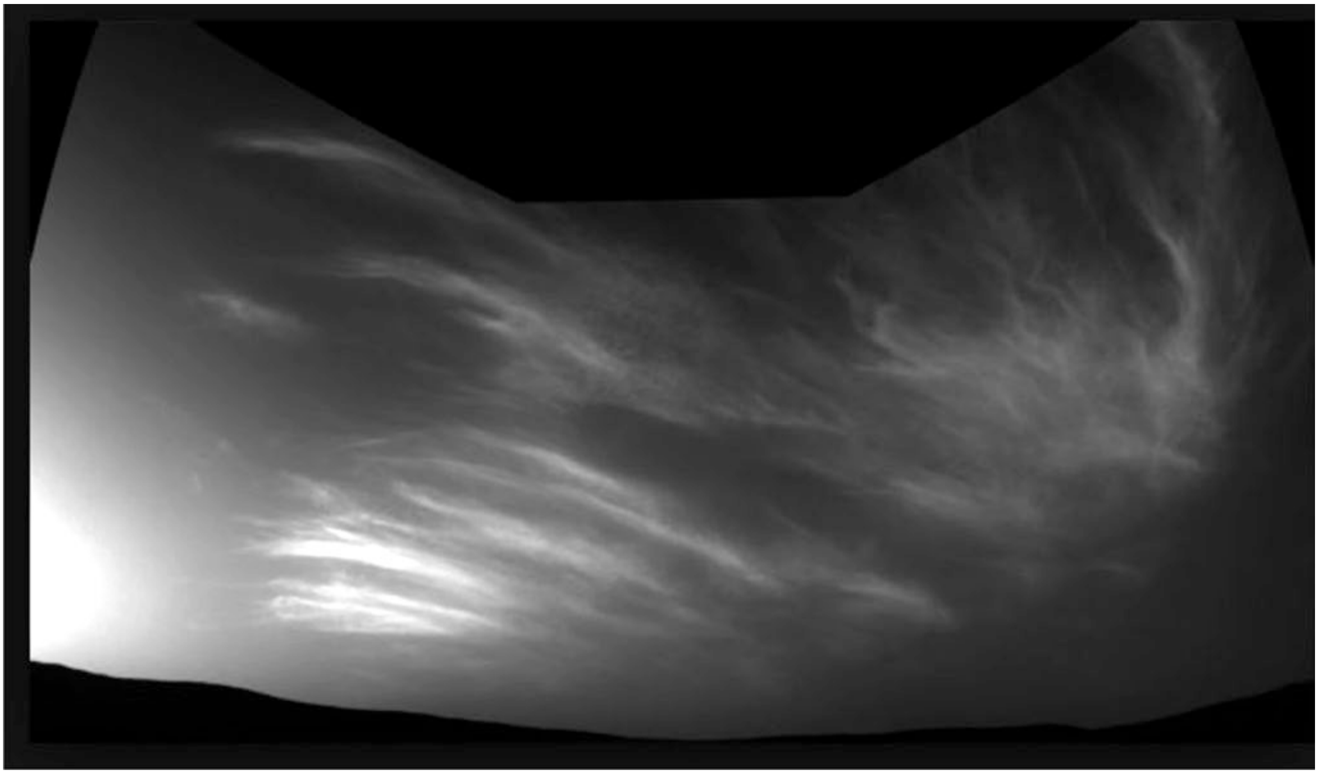

Fig. 1.3 The Curiosity rover photographed this mosaic of clouds on May 17, 2019, with a Navcam. (Image courtesy of NASA/JPL-Caltech)

Goal II, concerning the atmosphere, is addressed by two suites of instruments: the Sample Analysis at Mars (SAM), which periodically sniffs and analyzes the local atmosphere, and the Rover Environmental Monitoring System (REMS), which collects data such as temperature, pressure, and humidity. Also, the camera systems periodically scan the sky for clouds, dust, opacity, and dust devils (Fig. 1.3).

Goal IV addresses the question of whether humans can explore, colonize, or gain resources from Mars. As humans, we have adapted to nearly all the environments on Earth, even modifying our genetics (by evolution) to do so. Answers to these questions come from measuring and monitoring variations in the Martian surface, subsurface, and atmosphere. The MSL entry, descent and landing advanced the technology for dissipating energy in the Mars atmosphere and introduced the sky crane concept for depositing a heavy load (2 tons) on the surface of Mars. Further technical advances are needed for landing the masses of goal IV.

Data gathered by Curiosity will support protection of human biology from radiation at the lunar surface. The practicality of radioisotope thermal power for a long-term mission has been established. A great deal has been learned about the design of drive, suspension, and wheels for long distance driving on Mars (see Fig. 1.4).

Fig. 1.4 Artist's depiction of astronauts on Mars with spacesuits, backpacks for oxygen, a transporter, and equipment. (Image courtesy of NASA/JPL-Caltech)

Also, there is a related question of whether we can modify the environment of Mars to favor humanity. Curiosity can gather some data about the current and past environment, but experiments on modification are left to future missions.

Landing Site: Gale Crater NASA selected the MSL landing site to be on the floor of Gale crater, caused by a meteorite impact. The impact happened billions of years ago, near the edge of an enormous basin that covers nearly all the northern hemisphere of Mars. It has been proposed that this basin be called the Borealis Basin, the result of a very early impact event as Mars completed its aggregation as a planet. Meteorites that could cause such a large basin are sometimes thought to be more like planetoids or dwarf planets. The Borealis Basin may have once been flooded by an ocean in an early wet phase of Mars. If so, Gale crater would have been near its shore (see Fig. 1.5).

North of the Gale crater are several features that have the first name Aeolus, like Gale's central peak, Aeolus Mons (informally, Mount Sharp). In Greek mythology, Aeolus was the keeper of the winds. That's an appropriate name for features on windy Mars. The MSL Science Team selected the name Mount Sharp to honor a highly respected professor of geology, Robert Sharp, who had taught several members of the team. They were not aware that the International Astronomers' Union had already decided to name craters on Mars after deceased scientists and others related to Mars, but not to mountains in order to distinguish the classes of features. The MSL Science Team members have been free to

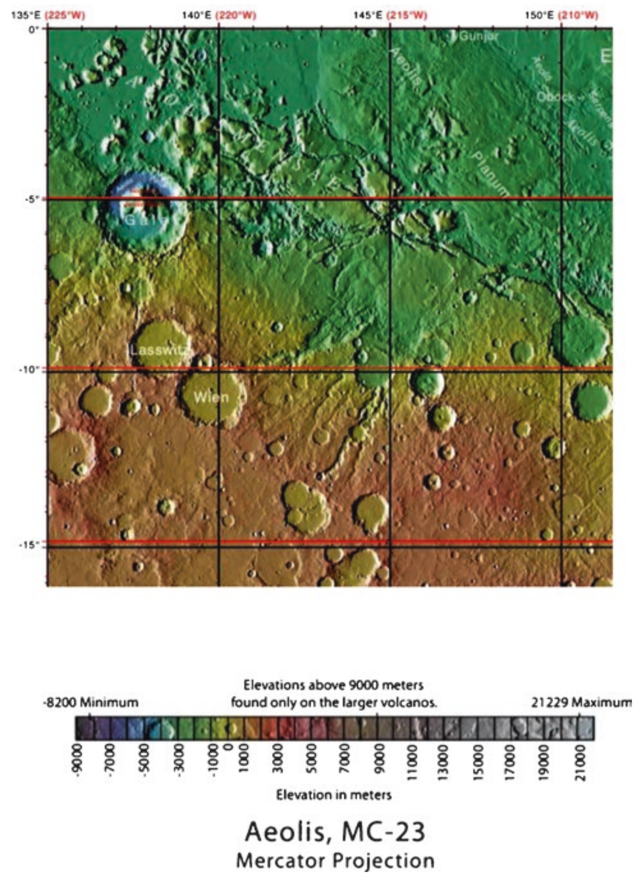

Fig. 1.5 Topographic map of the northwestern corner of the Aeolus quadrangle, containing Gale crater (upper left) and nearby Aeolis Mensae and Aeolis Planum. The highlands south of Gale are Terra Cimmeria. USGS made this nap for NASA from a Digital Elevation Map (DEM) based on the Mars Orbital Laser Altimeter (MOLA) instrument of NASA's Mars Global Surveyor (Image courtesy of NASA/GSFC/MOLA/USGS)

use either names in their peer reviewed papers. For more detail on this awkward issue, see an article by Kelly Beatty, "Mount Sharp or Aeolis Mons", Sky & Telescope, August 14, 2012.

South of Gale there is a steep rise in elevation that would mark the shore of the ocean in the Borealis Basin, if there was sufficient water. The steep rise is along the northern border of Terra Cimmeria, a very large highland region. Several channels on this steep slope are radial to the center of Gale crater and are thought to have brought liquid water to flood that crater through low points in its wall.

There is a very meaningful relation between Terra Cimmeria and Gale crater. In a period of heavy rainfall, water probably ran downslope from that very large highland and over the edge of Gale crater. In low spots of its edge, the water would have cascaded down to the crater floor, creating valleys. One of the younger of these valleys is called Peace Valley; its water was deposited as an alluvial fan (like a delta) on the crater floor. One stream of this fan flowed near the landing point of Curiosity! But that is getting a bit ahead of the tour. Let us proceed to a brief explanation of the geology of Gale crater (see Fig. 1.6).

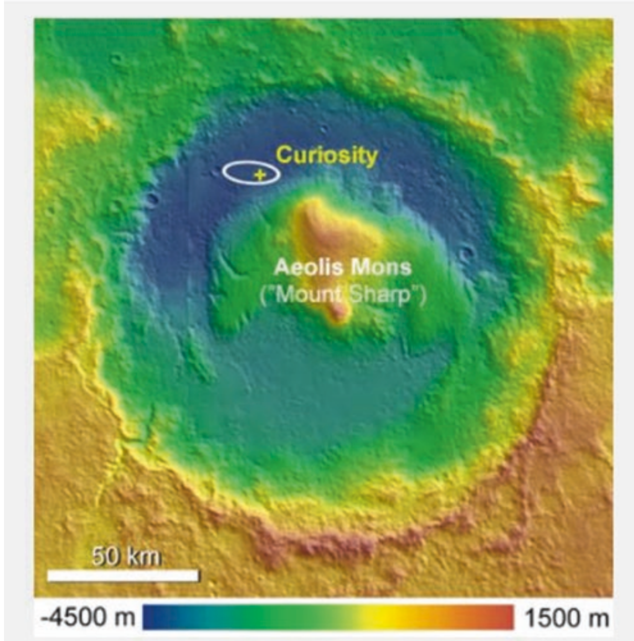

Fig. 1.6 The Curiosity landing target on the floor of Gale crater (Aeolus Palus) is shown in white, with the actual landing point in yellow. The latitude of Gale is 5.4 degrees South and the longitude is 137.8 degrees East. The diameter of the rim is 92 miles (156 km), and the peak of Mount Sharp is about 18,000 feet above the crater floor (Image courtesy of NASA/JPL-Caltech/GSFC/MOLA Science Team

Gale crater was formed by impact of a meteorite between 3.5 and 3.8 million years ago, judging by its degree of erosion and the relationship of its surrounding ejecta layer to nearby features. That age would correspond to the Noachian or earlier Hesperian global geologic ages. Based on orbital photography, including spectral data that distinguished minerals, Gale crater was formed of sedimentary rock, with windblown sand covering part of its surface. The southern half of the rim appears higher, relative to the floor, than the northern rim, which could be due to water covering Borealis Basin at the time of impact. It could also be due to its impacting meteoroid approaching a little north of vertical.

The central mound within Gale (Aeolis Mons, officially, but Mount Sharp, informally) appears to be covered with a succession of sedimentary layers of different minerals. Central peaks are not unusual for impact craters of this size, but this one seems to have acquired heavy deposits of sediment from external flooding that have been eroded to leave an irregular mound (Fig. 1.7).

Figure 1.7 combines data from three orbiters, elevation from ESA's Mars Express, high-resolution images from NASA's Mars Reconnaissance Orbiter, and color from NASA's Viking Orbiter.

Gale was chosen as a landing site for Curiosity because of several factors indicating the likely presence there of ancient liquid water. Concentric channels from the highlands to the south crossing low points on the rim were seen from orbit to lead to valleys on the floor and fans of material. Of course, these features are dry now, but they could have delivered a great deal of water in the past, draining from the highlands. Among the bands of diverse minerals on Aeolis Mons are clay and sulfates. Clay has been suggested as a medium for the origin of life. Sulfates could contribute atomic sulfur, known for preserving organic carbohydrates of past life.

These qualities have made a delightful playground for Curiosity's exploration, as we will see as we tour its route.

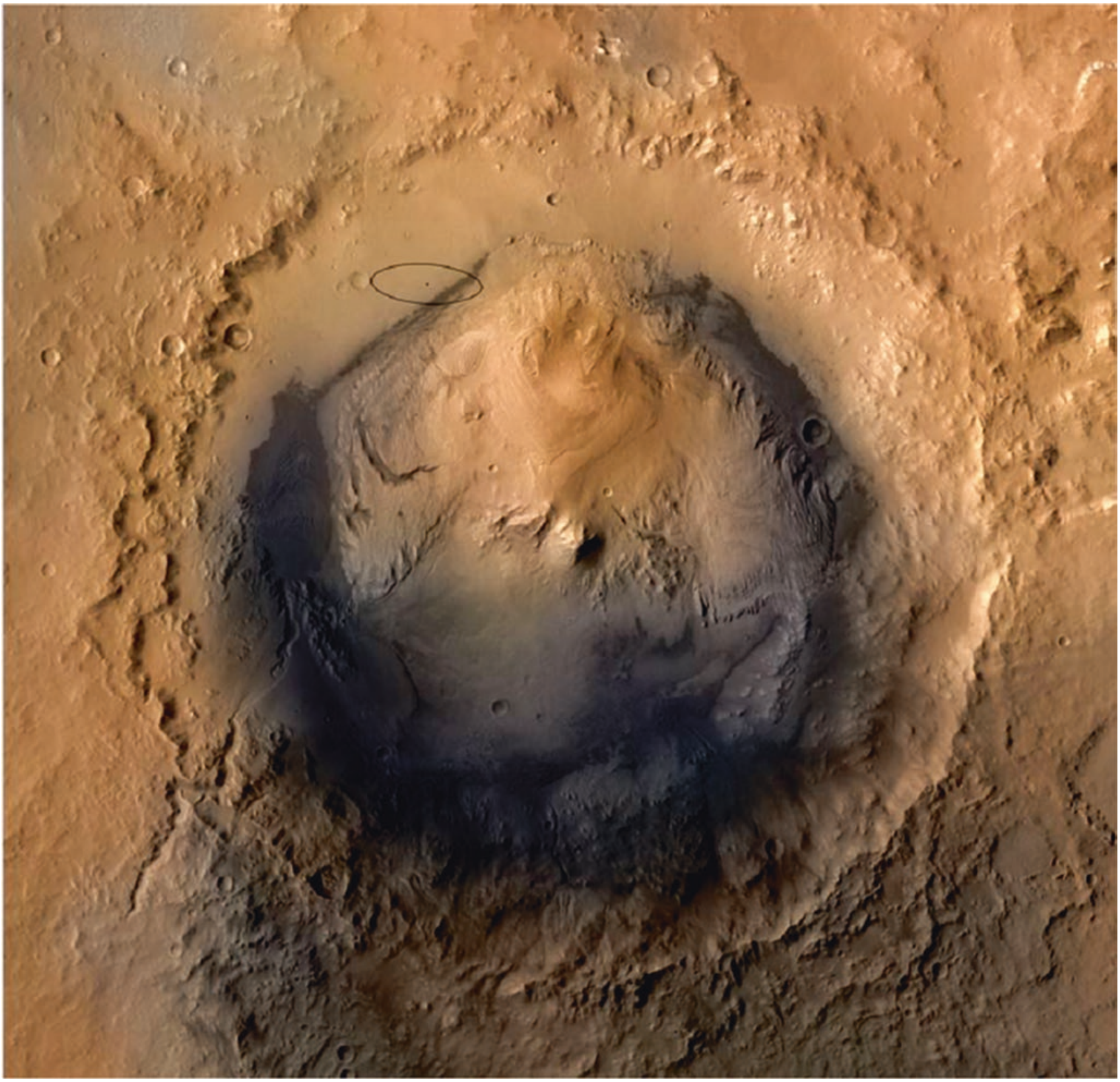

Fig. 1.7 Vertical view of Gale crater, showing the central peak surrounding a complex mound of sediment, formally named Aeolus Mons but widely known as Mount Sharp. (Image courtesy of NASA/JPL-Caltech/DLR/FU-Berlin/MS. Image obtained from JPL Photojournal, PIA 15687)

Mission Summary

The MSL mission is a challenging one. The size and weight of the Curiosity rover has been increased to accommodate a large array of instruments. These require a large amount of power. That power is supplied by a thermoelectric generator to assure long-time operation that takes into account the capricious Martian winds and dust. The diverse set of instrumentation is worthy of a stationary laboratory facility on Earth. The increase in weight has forced a more complex design of the sequence of descent and landing that is potentially scalable for the demands of human exploration. These increases in capability have resulted in a profound new understanding of Mars, even while the Curiosity rover is still climbing Mount Sharp, entering new geologic terrains as scores of scientists analyze the data to date and publish their results. The adventure continues! And it will continue with the next Mars mission.

2 Curiosity's Resources

Curiosity is the most recent addition to a series of Mars rovers. Mars Pathfinder's rover Sojourner was first, followed by the twin Mars Exploration Rovers Spirit, and Opportunity (see Fig. 1 from Preface). At least one of these has been operational since 2004. As the size and weights have increased, so have the number of instruments and the sophistication of the technology, supported by growth in operational experience and knowledge of the Mars environment.

The record for longevity and distance traveled is held by the Opportunity Rover that was still exploring the Endeavor crater when Curiosity landed. Opportunity traveled 45.16 km. in 14 years and 46 days. Will Curiosity set a new record? It is not obvious, because Opportunity traveled much of its distance going to the Endeavor crater without many distractions on the way, traveling through fairly uniform terrain. Powered by solar panels periodically dusted by winds, its mission was terminated by a global dust storm that not hurt Curiosity's Radioisotope Thermoelectric Generator (RTG).

Curiosity benefits not least from the experience of the designers and operations teams. It is not easy to survive in the Mars work environment, including the two-year launch cycle and the periodic asynchrony between Earth days and Mars sols. It took time for the operations teams to adjust to the rhythm of planning, reviewing data, and modifying the plans.

The increase in payload weight of Curiosity relative to all previous rovers allowed for a striking increase in the number and sophistication of the science investigators and the instruments they designed, tested, and operated. They came from a wide variety of American and international government agencies, universities and private firms, and bring experience in space operations. These scientists, about 500 in number, also analyze the voluminous data Curiosity generates and publishes peer-reviewed papers as the mission continues. This author attended a large gathering for the landing of Curiosity. The chant started up, "USA, USA …" and the crowd spontaneously shifted to the chant "JPL, JPL …" in recognition of the truly international nature of the achievement.

JPL was started by Caltech under the sponsorship of the U. S. Army during World War II and transitioned to NASA. The Principal Investigators for Curiosity are led by current and past professors from Caltech, and Mount Sharp is (unofficially) named after Robert Sharp, a former professor of geology at Caltech. The International Astronomical Union has formally named the Robert Sharp crater, located not far from the much younger Mount Sharp.

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Curiosity has the benefit of there being several Mars orbiters that can be used for two very important support contributions. First, there is the systematic and coordinated imagery and comprehensive mapping (including topographic and geologic maps) that are produced from orbital observations. These products are used for route planning and target selection. Second, the communication relay function performed by the Mars orbiters permits the floods of imagery data from the multitude of cameras on Curiosity, along with the data from the other scientific instruments, to be transmitted at a tremendous savings of weight and power for Curiosity.

The flood of data depends on the continued growth of the contribution of NASA's Deep Space Network, which was designed, built, and operated by JPL at the outset of Moon and planetary exploration by spacecraft in the early 1960's. Since the Earth is turning, a location anywhere else in the solar system is in view from a specific location on the surface of Earth for only a few hours. Continuous surveillance of a spacecraft requires communication systems at three locations around Earth. JPL established those three locations very early on, near Barstow California, near Canberra, Australia, and near Madrid, Spain. These three locations are roughly 120 degrees of longitude apart, so as a spacecraft sets towards the horizon at one, it has risen at another. It is a difficult scheduling problem for the operations team to operate the big antennas to cover all the spacecraft touring the solar system, some closer to the sun than Mercury and some further from the sun than the heliopause.

Elements of personality have been attributed to Curiosity, such as a practice of using feminine pronouns in reference to this complex robot with a flexible program. Artificial intelligence concepts are used for hazard avoidance and goal seeking. Yet when a group makes rule changes by consensus, the resulting behavior by Curiosity in response to its environment can produce a feeling of "personality."

Raw data is published by JPL as it is received, often on a daily basis. Calibrated and analyzed data is published on an approximately yearly basis, depending on the timing of peer reviews. In between, abstracts are published, often by several co-authors. New ideas have frequently arisen, especially as Curiosity has climbed into new geologically different areas.

As alternate hypotheses have been generated, groups of scientists with diverse experiences have proposed new theories. This process has involved new plans for Curiosity to change routes and observations to resolve the differences of opinion and reach a consensus. Examples of this process will be mentioned in the course of following the journey of Curiosity, emphasizing the interplay of observation and idea generation made possible by the extended duration of the mission.

A special contribution of the scientific community is the invention and development of new instruments and sensors for Curiosity, including testing, calibration, and operations throughout the mission. The special subject of Principal Investigators will be discussed in a further section.

Like Spirit and Opportunity before it, Curiosity has six wheels (see Fig. 1 from Preface and Fig. 2.1 and Fig. 2.2), with individual electric motors and flexible suspensions and axles to enable driving over very rough rock. The wheels and suspension have been scaled up to support the expanded scientific payload and also the heavy Radioisotope Thermoelectric Generator (RTG), which stores enough radioactive material for up to 10 years of power for mobility, heating, and instruments.