National Aeronautics and Space Administration

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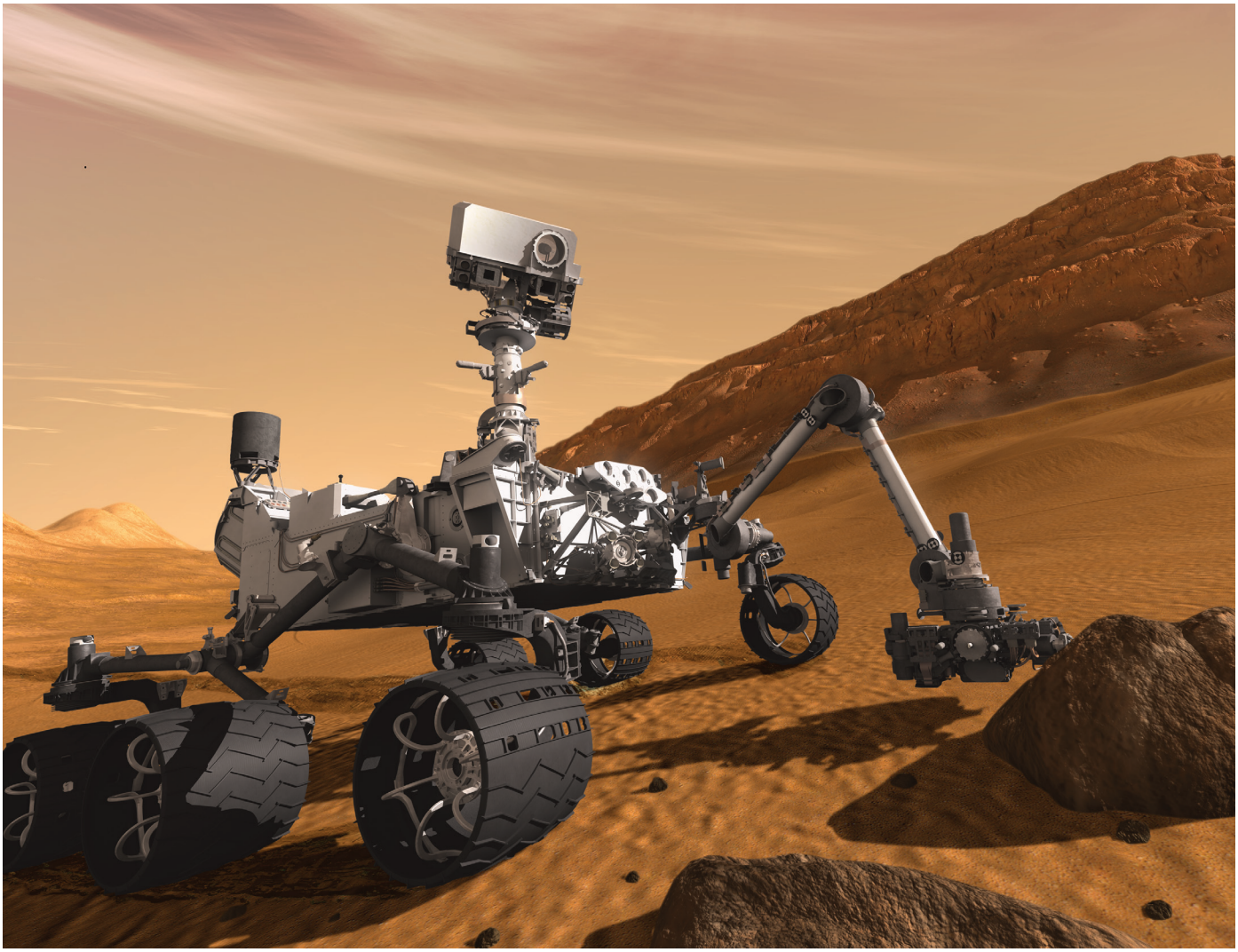
# Mars Science Laboratory Launch



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# Media Services Information

**NASA Television Transmission**

The NASA TV Media Channel is available on an MPEG-2 digital C-band signal accessed via satellite AMC-6, at 72 degrees west longitude, transponder 17C, 4040 MHz, vertical polarization. In Alaska and Hawaii, it's available on AMC-7 at 137 degrees west longitude, transponder 18C, at 4060 MHz, horizontal polarization. A Digital Video Broadcast-compliant Integrated Receiver Decoder is required for reception. For digital downlink information for NASA TV's Media Channel, access to NASA TV's Public Channel on the Web and a schedule of programming for Mars Science Laboratory activities, visit http://www.nasa.gov/ntv.

**Media Credentialing**

News media representatives who would like to cover the launch in person must be accredited through the NASA Kennedy Space Center newsroom. Journalists may contact the newsroom at 321-867-2468 for more information.

**Briefings**

An overview of the mission will be presented in a news briefing broadcast on NASA TV and on http://www.ustream.tv/nasajpl, originating from NASA Headquarters in Washington, at 1 p.m. EST on Nov. 10, 2011. A pre-launch briefing at Kennedy Space Center is scheduled at 1 p.m. EST on Nov. 22, 2011, followed by a briefing about the mission's science goals and capabilities. A post-launch briefing at KSC will begin approximately two to three hours after launch. Supplemental briefings at KSC will present information about Mars, at 1 p.m. EST on Nov. 21; about astrobiology, at 11 a.m. EST on Nov. 22; and about how excitement about Mars is used in education and other fields, at 1 p.m. EST on Nov. 23. All of these MSL and supplemental briefings will be carried on NASA TV and on http://www.ustream.tv/nasajpl .

Specific information about upcoming briefings, as they are scheduled, will be kept current on the Internet at http://www.nasa.gov/msl .

**Live Feed**

A live feed of video during key launch activities from the mission control room at Cape Canaveral Air Force Station will be carried on NASA TV and on http://www.ustream.tv/nasajpl between about 7:30 a.m. and 11:30 a.m. EST on Nov. 25.

**Internet Information**

Information about NASA's Mars Science Laboratory mission, including an electronic copy of this press kit, press releases, status reports and images, is available at http://www.nasa.gov/msl and http://marsprogram.jpl.nasa.gov/msl . Frequent updates about the mission, together with public feedback, are available by following Curiosity on Twitter at http://www.twitter.com/marscuriosity and on Facebook at http://www.facebook.com/marscuriosity .

# Quick Facts

**Spacecraft**

*Cruise vehicle dimensions (cruise stage and aeroshell with rover and descent stage inside):* Diameter: 14 feet, 9 inches (4.5 meters); height: 9 feet, 8 inches (3 meters)

*Rover name*: Curiosity

*Rover dimensions:* Length: 9 feet, 10 inches (3.0 meters) (not counting arm); width: 9 feet, 1 inch (2.8 meters); height at top of mast: 7 feet (2.1 meters); arm length: 7 feet (2.1 meters); wheel diameter: 20 inches (0.5 meter)

*Mass:* 8,463 pounds (3,893 kilograms) total at launch, consisting of 1,982-pound (899-kilogram) rover; 5,293-pound (2,401-kilogram) entry, descent and landing system (aeroshell plus fueled descent stage); and 1,188-pound (539-kilogram) fueled cruise stage

*Power for rover:* Multi-mission radioisotope thermoelectric generator and lithium-ion batteries

*Science payload:* 165 pounds (75 kilograms) in 10 instruments: Alpha Particle X-ray Spectrometer, Chemistry and Camera, Chemistry and Mineralogy, Dynamic Albedo of Neutrons, Mars Descent Imager, Mars Hand Lens Imager, Mast Camera, Radiation Assessment Detector, Rover Environmental Monitoring Station, and Sample Analysis at Mars

**Launch Vehicle**

*Type:* Atlas V 541

*Height with payload:* 191 feet (58 meters)

*Mass, fully fueled, with spacecraft on top:* 1.17 million pounds (531,000 kilograms)

**Mission**

*Launch period:* Nov. 25 through Dec. 18, 2011

*Launch windows:* Launch opportunities every five minutes during daily windows 103 minutes long at the start of the launch period and 44 minutes long at the end of the launch period. First launch opportunity on Nov. 25: 10:25 a.m. EST

*Launch site:* Launch Complex 41, Cape Canaveral Air Force Station, Fla.

*Earth–Mars distance on Nov. 25, 2011:* 127 million miles (205 million kilometers)

*Mars landing:* Between 1 p.m. and 10:30 p.m. Pacific Daylight Time, Aug. 5, 2012. (Aug. 6, 5 a.m. to 5:30 a.m. Universal Time; Aug. 6, 1 a.m. to 1:30 a.m., Eastern Daylight Time). This will be about 3 p.m. local time at the Mars landing site.

*Landing site:* 4.5 degrees south latitude, 137.4 degrees east longitude, inside Gale Crater

*Earth–Mars distance on Aug. 6, 2012:* 154 million miles (248 million kilometers)

*One-way radio transit time, Mars to Earth, on Aug. 6, 2012:* 13.8 minutes

*Total distance of travel, Earth to Mars:* About 354 million miles (570 million kilometers)

*Primary mission:* One Martian year (98 weeks)

*Expected near-surface atmospheric temperatures at landing site during primary mission:* minus 130 F to 32 F (minus 90 C to zero C)

**Program**

*Cost:* $2.5 billion, including $1.8 billion for spacecraft development and science investigations and additional amounts for launch and operations.

# Mars at a Glance

### General

- One of five planets known to ancients; Mars was the Roman god of war, agriculture and the state
- Yellowish brown to reddish color; occasionally the third-brightest object in the night sky after the moon and Venus

### Physical Characteristics

- Average diameter 4,212 miles (6,780 kilometers); about half the size of Earth, but twice the size of Earth's moon
- Same land area as Earth, reminiscent of a cold, rocky desert
- Mass 1/10th of Earth's; gravity only 38 percent as strong as Earth's
- Density 3.9 times greater than water (compared with Earth's 5.5 times greater than water)
- No planet-wide magnetic field detected; only localized ancient remnant fields in various regions

### Orbit

- Fourth planet from the sun, the next beyond Earth
- About 1.5 times farther from the sun than Earth is
- Orbit elliptical; distance from sun varies from a minimum of 128.4 million miles (206.7 million kilometers) to a maximum of 154.8 million miles (249.2 million kilometers); average is 141.5 million miles (227.7 million kilometers)
- Revolves around sun once every 687 Earth days
- Rotation period (length of day) 24 hours, 39 minutes, 35 seconds (1.027 Earth days)
- Poles tilted 25 degrees, creating seasons similar to Earth's

### Environment

- Atmosphere composed chiefly of carbon dioxide (95.3 percent), nitrogen (2.7 percent) and argon (1.6 percent)
- Surface atmospheric pressure less than 1/100th that of Earth's average
- Surface winds of 0 to about 20 miles per hour (0 to about 9 meters per second), with gusts of about 90 miles per hour (about 40 meters per second)
- Local, regional and global dust storms; also whirlwinds called dust devils
- Surface temperature averages minus 64 F (minus 53 C); varies from minus 199 F (minus 128 C) during polar night to 80 F (27 C) at equator during midday at closest point in orbit to sun

### Features

- Highest point is Olympus Mons, a huge shield volcano about 16 miles (26 kilometers) high and 370 miles (600 kilometers) across; has about the same area as Arizona
- Canyon system of Valles Marineris is largest and deepest known in solar system; extends more than 2,500 miles (4,000 kilometers) and has 3 to 6 miles (5 to 10 kilometers) relief from floors to tops of surrounding plateaus

### Moons

- Two irregularly shaped moons, each only a few kilometers wide
- Larger moon named Phobos ("fear"); smaller is Deimos ("terror"), named for attributes personified in Greek mythology as sons of the god of war

# Mars Science Laboratory Investigations

## Mars Science Laboratory Investigations

NASA's Mars Science Laboratory mission will study whether the Gale Crater area of Mars has evidence of past and present habitable environments. These studies will be part of a broader examination of past and present processes in the Martian atmosphere and on its surface. The research will use 10 instrument-based science investigations. The mission's rover, Curiosity, carries the instruments for these investigations and will support their use by providing overland mobility, sample-acquisition capabilities, power and communications. The primary mission will last one Mars year (98 weeks).

The payload includes mast-mounted instruments to survey the surroundings and assess potential sampling targets from a distance; instruments on Curiosity's robotic arm for close-up inspections; laboratory instruments inside the rover for analysis of samples from rocks, soils and atmosphere; and instruments to monitor the environment around the rover. In addition to the science payload, engineering sensors on the heat shield will gather information about Mars' atmosphere and the spacecraft's performance during its descent through the atmosphere.

To make best use of the rover's science capabilities, a diverse international team of scientists and engineers will make daily decisions about the rover's activities for the following day. Even if the rover's technology all performs flawlessly, some types of evidence the mission will seek about past environments may not have persisted in the rock record. While the possibility that life might have existed on Mars provokes great interest, a finding that conditions did not favor life would also pay off with valuable insight about differences and similarities between early Mars and early Earth.

## Habitability

The mission will assess whether the area Curiosity explores has ever been a potential habitat for Martian life.

Whether life has existed on Mars is an open question that this mission, by itself, is not designed to answer. Curiosity does not carry experiments to detect active processes that would signify present-day biological metabolism, nor does it have the ability to image microorganisms or their fossil equivalents. However, if this mission finds that the field site in Gale Crater has had conditions favorable for habitability and for preserving evidence about life, those findings can shape future missions that would bring samples back to Earth for life-detection tests or for missions that carry advanced life-detection experiments to Mars. In this sense, the Mars Science Laboratory is the prospecting stage in a step-by-step program of exploration, reconnaissance, prospecting and mining evidence for a definitive answer about whether life has existed on Mars. NASA's Astrobiology Program has aided in development of the Mars Science Laboratory science payload and in studies of extreme habitats on Earth that can help in understanding possible habitats on Mars.

Three conditions considered crucial for habitability are liquid water, other chemical ingredients utilized by life and a source of energy. The Mars Science Laboratory mission advances the "follow the water" strategy of NASA Mars exploration since the mid-1990s to a strategy of determining the best settings for seeking an answer to whether Mars ever supported life.

Every environment on Earth where there is liquid water sustains microbial life. For most of Earth's history, the only life forms on this planet were microorganisms, or microbes. Microbes still make up most of the living matter on Earth. Scientists who specialize in the search for life on other worlds expect that any life on Mars, if it has existed at all, has been microbial.

Curiosity will land in a region where this key item on the checklist of life's requirements has already been determined: It was wet. Observations from Mars orbit during five years of assessing candidate landing sites have made these areas some of the most intensely studied places on Mars. Researchers have used NASA's Mars Reconnaissance Orbiter to map the area's mineralogy, finding exposures of clay minerals. Clays, other phyllosilicates and sulfates form under conditions with adequate liquid water in a life-supporting, medium range between very acidic and very alkaline.

Curiosity will inventory other basic ingredients for life, seek additional evidence about water and investigate how conditions in the area have changed over time. The wet environment in which the clay minerals formed

is long gone, probably occurring more than 3 billion years ago. Examining the geological context for those minerals, such as the minerals in younger rock layers, could advance understanding of habitat change to drier conditions. The rover can also check for traces of water still bound into the mineral structure of rocks at and near the surface.

Carbon-containing compounds called organic molecules are an important class of ingredients for life that Curiosity can detect and inventory. This capability adds a trailblazing "follow the carbon" aspect to the Mars Science Laboratory, as part of the sequel to the "follow the water" theme.

Organic molecules contain one or more carbon atoms bound to hydrogen and, in many cases, additional elements. They can exist without life, but life as we know it cannot exist without them, so their presence would be an important plus for habitability. If Curiosity detects complex organics that are important to life on Earth, such as amino acids, these might be of biological origin, but also could come from non-biological sources, such as carbonaceous meteorites delivered to the surface of the planet.

Curiosity will also check for other chemical elements important for life, such as nitrogen, phosphorus, sulfur and oxygen.

The rover will definitively identify minerals, which provide a lasting record of the temperatures, pressures and chemistry present when the minerals were formed or altered. Researchers will add that information to observations about geological context, such as the patterns and processes of sedimentary rock accumulation, to chart a chronology of how the area's environments have changed over time. Energy for life on Mars could come from sunlight, heat or mixtures of chemicals (food) with an energy gradient that could be exploited by biological metabolism. The information Curiosity collects about minerals and about the area's modern environment will be analyzed for clues about possible past and present energy sources for life.

Curiosity will measure the ratios of different isotopes of several elements. Isotopes are variants of the same element with different atomic weights. Ratios such as the proportion of carbon-13 to carbon-12 can provide insight into planetary processes. For example, Mars once had a much denser atmosphere than it does today, and if the loss occurred at the top of the atmosphere, that process would favor increased concentration of heavier isotopes in the retained, modern atmosphere. Such processes can be relevant to habitability and biology. Curiosity will assess isotopic ratios in methane if that gas is in the air around the rover. Methane is an organic molecule, and its carbon isotope ratio can be very distinctive. Observations from orbit and from Earth indicate traces of it may be present in Mars' atmosphere. Isotopic ratios could hold clues about whether methane is being produced by microbes or by a non-biological process.

The mission has four primary science objectives to meet NASA's overall habitability assessment goal:

- Assess the biological potential of at least one target environment by determining the nature and inventory of organic carbon compounds, searching for the chemical building blocks of life and identifying features that may record the actions of biologically relevant processes.
- Characterize the geology of the rover's field site at all appropriate spatial scales by investigating the chemical, isotopic and mineralogical composition of surface and near-surface materials and interpreting the processes that have formed rocks and soils.
- Investigate planetary processes of relevance to past habitability (including the role of water) by assessing the long timescale atmospheric evolution and determining the present state, distribution and cycling of water and carbon dioxide.
- Characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar proton events and secondary neutrons.

**Preservation and Past Environments**

Some of the same environmental conditions favorable for life can, paradoxically, be unfavorable for preserving evidence about life. Water, oxidants and heat, all of which can contribute to habitability, can destroy organic molecules and other possible markers left by life, or biosignatures.

Life has thrived on Earth for more than 3 billion years, but only a miniscule fraction of Earth's past life has left evidence of itself in the rock record on this planet. Preserving evidence of life from the distant past has required specific, unusual conditions. On Earth, these windows of preservation have included situations such as insects encased in amber and mastodons im-

mersed in tar pits. Mars won't have fossils of insects or mastodons; if Mars has had any life forms at all, they were likely microbes. Understanding what types of environments may have preserved evidence of microbial life from billions of years ago, even on Earth, is still an emerging field of study.

To determine whether Mars ever supported life, a key step is learning where biosignatures could persist. Curiosity's findings about windows of preservation will serve this mission's prospector role: identifying good hunting grounds for possible future investigations about Martian life's existence and characteristics. They can also guide this mission's own course, informing decisions about where to drive and which rocks to sample in Curiosity's search for organics.

Accumulation of rock-forming sediments writes a record of environmental conditions and processes into those sedimentary rocks. The layers of the mountain inside Gale Crater provide a record of events arranged in the order in which they occurred. Researchers using Curiosity can look at how environments changed over time, possibly including transitions from habitable conditions to non-habitable conditions. Some of the clues are in the textures of the rocks, and Curiosity will be looking for distinctive rock textures. Other clues are in the mineral and chemical compositions.

Some conditions and processes, such as low temperatures and rapid entrapment in the sediments, can favor preservation of organics and evidence about life. As Curiosity looks for organics by analyzing samples drilled from sedimentary rocks, it will be reading the history of past environments whether or not it finds organics.

Some minerals and other geologic materials, such as sulfates, phosphates, carbonates and silica, can help preserve biosignatures. All of these materials, forming under just the right balance of environmental conditions, have the potential to preserve fragments of organic molecules derived from microbes or carbonaceous meteorites. But not just any rock formed of suitable minerals will do. Most on Earth do not. Expectations for Mars are similar, and the chances of a discovery — even if life had been present — are very small. If this sounds sobering, it should be, but this is the only known way to prospect for the vestiges of life on the early Earth.

The area at Gale Crater accessible to Curiosity as it drives during the mission contains rocks and soils that may have been originally deposited under differing conditions over a range of times. Analyzing samples from different points in that range could identify which, if any, hold organics. The rover might find that the answer is none. While such an answer could shrink prospects for finding evidence of ancient life on Mars, it would strengthen the contrast between early Mars and early Earth. The history of environmental changes on an Earthlike planet without life would be valuable for understanding the history of life's interaction with Earth's environment.

**Modern Environment**

The Mars Science Laboratory will study the current environment in its landing region as well as the records left by past environments. Curiosity carries a weather station, an instrument for monitoring natural high-energy radiation and an instrument that can detect soil moisture and water-containing minerals in the ground beneath the rover. The investigations of organics and other potential ingredients for life can analyze samples of modern-day soil for what nutrients would be available to soil microbes. The ability to check for methane in the atmosphere is a study of modern processes, too. Methane would break down and disappear from the atmosphere within a few centuries if not replenished by an active source, so its presence would be surprising.

Selection of Curiosity's landing site was not based on traits favoring present-day habitability. However, much of the information this mission contributes about the modern environment will enhance our general understanding of Mars. For example, can organic compounds delivered by meteorites persist in the soil close to the surface? How does the modern atmosphere affect the ultraviolet and high-energy radiation that reaches the surface, posing a hazard to life and to preservation of organics? How might we better estimate levels in the past? The rover's monitoring of radiation levels from cosmic rays and the sun also is designed to address astronaut safety on eventual human missions to Mars.

**Science Payload**

On April 14, 2004, NASA announced an opportunity for researchers to propose science investigations for the Mars Science Laboratory mission. The solicitation for proposals said, "The overall science objective of the MSL mission is to explore and quantitatively assess a potential habitat on Mars." Eight months later, the agency announced selection of eight investigations proposed competitively. In addition, Spain and Russia would each

provide an investigation through international agreements. The instruments for these 10 investigations make up the science payload on Curiosity.

The two instruments on the mast are a versatile, high-definition imaging system, and a laser-equipped, spectrum-reading camera that can hit a rock with a laser and observe the resulting spark for information about what chemical elements are in the rock. The tools on the turret at the end of Curiosity's 7-foot-long (2.1-meter-long) robotic arm include a radiation-emitting instrument that reads X-ray clues to targets' composition and a magnifying-lens camera. The arm can deliver soil and powdered-rock samples to an instrument that uses X-ray analysis to identify minerals in the sample and to an instrument that uses three laboratory methods for assessing carbon compounds and other chemicals important to life and indicative of past and present processes. For characterizing the modern environment, the rover also carries instruments to monitor the weather, measure natural radiation and seek evidence of water beneath the surface. To provide context for all the other instruments, a camera will record images of the landing area during descent.

The 10 science instruments on the Mars Science Laboratory have a combined mass of 165 pounds (75 kilograms), compared with a five-instrument science payload totaling 11 pounds (5 kilograms) on each of the twin rovers, Spirit and Opportunity, that landed on Mars in 2004. The mass of just one of Curiosity's 10 instruments, 88 pounds (40 kilograms) for Sample Analysis at Mars, is nearly four times the 23-pound (10.6-kilogram) total mass of the first Mars rover, 1997's Sojourner on the Mars Pathfinder mission.

Assessing past and present habitability of environments at sites visited by Curiosity will require integrating the results of the various instruments, not any single instrument. Science operations and analysis will be coordinated through the Mars Science Laboratory Project Science Group, whose members are Project Scientist John Grotzinger, of the California Institute of Technology, Pasadena, Calif.; Program Scientist Michael Meyer of NASA Headquarters, Washington; and the principal investigator for each of the following investigations.

**Mast Camera (Mastcam)**

Two two-megapixel color cameras on Curiosity's mast are the left and right eyes of the Mast Camera, or Mastcam investigation. These versatile cameras have complementary capabilities for showing the rover's surroundings in exquisite detail and in motion.

The right-eye Mastcam looks through a telephoto lens, revealing details near or far with about three-fold better resolution than any previous landscape-viewing camera on the surface of Mars. The left-eye Mastcam provides broader context through a medium-angle lens. Each can acquire and store thousands of full-color images. Each is also capable of recording high-definition video. Combining information from the two eyes can yield 3-D views where the images overlap.

Mastcam imaging of the shapes and colors of landscapes, rocks and soils will provide clues about the history of environmental processes that have formed them and modified them over time. Images and videos of the sky will document contemporary processes, such as the movement of clouds and dust.

The telephoto Mastcam is called "Mastcam 100" for its 100-millimeter focal-length lens. Its images cover an area about six degrees wide and five degrees tall, in 1,600 pixels by 1,200 pixels. This yields a scale of 2.9 inches (7.4 centimeters) per pixel at a distance of about six-tenths of a mile (1 kilometer) and about 0.006 inch (150 microns) per pixel at a distance of 6.6 feet (2 meters). The camera provides enough resolution to distinguish a basketball from a football at a distance of seven football fields, or to read "ONE CENT" on a penny on the ground beside the rover.

Its left-eye partner, called "Mastcam 34" for its 34-millimeter lens, catches a scene three times wider — about 18 degrees wide and 15 degrees tall — on an identical detector. It can obtain images with 8.7 inches (22 centimeters) per pixel at a distance of about six-tenths of a mile (1 kilometer) and 0.018 inch (450 microns) per pixel at a distance of 6.6 feet (2 meters).

The centers of Mastcam's lenses sit about 6.5 feet (2.0 meters) above ground level. The eyes are farther apart — about 10 inches (25 centimeters) — than the stereo eyes on earlier Mars surface robots. The cameras can focus on features at any distance from about 6 feet (just under 2 meters) to infinity.

When Curiosity drives to a new location, the Mastcam 34 can record a full-color, full-circle panorama showing everything from the nearby ground to the horizon by taking 150 images in about 25 minutes. Using the Mastcam 100, the team will be able to see farther off to the sides of

the rover's path, compared with what has been possible with earlier Mars rovers. That will help with selection of the most interesting targets to approach for analyzing with Curiosity's other instruments and will provide additional geological context for interpreting data about the chosen targets.

The Mastcams will provide still images and video to study motions of the rover — both for science, such as seeing how soils interact with wheels, and for engineering, such as aiding in use of the robotic arm. In other videos, the team may use cinematic techniques such as panning across a scene and using the rover's movement for "dolly" shots. Video from the cameras is 720p high definition at four to seven frames per second, depending on exposure time.

Malin Space Science Systems, San Diego, built the Mastcams and two of Curiosity's other science instruments: the Mars Hand Lens Imager and the Mars Descent Imager.

The four cameras from Malin Space Science Systems share several design features. They use a Bayer pattern filter, as found in many commercial digital cameras, for color imaging. The charge-coupled device (CCD) that detects each pixel of the image is covered with a grid of green, red and blue filters so that the camera gets the three color components over the entire scene in a single exposure. This is a change from color cameras on earlier Mars landers and rovers, which took a series of exposures through different filters to be combined into color composites by processing on Earth. The filter design used for Curiosity's science cameras results in pictures in which the color closely mimics the way the average human eye sees the world. Each of the cameras uses a focusing mechanism from MDA Information Systems Space Division, formerly Alliance Spacesystems, Pasadena, Calif. Each uses a Kodak CCD with an array of 1,600 by 1,200 active pixels. Each has an eight-gigabyte flash memory.

Besides the affixed red-green-blue filter grid, the Mastcams have wheels of other color filters that can be rotated into place between the lens and the CCD. These include science spectral filters for examining the ground or sky in narrow bands of visible-light or near-infrared wavelengths. These science filters can be used for follow-up observations to gain more information about rocks or other features of interest identified in red-green-blue images. One additional filter on each camera allows it to look directly at the sun to measure the amount of dust in the atmosphere, a key part of Mars' weather.

Mastcam's color-calibration target on the rover deck includes magnets to keep the highly magnetic Martian dust from accumulating on portions of color chips and white-gray-balance reference chips. Natural lighting on Mars tends to be redder than on Earth due to dust in Mars' atmosphere. "True color" images can be produced that incorporate that lighting effect — comparable to the warm, orange lighting that is experienced at sunset on Earth. Alternatively, a white-balance calculation can be used to adjust for the tint of the lighting, as the human eye tends to do and digital cameras can do. The Mastcams are capable of producing both true-color and white-balanced images.

The Mastcam principal investigator is Michael Malin, a geologist who founded Malin Space Science Systems and has participated in NASA Mars exploration since the Mariner 9 mission in 1971–72.

**Chemistry and Camera (ChemCam)**

The investigation using a rock-zapping laser and a telescope mounted atop Curiosity's mast is the Chemistry and Camera suite, or ChemCam. It also includes spectrometers and electronics down inside the rover.

The laser can hit rock or soil targets up to about 23 feet (7 meters) away with enough energy to excite a pinhead-size spot into a glowing, ionized gas, called plasma. The instrument observes that spark with the telescope and analyzes the spectrum of light to identify the chemical elements in the target.

The telescope, with a diameter of 4.33 inches (110 millimeters), doubles as the optics for the camera of ChemCam, which records monochrome images on a 1,024-pixel-by-1,024-pixel detector. The telescopic camera, called the remote micro-imager, will show context of the spots hit with the laser. It can also be used independently of the laser for observations of targets at any distance.

Information from ChemCam will help researchers survey the rover's surroundings and choose which targets to approach for study with the tools on the arm and the analytical laboratory instruments. ChemCam can also analyze many more targets than those instruments can. It can be used on multiple targets the same day,

while the analytical laboratory investigations — SAM and CheMin — take multiple days per target. It can also check the composition of targets inaccessible to the rover's other ingredient-identifying instruments, such as rock faces beyond the reach of Curiosity's robotic arm.

The spot hit by ChemCam's infrared laser gets more than a million watts of power focused on it for five one-billionths of a second. Light from the resulting flash comes back to ChemCam through the telescope, then through about 20 feet (6 meters) of optical fiber down the mast to three spectrometers inside the rover. The spectrometers record intensity at 6,144 different wavelengths of ultraviolet, visible and infrared light (wavelengths from 240 to 850 nanometers). Different chemical elements in the target, in their ionized state, emit light at different wavelengths. Dozens of laser pulses on the same spot will be used to achieve the desired accuracy in identifying elements. Among the many elements that the instrument can identify in rocks and soils are sodium, magnesium, aluminum, silicon, calcium, potassium, titanium, manganese, iron, hydrogen, oxygen, beryllium, lithium, strontium, sulfur, nitrogen and phosphorus.

If a rock has a coating of dust or a weathered rind, hundreds of repeated pulses from the laser can remove those layers to provide a reading of the rock's interior composition and a comparison between the interior and the coating.

Researchers also plan to use ChemCam to study the soil at each place Curiosity stops. These observations will document local and regional variations in the soil's composition and — from images taken through the telescope — in the size distribution of soil particles.

Another capability will be to check for water, either bound into mineral composition or as frost. By quickly identifying hydrogen and oxygen, ChemCam can provide unambiguous identification of water if any is on the surface in the area Curiosity explores.

ChemCam uses a technology called laser-induced breakdown spectroscopy. This method of determining the composition of an object has been used in other extreme environments, such as inside nuclear reactors and on the sea floor, and has had experimental applications in environmental monitoring and cancer detection, but ChemCam is its first use in interplanetary exploration.

Roger Wiens, a geochemist with the U.S. Department of Energy's Los Alamos National Laboratory in Los Alamos, N.M., is the principal investigator for ChemCam. For developing, building and testing the instrument, Los Alamos partnered with researchers in France funded by the French national space agency, Centre National d'Études Spatiales. The deputy principal investigator is Sylvestre Maurice, a spectroscopy expert with the Institut de Recherche en Astrophysique et Planétologie at the Observatoire Midi-Pyrénées, Toulouse, France.

France provided ChemCam's laser and telescope. The laser was built by Thales, Paris, France. Los Alamos National Laboratory supplied the spectrometers and data processors. The optical design for the spectrometers came from Ocean Optics, Dunedin, Fla. The ChemCam team includes experts in mineralogy, geology, astrobiology and other fields, with some members also on other Curiosity instrument teams.

**Alpha Particle X-Ray Spectrometer (APXS)**

The Alpha Particle X-Ray Spectrometer (APXS) on Curiosity's robotic arm, like its predecessors on the arms of all previous Mars rovers, will identify chemical elements in rocks and soils.

The APXS instruments on Sojourner, Spirit and Opportunity produced important findings from those missions, including salty compositions indicative of a wet past in bedrocks examined by Opportunity and the signature of an ancient hot spring or steam vent in soil examined by Spirit. The APXS on Curiosity delivers greater sensitivity, better scheduling versatility and a new mode for optimal positioning.

The Canadian Space Agency contributed this Canadian-made instrument for the Mars Science Laboratory. A pinch of radioactive material emits radiation that "queries" the target and an X-ray detector "reads" the answer.

The APXS sensor head, about the size of a cupcake, rides on the multi-tool turret at the end of Curiosity's arm. The rover will place the spectrometer's contact-sensing surface directly onto most rock targets selected for APXS readings or just above some soil targets.

The instrument determines the abundance of elements from sodium to strontium, including the major rock-forming and soil-forming elements sodium, magnesium, aluminum, silicon, calcium, iron and sulfur. In 10-minute quick looks, it can detect even minor ingredients down

to concentrations of about one-half percent. In three-hour readings, it can detect important trace elements down to concentrations of 100 or fewer parts per million. It has a high sensitivity to salt-forming elements such as sulfur, chlorine and bromine, which can indicate interaction with water in the past.

The APXS will characterize the geological context and inform choices about acquiring samples for analysis inside the mission's analytical laboratory instruments: SAM and CheMin. Learning which elements, in what concentrations, are in the targets will help researchers identify processes that formed the rocks and soils in the area of Mars where Curiosity is working.

The spectrometer uses the radioactive element curium as a source to bombard the target with energetic alpha particles (helium nuclei) and X-rays. This causes each element in the target to emit its own characteristic X-rays, which are then registered by an X-ray detector chip inside the sensor head. The investigation's main electronics package, which resides inside the rover, records all detected X-rays with their energy and assembles the detections into the X-ray spectrum of this sample.

On Spirit and Opportunity, the need for the X-ray detector chip to stay cold, and the length of time necessary for acquiring a measurement, have restricted most APXS measurements to Martian nighttime hours. One change in Curiosity's APXS is the possibility to activate a solid-state electric cooler for the detector, for use of the APXS during Martian daytime.

Curiosity's APXS can make measurements in about one-third the time needed for equivalent readings by its predecessors. This improvement in sensitivity results mainly from shrinking the distance between the X-ray detector and the sample by about one-third, to 0.75 inch (19 millimeters).

Additional improvement in sensitivity, mainly for heavy elements such as iron, comes from increasing the amount X-rays emitted by the curium. Curiosity's APXS has about 700 micrograms (in mass) or 60 millicuries (in radioactivity), which is twice as much as Spirit's or Opportunity's. Curium is a synthetic element first identified in a laboratory in 1944. The specific isotope used in all Mars rovers' APXS instruments is curium 244, which has a half-life of 18.1 years. This makes it ideal for long-duration missions, where even after more than seven years of the Opportunity mission, the loss in activity is hardly noticeable.

The additional X-ray intensity will benefit use of a technique called the scatter peak method, which was developed by physicist Iain Campbell, an APXS co-investigator at the University of Guelph, Ontario, Canada. This method extracts the content of elements invisible to X-rays, such as oxygen. It was used to detect and quantify water bound in the minerals of salty subsurface soils examined by Spirit at Gusev Crater.

When the spectrometer is in contact with the target, it examines a patch about 0.7 inch (1.7 centimeters) in diameter. It detects elements to a depth of about 0.0002 inch (5 microns) for low-atomic-weight elements and to about 10 times that depth for heavier elements. The dust removal tool on Curiosity's arm turret can be used to brush some rock surfaces clean before APXS examines them.

For some soil targets, to avoid pushing the instrument into the soil, the spectrometer will not be placed in direct contact with the target. In those cases, placement will use a standoff distance of about 0.4 inch (1 centimeter) or less.

Another new feature for Curiosity's APXS is an autonomous placement mode. With this software, as the arm moves the spectrometer step-by-step closer to the soil, the instrument checks X-rays from the target for several seconds at each step. When the count rate reaches a predetermined criterion of what would be adequate for a good compositional reading, the software knows, "OK. That's close enough." The arm's approach movements cease and the longer-duration APXS reading begins. A more complex variation of this autonomous placement mode may use brief readings at several positions parallel to the ground surface, scanning a larger area for certain compositional criteria, such as ratio of iron to sulfur, and quickly selecting the most distinctive spots for longer-duration readings.

Besides examining rocks and soils in place, the science team can use the APXS to check processed samples that the arm places on the rover's observation tray and soil freshly exposed by action of the rover's wheels. An onboard basaltic rock slab, surrounded by nickel plate, will be used periodically to check the performance and calibration of the instrument.

The principal investigator for Curiosity's APXS is Ralf Gellert, a physicist at the University of Guelph in Ontario, Canada. He was part of the team that designed and built the Spirit and Opportunity APXS instruments at

the Max Planck Institute in Mainz, Germany, and provided the new scientific design for the Mars Science Laboratory APXS based on the experience gained through the long operation of those predecessors. MDA, in Brampton, Ontario, Canada, built the instrument as the prime contractor for the Canadian Space Agency.

**Mars Hand Lens Imager (MAHLI)**

The Mars Hand Lens Imager, or MAHLI, is a focusable color camera on the tool-bearing turret at the end of Curiosity's robotic arm. Researchers will use it for magnified, close-up views of rocks and soils, and also for wider scenes of the ground, the landscape or even the rover. Essentially, it is a hand-held camera with a macro lens and autofocus.

The investigation takes its name from the type of hand lens magnifying tool that every field geologist carries for seeing details in rocks. Color, crystal shapes, mineral cleavage planes and other visible details from such close-up observation provide clues to a rock's composition. In sedimentary rocks, the sizes and shapes of the grains in the rock, and the scale of fine layering, provide information about how the grains were transported and deposited. Sharp-edge grains have not been worn down by tumbling long distances, for example. The size of grains can indicate whether the water or wind that carried them was moving quickly or not.

These clues garnered from MAHLI images can aid both in selection of which targets to analyze with other instruments and in directly reading the environmental history recorded in the rocks and soils the rover encounters.

As a close-up magnifying camera, MAHLI resembles the Microscopic Imager instrument mounted at the end of the robotic arm on each of the twin Mars rovers Spirit and Opportunity. MAHLI has significantly greater capabilities than those predecessors, however: full color, lights and adjustable focus. Also, it sits on a longer arm, one that can hold MAHLI up higher than the cameras on the rover's mast for seeing over an obstacle or capturing a rover self-portrait.

When positioned at its closest range — about 0.8 inch (21 millimeters) from its target — the camera's images have a resolution of slightly less than one one-thousandth of an inch (14 microns) per pixel. The field of view for that close-up is a rectangle about 0.9 inch (2.2 centimeters) by 0.7 inch (1.7 centimeters).

The camera can be held at a series of different distances from a target to show context as well as detail by adjusting the focus. At about 3 feet (1 meter) from a target, it still has a pixel resolution of about 0.02 inch (half a millimeter) in a view covering an area about 2 feet (70 centimeters) wide. By manipulation of arm position and focus, the camera can be used to examine hardware on the rover or record time-lapse views of activities such as opening a sample inlet cover.

MAHLI has two sets of white light-emitting diodes to enable imaging at night or in deep shadow. Two other light-emitting diodes on the instrument glow at the ultraviolet wavelength of 365 nanometers. These will make it possible to check for materials that fluoresce under this illumination.

Malin Space Science Systems, San Diego, developed, built and operates MAHLI. This camera shares some traits with three other cameras on Curiosity from the same company. It uses a red-green-blue filter grid like the one on commercial digital cameras for obtaining a full-color image with a single exposure. Its image detector is a charge-coupled device with an array of 1,600 by 1,200 active pixels. It stores images in an eight-gigabyte flash memory, and it can perform an onboard focus merge of eight images to reduce from eight to two the number of images returned to Earth in downlink-limited situations.

Curiosity carries a vertically mounted calibration target for MAHLI, for checking color, white balance, resolution, focus and the ultraviolet illumination.

Ken Edgett of Malin Space Science Systems, a geologist who has helped run cameras on several Mars orbiters, is the principal investigator for MAHLI. A unified imaging-science team for the three Malin-supplied instruments combines experience in geologic field work, Mars exploration and space cameras.

**Chemistry and Mineralogy (CheMin)**

The Chemistry and Mineralogy experiment, or CheMin, is one of two investigations that will analyze powdered rock and soil samples delivered by Curiosity's robotic arm. It will identify and quantify the minerals in the samples. Minerals provide a durable record of past environmental conditions, including information about possible ingredients and energy sources for life.

CheMin uses X-ray diffraction, a first for a mission to Mars. This is a more definitive method for identifying minerals than was possible with any instrument on previous missions. The investigation supplements the diffraction measurements with X-ray fluorescence capability to determine further details of composition by identifying ratios of specific elements present.

X-ray diffraction works by directing an X-ray beam at a sample and recording how X-rays are scattered by the sample at the atomic level. All minerals are crystalline, and in crystalline materials, atoms are arranged in an orderly, periodic structure, causing the X-rays to be scattered at predictable angles. From those angles, researchers can deduce the spacing between planes of atoms in the crystal. Each different mineral yields a known, characteristic series of spacings and intensities, its own fingerprint.

On Curiosity's deck, near the front of the rover, one funnel with a removable cover leads through the deck top to the CheMin instrument inside the rover. The instrument is a cube about 10 inches (25 centimeters) on each side, weighing about 22 pounds (10 kilograms).

The rover acquires rock samples with a percussive drill and soil samples with a scoop. A sample processing tool on the robotic arm puts the powdered rock or soil through a sieve designed to remove any particles larger than 0.006 inch (150 microns) before delivering the material into the CheMin inlet funnel. Vibration helps move the sample material — now a gritty powder — down the funnel. Each sample analysis will use about as much material as in a baby aspirin.

The funnel delivers the sample into a disc-shaped cell, about the diameter of a shirt button and thickness of a business card. The walls of the sample cell are transparent plastic. Thirty-two of these cells are mounted around the perimeter of a sample wheel. Rotating the wheel can position any cell into the instrument's X-ray beam. Five cells hold reference samples from Earth to help calibrate the instrument. The other 27 are reusable holders for Martian samples.

Each pair of cells is mounted on a metal holder that resembles a tuning fork. A tiny piezoelectric buzzer excites the fork to keep the particles in the sample moving inside the cell during analysis of the sample. This puts the particles in a random mix of orientations to the X-ray beam, improving detection of how the mineral crystals in the sample scatter the X-rays. The piezoelectric vibration, at about 200 cycles per second (middle C on a piano is 261 cycles per second) also helps keep the powder flowing during filling and dumping of the cell.

CheMin generates X-rays by aiming high-energy electrons at a target of cobalt. The X-rays emitted by the cobalt are then directed into a narrow beam. During analysis, the sample sits between the incoming beam on one side and the instrument's detector on the other. The detector is a charge-coupled device like the ones in electronic cameras, but sensitive to X-ray wavelengths and cooled to minus 76 degrees Fahrenheit (minus 60 degrees Celsius).

Each CheMin analysis of a sample requires up to 10 hours of accumulating data while the X-rays are hitting the sample. The time may be split into two or more Martian nights of operation.

The X-ray diffraction data show the angles at which the primary X-rays from the beam are deflected and the intensity at each angle. The detector also reads secondary X-rays emitted by the sample itself when it is excited by the primary X-rays. This is the X-ray fluorescence information. Different elements emit secondary X-rays at different frequencies. CheMin's X-ray fluorescence capability can detect elements with an atomic number greater than 11 (sodium) in the periodic table.

Instruments that previous missions to Mars have used for studying Martian minerals have not been able to provide definitive identification of all types of minerals. CheMin will be able to do so for minerals present in samples above minimal detection limits of about 3 percent of the sample composition. The instrument will also indicate the approximate concentrations of different minerals in the sample. X-ray fluorescence can add information about the ratio of elements in types of minerals with variable elemental composition, such as the proportion of iron to magnesium in iron magnesium sulfate (olivine). It can also aid in identifying non-crystalline ingredients in a sample, such as volcanic glass.

Each type of mineral forms under a certain set of environmental conditions: the chemistry present (including water), the temperature and the pressure. Thus, CheMin's identification of minerals will provide information about the environment at the time and place where the minerals in the rocks and soils formed or were altered. Some minerals the instrument might detect, such as phosphates, carbonates, sulfates and silica, can help preserve biosignatures. Whether or not the mission

determines that the landing area has offered a favorable habitat for life, the inventory of minerals identified by CheMin will provide information about processes in the evolution of the planet's environment.

David Blake, an expert in cosmochemistry and exobiology at NASA's Ames Research Center, Moffett Field, Calif., is the principal investigator for CheMin. He began work in 1989 on a compact X-ray diffraction instrument for use in planetary missions. His work with colleagues has resulted in commercial portable instruments for use in geological field work on Earth, as well as the CheMin investigation. The spinoff instruments have found applications in screening for counterfeit pharmaceuticals in developing nations and in analyzing archaeological finds.

NASA Ames Research Center won the 2010 Commercial Invention of the Year Award from NASA for the tuning-fork powder vibration system used on CheMin. Blake and Philippe Sarazin of inXitu Inc., Campbell, Calif., a co-investigator on the CheMin team, developed the technology while Sarazin was working as a post-doctoral fellow at Ames.

**Sample Analysis at Mars (SAM)**

The Sample Analysis at Mars investigation, or SAM, will use a suite of three analytical tools inside Curiosity to study chemistry relevant to life. One key job is checking for carbon-based compounds that on Earth are molecular building blocks of life. It will also examine the chemical state of other elements important for life, and it will assess ratios of different atomic weights of certain elements for clues about planetary change and ongoing processes.

SAM will examine gases from the Martian atmosphere and gases that ovens and solvents pull from powered rock and soil samples. Curiosity's robotic arm will deliver the powdered samples to one of two inlet funnels on the rover deck. Atmospheric samples enter through filtered inlet ports on the side of the rover.

SAM's analytical tools fit into a microwave-oven-size box inside the front end of the rover. While it is the biggest of the 10 instruments on Curiosity, this tightly packed box holds instrumentation that would take up a good portion of a laboratory room on Earth. One focus during development was power efficiency. For example, the two ovens heat powdered samples to about 1,800 degrees Fahrenheit (1,000 degrees Celsius) drawing a maximum power of just 40 watts. More than a third of a mile (more than 600 meters) of wiring is inside SAM.

SAM can detect a fainter trace of organics and identify a wider variety of them than any instrument yet sent to Mars. It also can provide information about other ingredients of life and clues to past environments.

One of SAM's tools, a mass spectrometer like those seen in many TV crime-solving laboratories, identifies gases by the molecular weight and electrical charge of their ionized states. It will check for several elements important for life as we know it, including nitrogen, phosphorous, sulfur, oxygen, hydrogen and carbon.

Another tool, a tunable laser spectrometer, uses absorption of light at specific wavelengths to measure concentrations of methane, carbon dioxide and water vapor. It also identifies the proportions of different isotopes in those gases. Isotopes are variants of the same element with different atomic weights, such as carbon-13 and carbon-12, or oxygen-18 and oxygen-16. Ratios of isotopes can be signatures of planetary processes, such as how Mars might have lost much of its former atmosphere.

The suite's third analytical tool, a gas chromatograph, separates different gases from a mixture to aid identification. It detects organic compounds exiting a capillary column, and then it feeds the separated fractions to the mass spectrometer for a more definitive identification.

SAM also includes a sample manipulation system, and a chemical separation and processing laboratory to support the analytical tools. The sample manipulation system maneuvers 74 sample cups, each about one-sixth of a teaspoon (0.78 cubic centimeter) in volume. The chemical separation and processing laboratory includes pumps, tubing, carrier-gas reservoirs, pressure monitors, ovens, temperature monitors and other components. Fifty-two specially designed microvalves direct the flow of gas through the system. Two soft-drink-can-size vacuum pumps rotate 100,000 times per minute to allow all three instruments to operate at their optimal pressures.

SAM's analysis of material from Martian rocks or soils begins after powder collected and processed by tools on the arm is dropped into one of SAM's two solid-sample inlets while the inlet's protective cover is open. The inlet tubes are highly polished funnels that vibrate to get the powder to fall into a reusable sample cup.

Fifty-nine of the instrument's 74 cups are quartz that can be heated to very high temperatures. The sample manipulation system pushes the quartz cup holding the powder into an oven that heats it to about 1,800 degrees Fahrenheit (about 1,000 degrees Celsius. That process releases gas from the sample at various temperatures, depending on the chemistry of the sample. The mass spectrometer measures the release continuously. Some of the gas goes to the tunable laser spectrometer for measurement of isotopes. Some goes to a trap that concentrates any organics, then to the gas chromatograph and mass spectrometer. After use, the quartz cup can be baked to prepare it for re-use with another sample.

Six of the cups hold calibration solids. SAM also carries samples of gases for calibration.

Nine of the cups are for using a solvent method called derivatization, rather than high temperature, to pull gases from samples of Martian rocks and soils. If the mission finds a site rich in organics, this method could be used to identify larger and more reactive organic molecules than is possible with the high-heat method. Each derivatization cup contains a mixture of a solvent and a chemical that, after it reacts with a compound of interest, turns it into a more volatile compound that can be separated in the gas chromatograph. These chemicals are entirely sealed in with a foil cover. For analysis of sample powder from a Martian rock or soil by this method, the sample manipulation system punctures the foil and adds the powder to the liquid in the cup, and the oven heats the sample to a modest temperature to let the reactions proceed rapidly.

Curiosity's "follow the carbon" investigation of organic compounds begins as a check for whether any are present. Although organic molecules are not, in themselves, evidence of life, life as we know it cannot exist without them. Their presence would be important evidence both about habitability and about the site's capability for preserving evidence of life. Meteorites bearing organic compounds have pelted Mars, as well as Earth, for billions of years. Uncertainty remains, however, about whether any organics close enough to the surface for Curiosity to reach them can persist in the harsh conditions there without the carbon in them transforming into a more polymerized state.

NASA's investigation of organics on Mars began with the twin Viking landers in 1976. The original reports from Viking came up negative for organics. SAM renews the search with three advantages.

The first is Curiosity's access. Mars is diverse, not uniform. Copious information gained from Mars orbiters in recent years has enabled the choice of a landing site with favorable attributes, such as exposures of clay and sulfate minerals good at entrapping organic chemicals. Mobility helps too, especially with the aid of high-resolution geologic mapping generated from orbital observations. The stationary Viking landers could examine only what their arms could reach. Curiosity can use mapped geologic context as a guide in its mobile search for organics and other clues about habitable environments. Additionally, SAM will be able to analyze samples from more protected interiors of rocks drilled into by Curiosity, rather than being restricted to soil samples, as Viking was.

Second, SAM has improved sensitivity, with a capability to detect less than one part-per-billion of an organic compound over a wider mass range of molecules and after heating samples to a higher temperature.

Third, the derivatization method for assessing organics in some SAM samples can reveal a wider range of organic compounds than was possible with the Viking experiment. In doing so, it can also check a recent hypothesis that a reactive chemical recently discovered in Martian soil — perchlorate — may have masked organics in soil samples baked during Viking tests.

If SAM does not detect any organics, that would be useful information about the unfavorable conditions for life near the Martian surface. Future missions might look deeper.

If SAM does detect organics, one challenge will be to confirm that these molecules are truly Martian, not stowaways from Earth carried to Mars on Curiosity. The rover carries five encapsulated bricks of organic check material to enable control experiments. The check material is a silicon-dioxide ceramic laced with small amounts of synthetic fluorinated organic chemicals not found in nature on Earth and not expected on Mars. The basic control experiment will collect a powdered sample from an organic check brick with the same drilling, processing and delivery system used for collecting samples from Martian rocks, and then will analyze the sample with SAM. If SAM finds any organics other than the fluorine-containing markers, they will be stowaway

suspects. If only the markers are detected, that would verify that organic-detection is working and that the sample-acquisition and handling pathway has passed a test of being clean of organic stowaways. That control experiment can assess characteristics of organic contamination at five different times during the mission, using the five bricks of organic check material.

If organic chemicals are present in Martian samples, SAM's inventory of the types and mixtures may provide clues to their origin. For example, organics delivered by meteorites without involvement of biology come with more random chemical structures than the patterns seen in mixtures of organic chemicals produced by organisms. Patterns, such as a predominance of molecules with an even number of carbon atoms, could be suggestive of biological origin. The derivatization process also allows searching for specific classes of organics with known importance to life on Earth. For example, it can identify amino acids, the chain links of proteins. While these clues may not add up to a definitive case either for or against biological origin, they could provide important direction for future missions.

Methane is one of the simplest organic molecules. Observations from Mars orbit and from Earth in recent years have suggested transient methane in Mars' atmosphere, which would mean methane is being actively added and then removed from the atmosphere of Mars. With SAM's laser spectrometer, researchers will check to confirm whether methane is present, monitor any changes in its concentration, and look for clues about whether Mars methane is produced by biological activity or by processes that do not require life.

The principal investigator for SAM is Paul Mahaffy, a chemist at NASA's Goddard Space Flight Center, Greenbelt, Md. He is a veteran of using spacecraft instruments to study planetary atmospheres. Mahaffy has coordinated work of hundreds of people in several states and Europe to develop, build and test SAM after NASA selected his team's proposal for it in 2004.

NASA Goddard Space Flight Center built and tested SAM. France's space agency, Centre National d'Études Spatiales, provided support to French researchers who developed SAM's gas chromatograph. NASA's Jet Propulsion Laboratory, Pasadena, Calif., provided the laser spectrometer. Honeybee Robotics, New York, designed SAM's sample manipulation system.

**Rover Environmental Monitoring Station (REMS)**

The Rover Environmental Monitoring Station, or REMS, will record information about daily and seasonal changes in Martian weather.

This investigation will assess wind speed, wind direction, air pressure, relative humidity, air temperature, ground temperature, and ultraviolet radiation. Operational plans call for taking measurements for at least five minutes every hour of the full-Martian-year (98-week) mission.

Spain provided this instrument for the Mars Science Laboratory.

Information about wind, temperatures and humidity comes from electronic sensors on two finger-like booms extending horizontally from partway up the main vertical mast holding the ChemCam laser and the Mastcam. Each of the booms holds a sensor for recording air temperature and three sensors for detecting air movement in three dimensions. Placement of the booms at an angle of 120 degrees from each other enables calculating the velocity even when the main mast is blocking the wind from one direction. The boom pointing toward the front of the rover, Boom 2, also holds the humidity sensor inside a downward-tilted protective cylinder. Boom 1, pointing to the side and slightly toward the rear, holds an infrared sensor for measuring ground temperature.

The pressure sensor sits inside the rover body, connected to the external atmosphere by a tube to a small, dust-shielded opening on the deck. Electronics controlling REMS are also inside the rover body.

The ultraviolet sensor is on the rover deck. It measures six different wavelength bands in the ultraviolet portion of the electromagnetic spectrum, including wavelengths also monitored from above by NASA's Mars Reconnaissance Orbiter. No previous mission to the surface of Mars has measured the full ultraviolet spectrum of radiation.

The REMS investigation will strengthen understanding about the global atmosphere of Mars and contribute to the mission's evaluation of habitability.

The data will provide a way to verify and improve atmosphere modeling based mainly on observations from Mars orbiters. For example, significant fractions of the Martian atmosphere freeze onto the ground as a south

polar carbon-dioxide ice cap during southern winter and as a north polar carbon-dioxide ice cap during northern winter, returning to the atmosphere in each hemisphere's spring. At Curiosity's landing site, far from either pole, REMS will check whether seasonal patterns of changing air pressure fit the existing models for effects of the coming and going of polar carbon-dioxide ice.

Monitoring ground temperature with the other weather data could aid in assessment of whether conditions have been favorable for microbial life. Even in the extremely low-humidity conditions anticipated in the landing area, the combination of ground temperature and humidity information could provide insight about the interaction of water vapor between the soil and the atmosphere. If the environment supports, or ever supported, any underground microbes, that interaction could be crucial.

Ultraviolet radiation can also affect habitability. The ultraviolet measurements by REMS will allow scientists to better predict the amount of ultraviolet light that reaches Mars' surface globally in the present and past. Ultraviolet light is destructive to organic material and the reason that sunscreen is worn on Earth.

The principal investigator for REMS is Javier Gómez-Elvira, an aeronautical engineer with the Center for Astrobiology (Centro de Astrobiología), Madrid, Spain. The center is affiliated with the Spanish National Research Council (Consejo Superior de Investigaciones Científicas) and the National Institute for Aerospace Technology (Instituto Nacional de Técnica Aerospacial). Spain's Ministry of Science and Innovation (Ministerio de Ciencia e Innovación) and Spain's Center for Industrial Technology Development (Centro para el Desarrollo Tecnológico Industrial) supplied REMS. The Finnish Meterological Insitute developed the pressure sensor.

To develop the instrument and prepare for analyzing the data it will provide, Spain has assembled a team of about 40 researchers — engineers and scientists.

The team plans to post daily weather reports from Curiosity. Air temperature around the rover mast will likely drop to about minus 130 degrees Fahrenheit (about minus 90 degrees Celsius) on some winter nights and climb to about minus 22 Fahrenheit (about minus 30 Celsius) during winter days. In warmer seasons, afternoon air temperature could reach a balmy 32 Fahrenheit (0 degrees Celsius).

**Radiation Assessment Detector (RAD)**

The Radiation Assessment Detector, or RAD, investigation on Curiosity will monitor high-energy atomic and subatomic particles reaching Mars from the sun, from distant supernovas and other sources. These particles constitute naturally occurring radiation that could be harmful to any microbes near the surface of Mars or to astronauts on a future Mars mission.

RAD's measurements will help fulfill the Mars Science Laboratory mission's key goals of assessing whether Curiosity's landing region has had conditions favorable for life and for preserving evidence about life. This investigation will also do an additional job. Unlike the rest of the mission, RAD has a special task and funding from the part of NASA that is planning human exploration beyond Earth orbit. It will aid design of human missions by reducing uncertainty about how much shielding from radiation future astronauts will need. RAD will take measurements during the trip from Earth to Mars as well as during Curiosity's roving on Mars because the radiation levels in interplanetary space are also important in design of human missions.

The 3.8-pound (1.7-kilogram) RAD instrument has a wide-angle telescope looking upward from the hardware's position inside the left-front area of the rover. The telescope has detectors for charged particles with masses up to that of an iron ion. RAD can also detect neutrons and gamma rays coming from the Mars atmosphere above or the Mars surface material below the rover.

Galactic cosmic rays make up one type of radiation that RAD will monitor. These are a variable shower of charged particles coming from supernova explosions and other events extremely far from our solar system.

The sun is the other main source of energetic particles that this investigation will detect and characterize. The sun spews electrons, protons and heavier ions in "solar particle events" fed by solar flares and ejections of matter from the sun's corona. Astronauts might need to move into havens with extra shielding on an interplanetary spacecraft or on Mars during solar particle events.

Earth's magnetic field and atmosphere provide effective shielding against the possible deadly effects of galactic cosmic rays and solar particle events. Mars lacks a global magnetic field and has only about one percent as much atmosphere as Earth does. Just to find high-

enough radiation levels on Earth for checking and calibrating RAD, the instrument team needed to put it inside major particle-accelerator research facilities in the United States, Europe, Japan and South Africa.

The radiation environment at the surface of Mars has never been fully characterized. NASA's Mars Odyssey orbiter, which reached Mars in 2001, assessed radiation levels above the Martian atmosphere with an investigation named the Mars Radiation Environment Experiment. Current estimates of the radiation environment at the surface rely on modeling of how the thin atmosphere affects the energetic particles, but uncertainty in the modeling remains large. A single energetic particle hitting the top of the atmosphere can break up into a cascade of lower-energy particles that might be more damaging than a single high-energy particle.

In addition to its precursor role for human exploration, RAD will contribute to the mission's assessment of Mars' habitability for microbes and search for organics. Radiation levels probably make the surface of modern Mars inhospitable for microbial life and would contribute to the breakdown of any near-surface organic compounds. The measurements from RAD will feed calculations of how deeply a possible future robot on a life-detection mission might need to dig or drill to reach a microbial safe zone. For assessing whether the surface radiation environment could have been hospitable for microbes in Mars' distant past, researchers will combine RAD's measurements with estimates of how the activity of the sun and the atmosphere of Mars have changed in the past few billion years.

Radiation levels in interplanetary space vary on many time scales, from much longer than a year to shorter than an hour. Assessing the modern radiation environment on the surface will not come from a one-time set of measurements. Operational planning for Curiosity anticipates that RAD will record measurements for 15 minutes of every hour throughout the prime mission, on steady watch so that it can catch any rare but vitally important solar particle events.

The first science data from the mission will come from RAD's measurements during the trip from Earth to Mars. These en-route measurements will, first, enable correlations with instruments on other spacecraft that monitor solar particle events and galactic cosmic rays in Earth's neighborhood and then will yield data about the radiation environment farther from Earth.

RAD's principal investigator is physicist Don Hassler of the Southwest Research Institute's Boulder, Colo., branch. His international team of co-investigators includes experts in instrument design, astronaut safety, atmospheric science, geology and other fields.

Southwest Research Institute in Boulder and in San Antonio, Texas, together with Christian Albrechts University in Kiel, Germany, built RAD with funding from the NASA Exploration Systems Mission Directorate and Germany's national aerospace research center, Deutsches Zentrum für Luft- und Raumfahrt.

Measurements of ultraviolet radiation by Curiosity's Rover Environmental Monitoring Station will supplement RAD's measurements of other types of radiation.

**Dynamic Albedo of Neutrons (DAN)**

The Dynamic Albedo of Neutrons investigation, or DAN, can detect water bound into shallow underground minerals along Curiosity's path.

The DAN instrument shoots neutrons into the ground and measures how they are scattered, giving it a high sensitivity for finding any hydrogen to a depth of about 20 inches (50 centimeters) directly beneath the rover.

The Russian Federal Space Agency contributed DAN to NASA as part of a broad collaboration between the United States and Russia in the exploration of space.

The instrument can be used in reconnaissance to identify places for examination with Curiosity's other tools. Also, rock formations that Curiosity's cameras view at the surface may be traced underground by DAN, enhancing the ability of scientists to understand the geology.

DAN will bring to the surface of Mars an enhancement of nuclear technology that has already detected Martian water from orbit. "Albedo" in the investigation's name means reflectance — in this case, how high-energy neutrons injected into the ground bounce off of atomic nuclei in the ground. Neutrons that collide with hydrogen atoms bounce off with a characteristic decrease in energy, like one billiard ball hitting another. By measuring the energies of the reflected neutrons, DAN can detect the fraction that was slowed in these collisions, and therefore the amount of hydrogen.

Oil prospectors use this technology in instruments lowered down exploration holes to detect the hydrogen in petroleum. Space explorers have adapted it for missions to the moon and Mars, where most hydrogen is in water ice or in water-derived hydroxyl ions.

DAN Principal Investigator Igor Mitrofanov of Space Research Institute, Moscow, is also the principal investigator for a Russian instrument on NASA's Mars Odyssey orbiter, the high energy neutron detector, which measures high energy of neutrons coming from Mars. In 2002, it and companion instruments on Odyssey detected hydrogen interpreted as abundant underground water ice close to the surface at high latitudes.

The neutron detectors on Odyssey rely on galactic cosmic rays hitting Mars as a source of neutrons. DAN can work in a passive mode relying on cosmic rays, but it also has its own pulsing neutron generator for an active mode of shooting high-energy neutrons into the ground. In active mode, it is sensitive enough to detect water content as low as one-tenth of 1 percent in the ground beneath the rover.

The neutron generator is mounted on Curiosity's right hip, a pair of neutron detectors on the left hip. Pulses last about one microsecond and repeat as frequently as 10 times per second. The detectors measure the flow of moderated neutrons with different energy levels returning from the ground, and their delay times. Neutrons that arrive later may indicate water buried beneath a drier soil layer. The generator will be able to emit a total of about 10 million pulses during the mission, with about 10 million neutrons at each pulse.

The most likely form of hydrogen in the ground of the landing area is hydrated minerals. These are minerals with water molecules or hydroxyl ions bound into the crystalline structure of the mineral. They can tenaciously retain water from a wetter past when all free water has gone. DAN may also detect water that comes and goes with the Martian seasons, such as soil moisture that varies with the atmospheric humidity. Together with Curiosity's cameras and weather station, DAN will observe how the sparse water cycle on Mars works in the present. DAN also could detect any water ice in the shallow subsurface, a low probability at Curiosity's Gale Crater landing site.

Operational planning anticipates using DAN during short pauses in drives and while the rover is parked. It will check for any changes or trends in subsurface hydrogen content from place to place along the traverse.

Russia's Space Research Institute developed the DAN instrument in close cooperation with the N.L. Dukhov All-Russia Research Institute of Automatics, Moscow, and the Joint Institute of Nuclear Research, Dubna.

**Mars Descent Imager (MARDI)**

During the final few minutes of Curiosity's flight to the surface of Mars, the Mars Descent Imager, or MARDI, will record a full-color video of the ground below. This will provide the Mars Science Laboratory team with information about the landing site and its surroundings, to aid interpretation of the rover's ground-level views and planning of initial drives. Hundreds of the images taken by the camera will show features smaller than what can be discerned in images taken from orbit.

The video will also give fans worldwide an unprecedented sense of riding a spacecraft to a landing on Mars.

MARDI will record the video on its own 8 gigabyte flash memory at about four frames per second and close to 1,600 by 1,200 pixels per frame. Thumbnails and a few samples of full-resolution frames will be transmitted to Earth in the first days after landing. The nested set of images from higher altitude to ground level will enable pinpointing of Curiosity's location. The pace of sending the rest of the frames for full-resolution video will depend on sharing priority with data from the rover's other investigations.

The full video — available first from the thumbnails in YouTube-like resolution and later in full detail — will begin with a glimpse of the heat shield falling away from beneath the rover. The first views of the ground will cover an area several kilometers (a few miles) across. Successive frames taken as the vehicle descends will close in and cover successively smaller areas. The video will likely nod up and down to fairly large angles owing to parachute-induced oscillations. Its roll clockwise and counterclockwise will be smaller, as thrusters on the descent stage control that motion. When the parachute is jettisoned, the video will show large angular motions as the descent vehicle maneuvers to avoid re-contacting the back shell and parachute. Rocket engine vibration may also be seen. A few seconds before landing, the rover will be lowered on tethers beneath the descent stage, and the video will show the relatively slow approach to the surface. The final frames, after landing,

will cover a bath-towel-size patch of ground under the front-left corner of the rover.

Besides the main objective of providing geologic context for the observations and operations of the rover during the early part of mission on Mars, MARDI will provide insight about Mars' atmosphere. Combining information from the descent images with information from the spacecraft's motion sensors will allow for calculating wind speeds affecting the spacecraft on its way down, an important atmospheric science measurement. The descent data will later aid in designing and testing future landing systems for Mars that could add more control for hazard avoidance.

Throughout Curiosity's mission on Mars, MARDI will offer the capability to obtain images of ground beneath the rover at resolutions down to 0.06 inch (1.5 millimeters) per pixel, for precise tracking of its movements or for geologic mapping. The science team will decide whether or not to use that capability. Each day of operations on Mars will require choices about how to budget power, data and time.

Malin Space Science Systems, San Diego, provided MARDI, as well as three other cameras on Curiosity: the Mast Camera pair and the Mars Hand Lens Imager. Michael Malin is the principal investigator for MARDI, which shares a unified imaging-science team with the other two instruments from his company.

MARDI consists of two parts: the wide-angle camera mounted toward the front of the port side of Curiosity and a digital electronics assembly inside the warm electronics box of the rover's chassis. The instrument's electronics, including the 1,600-pixel-by-1,200-pixel charge-coupled device (CCD) in the camera, are the same design as used in the Mast Camera and Mars Hand Lens Imager.

The rectangular field of the CCD sits within a 90-degree circular field of view of the camera lens, yielding a recorded field of view of 70 degrees by 55 degrees. From an altitude of 1.2 miles (2 kilometers) during descent that will provide a resolution of about 5 feet (1.5 meters) per pixel, though swinging and shaking of the spacecraft will likely blur some frames despite a fast (1.3 millisecond) exposure time.

Color information comes from a Bayer pattern filter array, as used in many commercial digital cameras. The camera's CCD is covered with a grid of green, red and blue filters so that each exposure samples all of those colors throughout the field of view. A piece of white material on the inside surface of the heat shield will serve as a white-balance target as the heat shield falls away at the beginning of the recorded descent video.

Malin Space Science Systems also provided descent imagers for NASA's Mars Polar Lander, launched in 1999, and Phoenix Mars Lander, launched in 2007. However, the former craft was lost during its landing and the latter did not use its descent imager due to concern about the spacecraft's data-handling capabilities during crucial moments just before landing.

**Engineering Instruments**

Some of the tools that primarily serve engineering purposes on Mars Science Laboratory will also generate information useful to scientific understanding about Mars. Most of these, including the engineering cameras and the drill, are described in the spacecraft section of this document. One set of instruments carried on the heat shield of the spacecraft's entry vehicle serves specifically to gather data about the Martian atmosphere and performance of the heat shield for use in designing future systems for descending through planetary atmospheres.

**MSL Entry, Descent and Landing Instrument (MEDLI) Suite**

A set of sensors attached to the heat shield of the Mars Science Laboratory (MSL) is collectively named the MSL Entry, Descent and Landing Instrument (MEDLI) Suite. MEDLI will take measurements eight times per second during the period from about 10 minutes before the vehicle enters the top of the Martian atmosphere until after the parachute has opened, about four minutes after entry. The measurements will be analyzed for information about atmospheric conditions and performance of the entry vehicle.

Due to the mass of the entry vehicle (5,359 pounds, or 2,431 kilograms, after jettison of the spacecraft's cruise stage), the diameter of its heat shield (14.8 feet, or 4.5 meters) and the speed at which the vehicle will enter the atmosphere (13,645 miles per hour, or 6.1 kilometers per second), the heating and stress on the heat shield will be the highest ever for an entry vehicle at Mars. Experience gained with this mission will aid planning for

future missions that could be even heavier and larger, such as would be necessary for a human mission to Mars.

Models of the Martian atmosphere, heating environments, vehicle aerodynamics, and heat-shield performance, among other factors, were employed in designing the Mars Science Laboratory entry vehicle. Uncertainties in these parameters must also be modeled. To account for those uncertainties, the design incorporates large margins for success. The margin comes at a cost of additional mass. The goal of MEDLI is to better quantify these atmospheric entry characteristics and possibly reduce unnecessary mass on future Mars missions, by collecting data on the performance of the Mars Science Laboratory entry vehicle during its atmospheric entry and descent.

MEDLI consists of seven pressure sensors (Mars entry atmospheric data system sensor, or MEADS), seven plugs with multiple temperature sensors (Mars integrated sensor plug, or MISP) and a support electronics box. Data from the entry vehicle's inertial measurement unit, which senses changes in velocity and direction, will augment the MEDLI data. Each of the temperature-sensing plugs has thermocouples to measure temperatures at four different depths in the heat shield's thermal protection tiles, plus a sensor to measure the rate at which heat shield material is removed due to atmospheric entry heating.

Analysis of data from the pressure sensors and inertial measurement unit will provide an altitude profile of atmospheric density and winds, plus information about pressure distribution on the heat shield surface, orientation of the entry vehicle and velocity. Data from the temperature sensors will be used to evaluate peak heating, distribution of heating over the heat shield, turbulence in the flow of gas along the entry vehicle's surface, and in-depth performance of the heat shield material.

NASA's Exploration Systems Mission Directorate (which has responsibility for planning human missions beyond Earth orbit) and Aeronautics Research Mission Directorate (which invests in fundamental research of atmospheric flight) have funded MEDLI. F. McNeil Cheatwood of NASA's Langley Research Center, Hampton, Va., is the principal investigator for MEDLI. Deputy principal investigator is Michael Wright of NASA's Ames Research Center, Moffett Field, Calif.

# Mission Overview

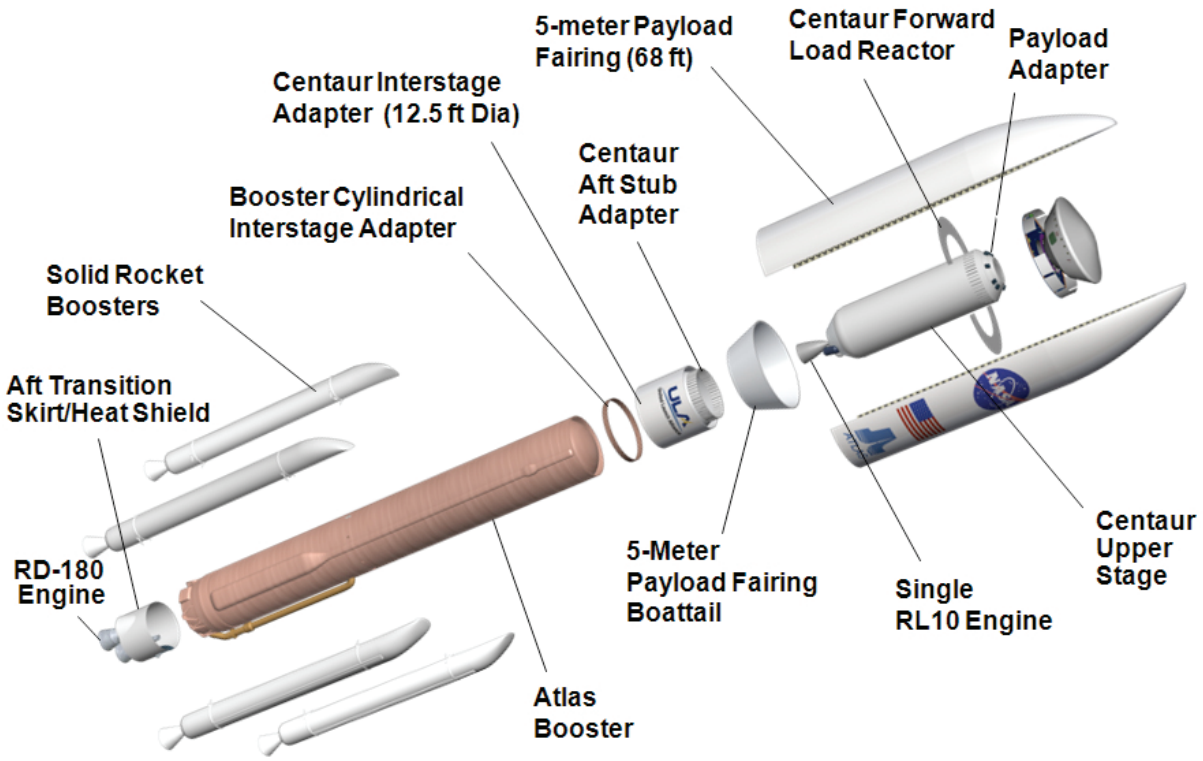
NASA's Mars Science Laboratory mission will put a mobile laboratory onto the surface inside Gale Crater on Mars and use it to investigate the area's past and present environments. The landing will use active guidance for improved landing accuracy and a skycrane for touchdown. The mobile laboratory is the Curiosity rover, equipped with 10 science investigations and a robotic arm that can drill into rocks, scoop up soil and deliver samples to internal analytical instruments. The mission will assess whether the area has offered conditions favorable for life and favorable for preserving a rock record of evidence about whether life has existed there. Curiosity has the capability to drive for 12.4 miles (20 kilometers) or more during a mission lasting one Martian year (98 weeks).

**Launch Vehicle**

A two-stage Atlas V 541 launch vehicle will lift the Mars Science Laboratory spacecraft from Launch Complex 41 at Cape Canaveral Air Force Station, Fla. The vehicle is provided by United Launch Alliance, a joint venture of Boeing Co. and Lockheed Martin Corp. The thee numbers in the 541 designation signify a payload fairing, or nose cone, that is approximately 5 meters (16.4 feet) in diameter; four solid-rocket boosters fastened alongside the central common core booster; and a one-engine Centaur upper stage.

Centerpiece of the first stage is the common core booster, 106.5 feet (32.5 meters) in length and 12.5 feet (3.8 meters) in diameter. It has a throttleable, RD-180 engine from a joint venture of Pratt & Whitney Rocketdyne, West Palm Beach, Fla., and NPO Energomash, Moscow. Thermally stable kerosene fuel (type RP-1) and liquid oxygen will be loaded shortly before launch into cylindrical fuel tanks that make up about half of the total height of the vehicle. The common core booster can provide thrust of up to about 850,000 pounds (3.8 million newtons) at full throttle.

Four solid rocket boosters strapped onto the common core booster add to the thrust that will be produced by the first stage. Each of these boosters is 64 feet (19.5 meters) long and 61 inches (155 centimeters) in diam-




*Atlas V 541 launch vehicle, expanded view*

eter, and delivers about 306,000 pounds (1.36 million newtons) of thrust.

Two interstage adaptors connect the first stage of the Atlas with its Centaur upper stage. The Centaur has a restartable RL-10 engine from Pratt & Whitney Rocketdyne. This engine uses liquid hydrogen and liquid oxygen and can provide up to about 22,300 pounds (99,200 newtons) of thrust. The Centaur can control its orientation precisely, which is important for managing the direction of thrust while its engine is firing. It carries its own flight control computer and can release its payload with the desired attitude and spin rate.

The spacecraft will ride into the sky inside a protective payload fairing atop the Centaur stage. With the payload fairing on top, the vehicle ready for launch will stand approximately 191 feet (58 meters) tall.

The first Atlas V was launched in August 2002. An Atlas V 401 sent NASA's Mars Reconnaissance Orbiter on its way to Mars on Aug. 12, 2005, from the same launch complex where the Mars Science Laboratory will be launched.

**Launch Timing Factors**

As Earth and Mars race around the sun, with Earth on the inside track, Earth laps Mars about once every 26 months. Launch opportunities to Mars occur at the same frequency, when the planets are configured so that a spacecraft launched from Earth will move outward and intersect with Mars in its orbit several months later. This planetary clockwork, plus the launch vehicle's power, the spacecraft's mass, and the desired geometry and timing for the landing on Mars were all factors in determining the range of possible launch dates.

An additional factor in determining the launch period for the Mars Science Laboratory was the launch period from Aug. 5 to Aug. 26, 2011, for NASA's Juno mission to Jupiter. The Juno launch on Aug. 5 used an Atlas V 551 vehicle from the same launch complex as the Mars Science Laboratory, Launch Complex 41 at Cape Canaveral Air Force Station, Fla. Consideration was given to the minimum time required to process the Mars Science Laboratory launch vehicle for its launch following Juno's departure. This was an important factor in the choice of the type of trajectory to Mars and the timing of the launch period for the Mars Science Laboratory.

One priority for choice of a launch period within the range of possible dates has been to have the landing occur when NASA orbiters at Mars are passing over the landing site so they can receive radio transmissions from the Mars Science Laboratory spacecraft during its descent through the atmosphere and landing. If the landing is not successful, this strategy will provide much more information than would be possible with the alternative of relying on transmissions from the Mars Science Laboratory directly to Earth. Landing on Mars is always difficult, with success uncertain. After an unsuccessful attempted Mars landing by Mars Polar Lander in 1999 without definitive information on the cause of the mishap, NASA set a high priority on communication during subsequent Mars landings.

The selected launch period for the Mars Science Laboratory begins Nov. 25, 2011, and ends Dec. 18, 2011. The durations of the daily launch windows during this 24-day launch period vary from day to day. On the first day in the launch period, the launch window is 103 minutes long. The windows will shorten to 44 minutes by the end of the period. Within each window, regardless of length, unique launch opportunities will occur once every five minutes.

The first launch opportunity on Nov. 25 is for liftoff at 10:25 a.m. EST.

**Launch Sequences**

The launch time, called "T Zero," is 1.1 seconds before liftoff. Ignition of the Atlas V 541 first-stage common core booster is at 2.7 seconds before T Zero, or 3.8 seconds before liftoff.

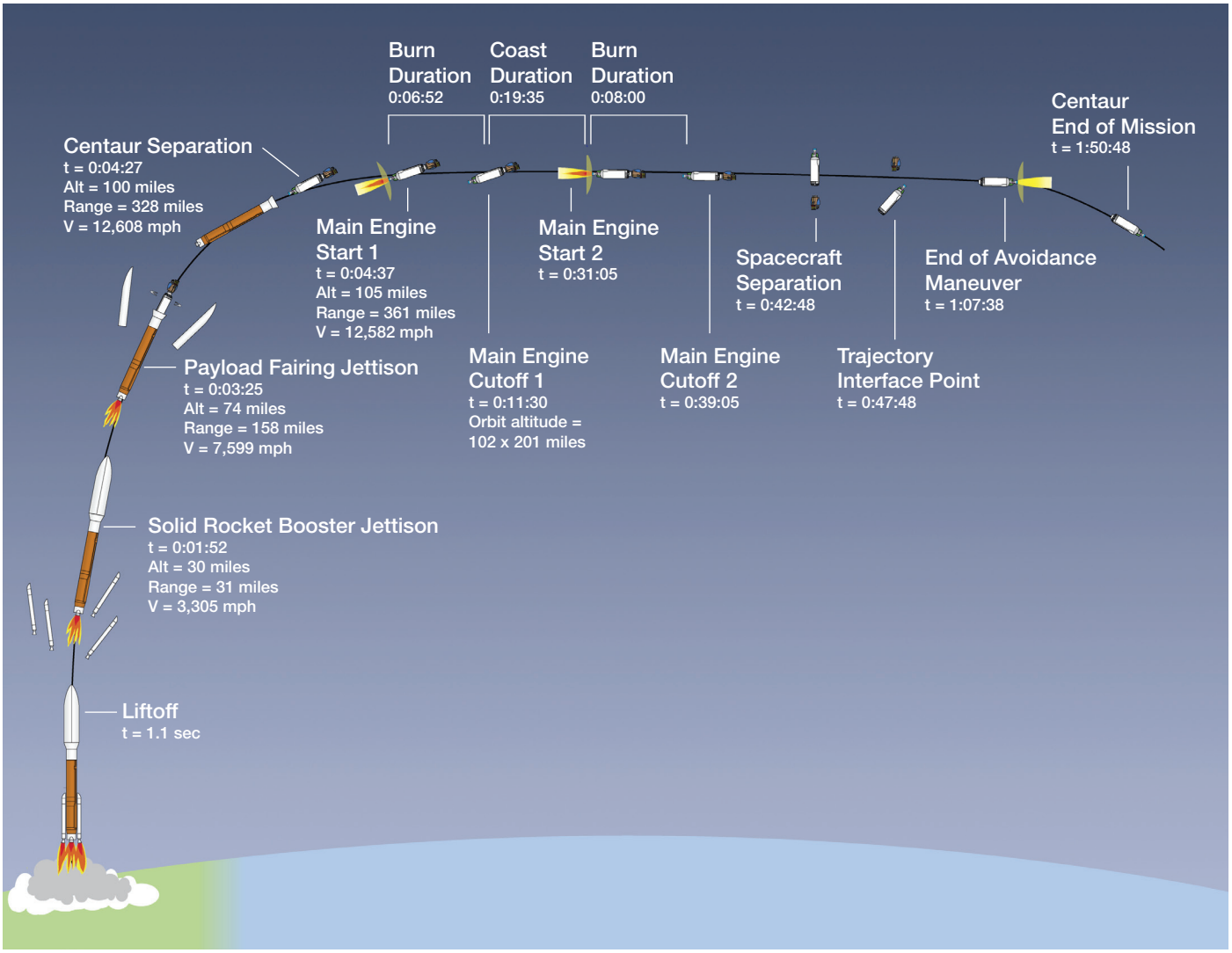
The four solid rocket boosters ignite 3.5 seconds after ignition of the common core booster (0.3 second before liftoff). They burn for about a minute and a half, and then their spent casings are jettisoned in pairs several seconds after burnout.

The common core booster engine of the first stage continues to burn until about 4 minutes and 20 seconds after liftoff. During that burn, at about 3 minutes and 25 seconds after liftoff, the payload fairing around the spacecraft is jettisoned. The booster engine finishes its work at an event called the booster engine cutoff. At that point, these engines have consumed about 623,000 pounds (284,000 kilograms) of propellant in less than five minutes and, with the help of the solid rocket boosters, taken the spacecraft to an altitude of

about 98 miles (158 kilometers) down range from Cape Canaveral about 307 miles (494 kilometers).

After coasting for a few seconds following booster engine cutoff, the launch vehicle's second stage Centaur separates from the first stage, which drops into the Atlantic Ocean. About 10 seconds after that separation, the Centaur engine is started for the first of two burns. That burn lasts about 7 minutes and inserts the Centaur-and-spacecraft stack into a parking orbit. The shape of the parking orbit is an ellipse varying in altitude from 102 miles (165 kilometers) to 201 miles (324 kilometers). However, the spacecraft will not complete even one orbit. After completion of the Centaur main engine's first burn (main engine cutoff 1), the stack coasts in the parking orbit until it reaches the proper position for start of the second Centaur burn, depending on launch date and launch time. This coast lasts 14 to 30 minutes, depending on launch timing — about 20 minutes for a launch at the initial Nov. 25 opportunity at the opening of the launch window.

The second Centaur burn, continuing for nearly 8 minutes (for a launch at the opening of the Nov. 25 launch window), lofts the spacecraft out of Earth orbit and on its way toward Mars. The burn ends with main engine cutoff 2. Three minutes and 43 seconds after that cutoff, pyrotechnic actuators and push-off springs on the second stage of the Atlas release the spacecraft with a separation velocity (relative to the launch vehicle) of 0.6 miles per hour (0.27 meters per second) and a spin rate of about 2.5 rotations per minute. By that point, 43 minutes after liftoff for the first Nov. 25 opportunity at the opening of the launch window, the two stages of the Atlas have accelerated the spacecraft to about 22,866 miles per hour (10.22 kilometers per second) relative to




*Profile of Mars Science Laboratory launch events, for a launch at first opportunity: Nov. 25, 2011, at 10:25 a.m. EST*

Earth. Shortly after that, the separated Centaur performs its last task, an avoidance maneuver taking itself out of the spacecraft's flight path to avoid hitting either the spacecraft or Mars.

Throughout the launch sequence, radio transmissions from the Atlas to NASA's Tracking and Data Relay Satellite System enable ground controllers to monitor critical events and the status of the launch vehicle and the spacecraft. The Mars Science Laboratory spacecraft cannot begin its own direct transmissions until after it separates from the launch vehicle and an antenna on the spacecraft is exposed. One minute after spacecraft separation, the flight software transitions the Mars Science Laboratory to cruise phase and turns on the X-band transmitter. The spacecraft does not start transmitting data until five minutes after that, allowing time for warming up the amplifier and configuring the telecommunications system.

The first antenna station of NASA's Deep Space Network to receive communication from the spacecraft is near Canberra, Australia. Use of an antenna operated by the private-sector United Space Network on the Indian Ocean island nation of Mauritius provides a bonus opportunity for earlier establishment of communications with the spacecraft.

Data received from the spacecraft in the initial acquisition will provide the first evaluation of the spacecraft's health in cruise mode, including confirmation that the cruise-stage solar arrays are producing electricity. Once the spacecraft is in a stable state, cruise phase activities can begin.

**Interplanetary Cruise and Approach to Mars**

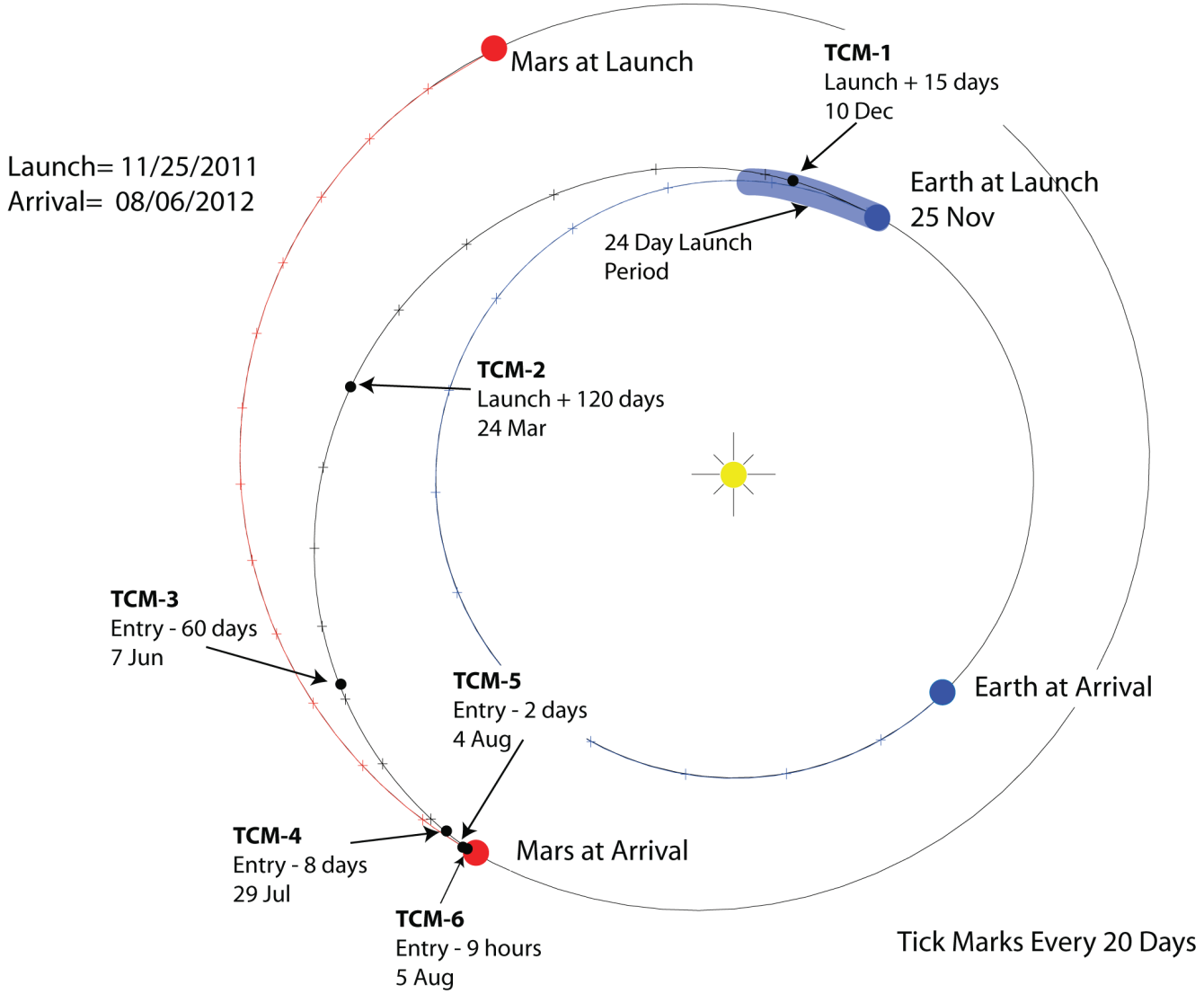
The trip from Earth to Mars will take about 36 weeks (255 days if launch is at the opening of the launch period on Nov. 25, 2011). Most of this period (210 days if launch is Nov. 25) is the cruise phase of the mission. The final 45 days are the approach phase.

Key activities during cruise include checkouts of the spacecraft and its science instruments, tracking of the spacecraft, attitude adjustments for changes in pointing of the solar array and antennas, and planning and execution of three scheduled maneuvers to adjust the spacecraft's trajectory. Three additional trajectory correction maneuvers are scheduled during the approach phase, plus a final, contingency maneuver opportunity, if needed.

The Mars Science Laboratory uses what is called a Type 1 trajectory to Mars, meaning the spacecraft will fly less than halfway around the sun while in transit from one planet to the other.

During cruise and approach, the spacecraft is spin-stabilized at two rotations per minute. The attitude of the spacecraft's axis of rotation relative to Earth and the sun affects telecommunications, power and thermal performance. The plane of the solar array on the cruise stage is perpendicular to that axis, and the two antennas used during cruise are pointed in line with that axis, in the direction the array faces. The parachute low-gain antenna, used during the first two months of the trip when the angle between the sun and Earth is relatively large, works at a wider range of pointing angles than possible with the medium-gain antenna, which is mounted on the cruise stage. As the spacecraft gets farther from Earth, the medium-gain antenna is needed for providing communication capability used for navigation, so the spacecraft's attitude must be maintained with pointing closer to Earth. The sun will not be in the same direction as Earth. To accommodate keeping the medium-gain antenna pointed within less than 10 degrees away from Earth during the later part of the cruise and approach, the power and thermal subsystems have been designed to cope with an off-sun angle greater than the off-Earth angle.

Thrusters on the cruise stage are fired to adjust the spacecraft's flight path three times during the cruise phase and additional times, as needed, during the approach phase. The first one is planned for 15 days after launch; the second for 120 days after launch. These two are used to remove most of the launch-day trajectory's intentional offset from Mars, which is a planetary protection precaution to avoid the possibility of the launch vehicle's upper stage reaching Mars without having been cleaned to the standards of a Mars-landing spacecraft. The spacecraft spends the first two weeks of cruise on a trajectory that would miss Mars by hundreds of thousands of miles or kilometers. The first two trajectory correction maneuvers direct the trajectory closer to Mars, but still leave some off-Mars bias as a precaution against the spacecraft hitting Mars in a way that could prevent the mission's planetary protection precautions from being effective. The third trajectory correction maneuver, about two months after the second and 60 days before landing, is the first one to actually target the desired Mars atmospheric entry point.




*Schematic view of Mars Science Laboratory cruise phase from Earth to Mars*

*Six trajectory correction maneuvers (TCMs) are scheduled during the voyage from Earth to Mars. Arrival at Mars will be Aug. 6, 2012, Universal Time.*

Three additional trajectory maneuvers are scheduled during the approach phase, at eight days before landing, two days before landing and nine hours before landing. As a precaution in case of any problem with the trajectory correction maneuver at two days out, the schedule holds a contingency maneuver at 24 hours before landing.

Trajectory correction maneuvers combine assessments of the spacecraft's trajectory with calculations of how to use the eight thrusters on the cruise stage to alter the trajectory. Navigators' assessments of the spacecraft's trajectory use three types of tracking information from ground antennas of NASA's Deep Space Network in California, Spain and Australia. One method is ranging, which measures the distance to the spacecraft by timing precisely how long it takes for a radio signal to travel to the spacecraft and back. A second is Doppler, which measures the spacecraft's speed relative to Earth by the amount of shift in the pitch of a radio signal from the craft. A newer method, called delta differential one-way range measurement, adds information about the location of the spacecraft in directions perpendicular to the line of sight. For this method, pairs of antennas on different continents simultaneously receive signals from the spacecraft, and then the same antennas observe natural radio waves from a known celestial reference point, such as a quasar, which serves as a navigation reference point.

All of the spacecraft's science instruments get health checks during the cruise phase. One, the Radiation Assessment Detector, will be used on a power-available basis to collect information about the radiation environment near Earth and between Earth and Mars.

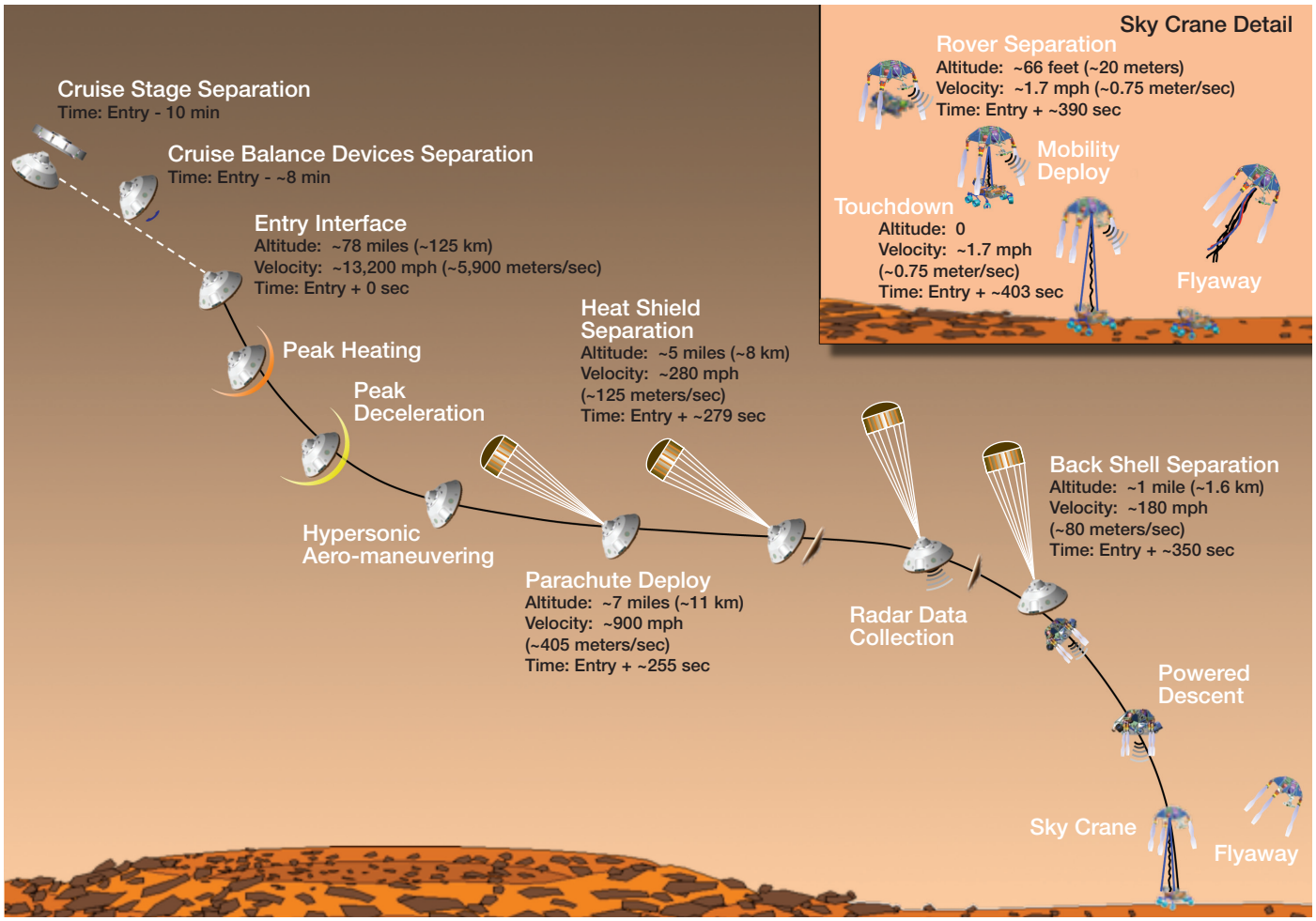
The final five days of the approach phase include activities in preparation for the spacecraft's atmospheric entry, descent and landing. These include preheating of some components and enabling others. The schedule includes four opportunities to update parameters for the autonomous software controlling events during the entry, descent and landing.

## Entry, Descent and Landing

The intense period called the entry, descent and landing (EDL) phase of the mission begins when the spacecraft reaches the Mars atmosphere, traveling at about 13,200 miles per hour (5,900 meters per second). It ends about seven minutes later with the rover and descent stage stationary on the surface — one about to begin its mission and the other with its job completed.

The top of Mars' atmosphere is actually a gradual transition to interplanetary space, not a sharp boundary. The atmospheric entry interface point — the aim point for the flight to Mars — is set at 2,188.6 miles (3,522.2 kilometers) from the center of Mars. That altitude is 81.46 miles (131.1 kilometers) above the ground elevation of the landing site at Gale Crater, though the entry point is not directly above the landing site.

Ten minutes before the spacecraft enters the atmosphere, it sheds the cruise stage. The Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI) Suite begins taking measurements. The data MEDLI provides about the atmosphere and about the heat shield's performance will aid in design of future Mars landings.




*Profile of entry, descent and landing events, for one typical case. Exact timing will be determined by atmospheric conditions on landing day.*

Beginning a minute later, small thrusters on the back shell halt the two-rotation-per-minute spin that the spacecraft had maintained during cruise and approach phases. Nine minutes before entry, the back shell thrusters orient the spacecraft so the heat shield faces forward, a maneuver called "turn to entry."

After the turn to entry, the back shell jettisons two solid-tungsten weights, called the "cruise balance mass devices." Ejecting these devices, which weigh about 165 pounds (75 kilograms) each, shifts the center of mass of the spacecraft. During the cruise and approach phases, the center of mass is on the axis of the spacecraft's stabilizing spin. Offsetting the center of mass for the period during which the spacecraft experiences dynamic pressure of interaction with the atmosphere gives the Mars Science Laboratory the ability to fly through the atmosphere with an angle of attack, generating lift. The mission manipulates that lift, using a technique called "guided entry," to steer out unpredictable variations in the density of the Mars atmosphere and improve the precision of landing on target.

As the spacecraft interacts with the upper atmosphere, small thrusters on the back shell can adjust the angle and direction of tilt, enabling the spacecraft to fly a series of "S" curves. The S curves reduce the net horizontal distance that the spacecraft covers as it descends. Using fewer of them prevents undershooting the target area; using more of them prevents overshooting the target area. The guided entry maneuvers can also correct for net drift to the left or right due to winds. The spacecraft autonomously controls the guided entry movements in response to information that its gyroscope-containing inertial measurement unit provides about deceleration and direction, indirect indicators of atmospheric density and winds.

More than nine-tenths of the deceleration before landing results from friction with the Mars atmosphere before the parachute opens. Peak heating occurs about 80 seconds after atmospheric entry, when the temperature at the external surface of the heat shield will be about 3,800 degrees Fahrenheit (about 2,100 degrees Celsius). Peak deceleration occurs about 10 seconds later.

The span of time from atmospheric entry until touchdown is not predetermined. The exact timing and altitude for key events depends on unpredictable factors in atmospheric conditions on landing day. The guided entry technique enables the spacecraft to be more responsive to unpredictable atmospheric conditions than any previous Mars mission. The span between the moment the spacecraft passes the entry interface point and a successful touchdown in the target area of Gale Crater could be as short as about 369 seconds or as long as about 460 seconds. Times for the opening of the parachute could vary by 10 to 20 seconds for a successful landing. Times given in the following description and on the accompanying graphic are for a typical case, with touchdown 403 seconds after entry.

After the spacecraft finishes its guided entry maneuvers, a few seconds before the parachute is deployed, the back shell jettisons another set of tungsten weights to shift the center of mass back to the axis of symmetry. This set of six weights, the "entry balance mass devices," each has a mass of about 55 pounds (25 kilograms). Shedding them re-balances the spacecraft for the parachute portion of its descent.

The parachute deploys about 255 seconds after entry, at an altitude of about 7 miles (11 kilometers) and a velocity of about 900 miles per hour (about 405 meters per second). After about 24 more seconds, the heat shield separates and drops away when the spacecraft is at an altitude of about 5 miles (about 8 kilometers) and a velocity of about 280 miles per hour (125 meters per second). The Mars Descent Imager begins recording video of the ground beneath the spacecraft. The rover, with its descent-stage "rocket backpack," is still attached to the back shell on the parachute. The terminal descent sensor, a radar system mounted on the descent stage, begins collecting data about velocity and altitude.

The back shell, with parachute attached, separates from the descent stage and rover about 80 seconds after heat shield separation. At this point, the spacecraft is about 0.9 mile (1.4 kilometers) above the ground and rushing toward it at about 180 miles per hour (about 80 meters per second). All eight throttleable retrorockets on the descent stage, called Mars landing engines, begin firing for the powered descent phase.

After the engines have decelerated the descent to about 1.7 miles per hour (0.75 meters per second), the descent stage maintains that velocity until rover touchdown. Four of the eight engines shut off just before nylon cords begin to spool out to lower the rover from the descent stage in the "sky crane" maneuver. The rover separates its hard attachment to the descent stage, though still attached by the sky crane bridle, at an altitude of about 66 feet (about 20 meters), with about 12 seconds to go before touchdown.

The rover's wheels and suspension system, which double as the landing gear, pop into place just before touchdown. The bridle is fully spooled out as the spacecraft continues to descend, so touchdown occurs at the descent speed of about 1.7 miles per hour (0.75 meters per second). When the spacecraft senses touchdown, the connecting cords are severed and the descent stage flies out of the way, coming to the surface at least 492 feet (150 meters) from the rover's position, probably more than double that distance.

The rover's computer switches from entry, descent and landing mode to surface mode. This initiates autonomous activities for the first Martian day on the surface of Mars, Sol 0. The time of day at the landing site is mid afternoon — about 3 p.m. local mean solar time at Gale Crater.

**Mars Surface Operations**

The planned operational life for the Mars Science Laboratory is one Martian year on the surface. One Martian year is 687 Earth days, or 669 Martian days, which are called sols. Each sol is 24 hours, 39 minutes, 35.244 seconds long. The landing site is in an equatorial region, at 4.5 degrees south latitude. The season in Mars' southern hemisphere at the beginning and end of the prime mission is late winter, about two thirds of the way from winter solstice to spring equinox.

One Martian year is how long the scientists and engineers operating the rover will have to achieve the mission's science goals. Adding to the challenge, some periods of the mission will not be fully available for science tasks. These include an initial health checkout for about 10 sols or more after landing and about 20 sols in April 2013 when communications will be restricted due to Mars' position nearly behind the sun from Earth. Strategies for maximizing the science accomplishments in the time available include extensive preparations before landing, efficiently coordinated use of the rover's capabilities and flexibility for responding to discoveries.

The structure of science activities is based on sending a set of commands to the rover each Martian morning for the activities to be performed during that sol. The activity plan for the sol needs to fit within the constraints of time, power, temperature factors and data volume for the sol. During a communication relay opportunity when an orbiter passes overhead in the Martian midafternoon, the rover transmits data about the sol's activities. Any of the sol's results that will influence the next sol's activities need to be included in this downlink, though additional data from the sol can be transmitted during later relay opportunities.

With data from preceding sols, the rover team needs to make decisions for each sol, such as what targets to approach, what instruments to use, what observations to make and what downlink priority level to assign for each set of data generated during the sol or stored onboard from earlier sols. The rover team's engineers collaborate with scientists to determine what activities are safe and feasible, and to develop and check the sequences of commands for transmission to the rover.

In initial weeks of Mars surface operations, the team will work on a Mars time schedule to make best use of the key hours between when one sol's downlink is received and when the next sol's commands must be ready, whatever time of day that is at the operations center at NASA's Jet Propulsion Laboratory, Pasadena, Calif. Team members' work shift will begin about 40 minutes later each day than on the preceding day because a sol is that much longer than an Earth day. Later in the mission, operations will transition to an Earth-day work schedule and will become more geographically distributed as non-Pasadena team members return to their home institutions and participate through teleconferencing.

The landing sol is designated as Sol 0, a change from the practice of the Mars Exploration Rover missions, which designated landing sols of Spirit and Opportunity as Sol 1. On Curiosity's Sol 0, the information expected from the rover will confirm its status after landing. Additional information about rover health and status may come about 12 hours after landing via relay from the Mars Reconnaissance Orbiter passing over the landing site at about 3 a.m. local Mars time on Sol 1.

Priority activities for Sol 1, built into command sequences stored onboard from before landing, are to raise the camera mast, image the sky with the navigation camera, determine the location of the sun from those images, calculate the angle toward Earth, then point the high-gain antenna toward Earth.

Activities over the next few sols will characterize the rover and landing site by conducting health checks of various rover subsystems, completing a color panorama from the Mastcam and taking weather measurements. The first drive may be more than a week after landing, and

the first use of the robotic arm will probably be after the first drive.

After completion of the characterization activities, the pace of driving and the frequency of multi-sol stops for acquiring and analyzing rock or soil samples will be determined by the team decisions about science priorities. Some possible destinations identified in advance from orbit may be within several weeks of driving distance from the landing site. With the time taken to investigate nearer stopping points, other likely destinations are more than a year away.

**Communications Strategy**

Like all of NASA's interplanetary missions, the Mars Science Laboratory will rely on the agency's Deep Space Network to communicate with the spacecraft and to track it during flight. The network has groups of antennas at three locations: at Goldstone in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. These locations are about one-third of the way around the world from each other. That assures, whatever time of day it is on Earth, at least one of them will have the spacecraft in view during its trip from Earth through landing. At least one location will have Mars in view at any time during the rover's Mars-surface operations. Each complex is equipped with one antenna 230 feet (70 meters) in diameter, at least two antennas 112 feet (34 meters) in diameter, and smaller antennas. All three complexes communicate directly with the control hub at NASA's Jet Propulsion Laboratory, Pasadena, Calif.

As the spacecraft travels from Earth to Mars during the cruise and approach phases of the mission it communicates directly with Earth in the X-band portion of the radio spectrum (at 7 to 8 gigahertz). For this, the spacecraft uses a transponder and amplifier in the spacecraft's descent stage and two antennas. One of the antennas, the parachute low-gain antenna, is on the aeroshell's parachute cone, which is exposed through the center of the cruise stage. The other, the medium-gain antenna, is mounted on the cruise stage. The parachute low-gain antenna serves during the early weeks of the cruise to Mars, then again during cruise-stage separation. During most of the voyage, the job switches to the medium-gain antenna, which provides higher data rates but requires more restrictive pointing toward Earth. The telecommunications system provides position and velocity information for navigation, as well carrying data and commands.

Communication during atmospheric entry, descent and landing is a high priority. Landings on Mars are notoriously difficult. If this landing were not successful, maintaining communications during the entry, descent and landing would provide critical diagnostic information that could influence the design of future missions.

All three orbiters currently active at Mars — NASA's Mars Odyssey and Mars Reconnaissance Orbiter and the European Space Agency's Mars Express — will be at positions where they can receive transmissions from the Mars Science Laboratory spacecraft during its entry, descent and landing. These transmissions to the orbiters use the ultra-high frequency (UHF) portion of the radio spectrum (at about 400 megahertz) from three different UHF antennas. The parachute UHF antenna, mounted on the back shell, transmits information from a few minutes before atmospheric entry until the rover and descent stage separate from the back shell. At that point, the descent UHF antenna on the descent stage takes over. When the rover drops away from the descent stage on its sky-crane bridle, the rover UHF antenna is exposed to begin transmissions that continue through landing. The orbiters relay to Earth via X band the information they receive from the Mars Science Laboratory during this critical period.

The Mars Science Laboratory spacecraft will also transmit in X band during its entry, descent and landing. Due to signal strength constraints, these transmissions will be simple semaphore codes rather than full telemetry. The Deep Space Network will listen for those direct-to-Earth transmissions. The X-band antenna in use at the start of atmospheric entry is the parachute low-gain antenna on the back shell. Transmissions are shifted to the tilted low-gain antenna, also on the back shell, before the start of the banking maneuvers of the guided entry. After the separation of the back shell, the descent low-gain antenna, mounted on the descent stage, handles X-band transmission. The rover low-gain antenna transmits in X band, but not until after landing.

During Mars surface operations, the rover Curiosity has multiple options available for receiving commands from mission controllers on Earth and for returning rover science and engineering information.

Curiosity has the capability to communicate directly with Earth via X-band links with the Deep Space Network. This capability will be used routinely to deliver commands to the rover each morning on Mars. It can also be used to return information to Earth, but only at

relatively low data rates — on the order of kilobits per second — due to the rover's limited power and antenna size, and to the long distance between Earth and Mars.

Curiosity will return most information via UHF relay links, using one of its two redundant Electra-Lite radios to communicate with a Mars orbiter passing overhead. In their trajectories around Mars, the Mars Reconnaissance Orbiter and Mars Odyssey orbiter each fly over the Curiosity landing site at least once each afternoon and once each morning before dawn. While these contact opportunities are short in duration, typically lasting only about 10 minutes, the proximity of the orbiters allows Curiosity to transmit at much higher data rates than the rover can use for direct-to-Earth transmissions. The rover can transmit to Odyssey at up to about 0.25 megabit per second and to the Mars Reconnaissance Orbiter at up to about 2 megabits per second. The orbiters, with their higher-power transmitters and larger antennas, then take the job of relaying the information via X-band to the Deep Space Network on Earth. Mission plans call for the return of 250 megabits of Curiosity data per Martian day over these relay links. The links can also be used for delivering commands from Earth to Curiosity.

While not planned for routine operational use during Curiosity's surface mission, the European Space Agency's Mars Express orbiter will be available as a backup communications relay asset should NASA's relay orbiters become unavailable for any period of time.

**Planetary Protection**

When sending missions to Mars, precautions must be taken to avoid introduction of microbes from Earth by robotic spacecraft. This is consistent with United States obligations under the 1967 Outer Space Treaty, the international treaty stipulating that exploration must be conducted in a manner that avoids harmful contamination of celestial bodies. "Planetary protection" is the discipline responsible for the development of rules and practices used to avoid biological contamination in the process of exploration. NASA has a planetary protection officer responsible for establishing and enforcing planetary protection regulations. Each spacecraft mission is responsible for implementing measures to comply with the regulations. In compliance with the treaty and NASA regulations, the Mars Science Laboratory flight hardware has been designed and built to meet planetary protection requirements.

NASA's primary strategy for preventing contamination of Mars with Earth organisms is to be sure that all hardware going to the planet is biologically clean. The Mars Science Laboratory mission is allowed to carry up to 500,000 bacterial spores on the entire flight system. That's about one tenth as many as in a typical teaspoon of seawater. Spore-forming bacteria have been the focus of planetary protection standards because these bacteria can survive harsh conditions for many years as inactive spores. One requirement for this mission is that the exposed interior and exterior surfaces of the landed system, which includes the rover, parachute and back shell, must not carry a total number of bacterial spores greater than 300,000, with the average spore density not exceeding 300 spores per square meter (about 11 square feet). This ensures that the biological load is not concentrated in one place. The heat shield and descent stage will hit the ground hard enough that hardware could break open. The number of spores inside this hardware that could be exposed by the hard landings of these components must be included in the 500,000 maximum number.

The two primary methods used for reducing the number of spores on the spacecraft are alcohol wipe cleaning and dry heat microbial reduction. Technicians and engineers assembling the spacecraft and preparing it for launch have routinely cleaned surfaces by wiping them with alcohol and other solvents. Components tolerant of high temperature were heated to reduce spore burden according to NASA specification, at temperatures ranging from 230 to 295 degrees Fahrenheit (110 to 146 degrees Celsius) for durations up to 144 hours. The planetary protection team carefully samples the surfaces and performs microbiological tests to demonstrate that the spacecraft meets requirements for biological cleanliness.

The Mars Science Laboratory is also complying with a requirement to avoid going to any site on Mars known to have water or water-ice within 3.3 feet (one meter) of the surface. This is a precaution against any landing-day accident that could introduce hardware not fully sterilized by dry heat into an environment where heat from the mission's radioisotope thermoelectric generator and a Martian water source could provide conditions favorable for microbes from Earth to grow on Mars.

Another way of making sure the mission does not transport Earth life to Mars is to ensure that any hardware not meeting cleanliness standards does not go to Mars ac-

cidentally. When the Atlas launch vehicle's upper stage Centaur separates from the spacecraft, the two objects are traveling on nearly identical trajectories. To prevent the possibility of the Centaur hitting Mars, that shared flight path is deliberately set so that the spacecraft would miss Mars if not for later maneuvers to adjust its trajectory. By design, the Centaur is never aimed at Mars.

Portions of the flight hardware will impact the surface of Mars as part of a normal landing event. This impact may cause the hardware to split open and potentially release spores trapped inside the hardware during manufacturing processes. To ensure MSL does not exceed the spore allocation, studies were conducted on various materials, including paint, propellants and adhesives, to determine the number of spores in a given volume. In many cases the parts of the spacecraft containing these materials used dry heat microbial reduction to reduce the number of spores. For hardware expected to impact Mars, such as the cruise stage after its separation from the aeroshell, a detailed thermal analysis was conducted to make sure that plunging through Mars' atmosphere creates enough heat that few to no spores survive.

# Comparing Two Mars Rover Projects

| | **Mars Science Laboratory** | **Mars Exploration Rovers** |
|---|---|---|
| **Rovers** | 1 (Curiosity) | 2 (Spirit and Opportunity) |
| **Launch vehicle** | Atlas V | Delta II |
| **Heat shield diameter** | 14.8 feet (4.5 meters) | 8.7 feet (2.65 meters) |
| **Design mission life on Mars** | 1 Mars year (98 weeks) | 90 Mars sols (13 weeks) |
| **Science Payload** | 10 instruments, 165 pounds (75 kilograms) | 5 instruments, 11 pounds (5 kilograms) |
| **Rover mass** | 1,982 pounds (899 kilograms) | 374 pounds (170 kilograms) |
| **Rover size** (excluding arm) | Length 10 feet (3 meters); width 9 feet (2.7 meters); height 7 feet (2.2 meters) | Length 5.2 feet (1.6 meters); width 7.5 feet (2.3 meters); height 4.9 feet (1.5 meters) |
| **Robotic arm** | 7 feet (2.1 meters) long, deploys two instruments, collects powdered samples from rocks, scoops soil, prepares and delivers samples for analytic instruments, brushes surfaces | 2.5 feet (0.8 meter) long, deploys three instruments, removes surfaces of rocks, brushes surfaces |
| **Entry, descent and landing** | Guided entry, sky crane | Ballistic entry, air bags |
| **Landing ellipse** (99-percent confidence area) | 15.5 miles (25 kilometers) long | 50 miles (80 kilometers) long |
| **Power supply on Mars** | Multi-mission radioisotope thermoelectric generator (about 2,700 watt hours per sol) | Solar photovoltaic panels (less than 1,000 watt hours per sol) |
| **Computer** | Redundant pair, 200 megahertz, 250 MB of RAM, 2 GB of flash memory | Single, 20 megahertz, 128 MB of RAM, 256 MB of flash memory |

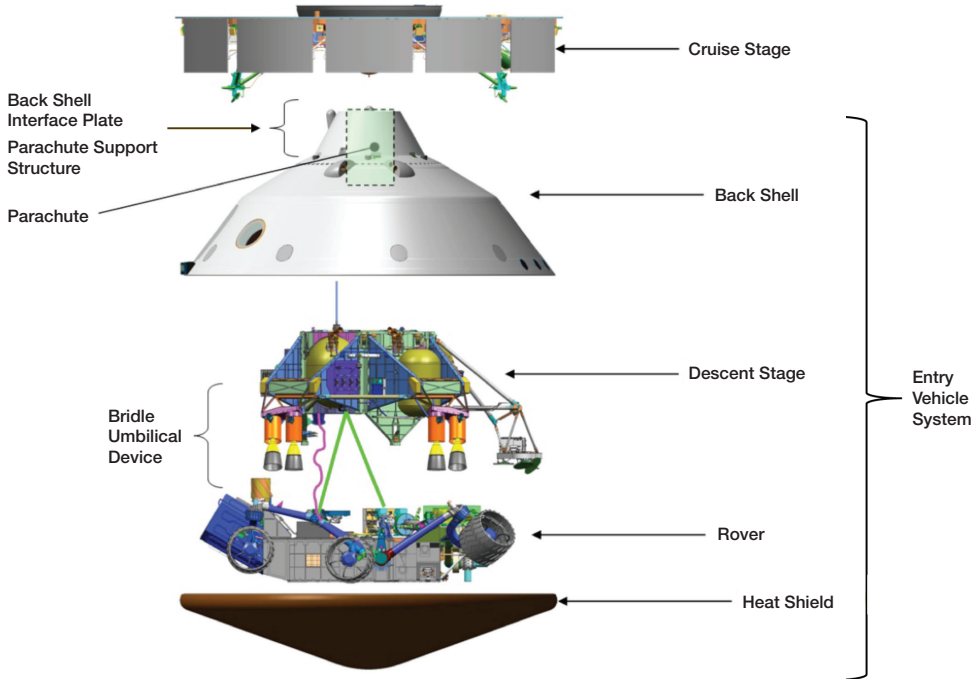
# Spacecraft

The Mars Science Laboratory spacecraft consists of four major elements: rover, descent stage, aeroshell and cruise stage. The rover, Curiosity, has the science payload and systems that enable the rover to use the payload effectively and send home the results. The descent stage performs the final moments of delivering the rover to the surface of Mars. The aeroshell, which includes the heat shield and the back shell, provides thermal protection and maneuverable lift during the initial portion of descent through the Martian atmosphere, and then a parachute ride for the next portion of the descent. The cruise stage provides trajectory maneuvers, electrical power, communications and other functions during the eight months from launch to landing.

**Cruise Stage**

The cruise stage is doughnut-shaped, about five times wider than it is tall, with 10 radiators arranged around the perimeter. The hole of the doughnut sits over a cone holding the parachute on top of the aeroshell. One surface of the cruise stage attaches to the launch vehicle. That attachment is severed within the first hour after launch. The other surface of the cruise stage attaches to the top of the aeroshell. That attachment is severed 10 minutes before the spacecraft enters Mars' atmosphere. During the roughly eight months between those two separation events (232 to 260 days, depending on launch date), the cruise stage performs essential tasks of the flight, though it uses the computer inside the rover.

The cruise stage primary structure is aluminum. An inner ring connects to the launch vehicle interface and the back shell interface plate. A series of ribs connect other components. The cruise propulsion system is used to maintain the spacecraft's spin rate, adjust the spacecraft's orientation, and provide propulsion for trajectory correction maneuvers scheduled into the trip between Earth and Mars. Two clusters of thrusters each include four thruster engines in different orientations enabling different directions of thrust. Each of the eight thrusters can provide about 1.1 pounds (5 newtons) of force. They use hydrazine, a monopropellant that does not require an oxygen source. Hydrazine is a corrosive liquid compound of nitrogen and hydrogen that decomposes explosively into expanding gases when exposed to a catalyst in the thrusters. Two spherical propellant tanks on the cruise stage, each 19 inches (48 centimeters) in diameter, supply the pressurized propellant. Aerojet built the thrusters at its Redmond, Wash., facility. On both the cruise stage and descent stage, fuel tanks are from ATK Space Systems, Inc., Commerce, Calif.; and pressurant tanks are from Arde, Inc., Carlstadt, N.J.




*Mars Science Laboratory flight system, expanded view*

The spacecraft spins at two rotations per minute for stability on its way to Mars. The cruise stage monitors the spin rate and the spacecraft's attitude (orientation) with a star scanner and one of two sun sensor assemblies. Each of the sun sensor assemblies, from Adcole Corp., Marlborough, Mass., includes four sun-sensor heads pointing in different directions. Based on star tracking and sun sensing information, the cruise stage uses its thrusters as necessary to maintain the spin rate and attitude.

Most of the electrical power for the spacecraft during the trip from Earth to Mars is provided by sunshine hitting a ring-shaped array of photovoltaic cells on the upper surface of the cruise stage. The Multi Mission Radioisotope Thermoelectric Generator on the rover supplements the electricity provided by the cruise solar array on the way to Mars. The solar array has six physical panels totaling 138 square feet (12.8 square meters) of active photovoltaic area. The photovoltaic cells from Emcore Corp., Albuquerque, N.M., use layers of three different materials to gain electricity from different portions of the solar spectrum. The layers are gallium indium phosphorus, gallium arsenide and germanium. If operated at full capacity at Earth, the array could produce about 2,500 watts, which would exceed the spacecraft's needs. The array and its operation are designed to satisfy the mission's requirements from launch day to the Mars approach. At its farthest from the sun, during the approach to Mars, the array will produce 1,080 watts or more, even when facing as much as 43 degrees away from the sun.

Another important function for the cruise stage is to maintain temperatures within designed ranges for the parts of the spacecraft inside the aeroshell as well as for the cruise stage itself. The 10 radiators of the heat-rejection system are mounted as a ring around the outer edge of the cruise stage. Fluid pumped through a circulatory system disperses heat from the rover's multi-mission radioisotope thermoelectric generator to warm the electronics of the cruise stage and to be released into space by the radiators.

The medium-gain antenna mounted on the cruise stage serves in telecommunications with Earth during most of the trip from Earth to Mars.

**Aeroshell**

The aeroshell that encapsulates the rover and descent stage during the flight to Mars protects them from friction with Mars' atmosphere and provides other functions.

The Mars Science Laboratory aeroshell is not only the biggest ever built for a planetary mission, but also incorporates major innovations in attitude control for guided entry and in thermal protection material. Lockheed Martin Space Systems, Denver, built the areoshell's heat shield and back shell.

The diameter of the heat shield is 14.8 feet (4.5 meters). For comparison, heat shields of the Apollo capsules that returned astronauts to Earth after visits to the moon were just under 13 feet (4 meters) in diameter, and the heat shields for the Mars Exploration Rovers, Spirit and Opportunity, were 8.7 feet (2.65 meters).

This aeroshell, unlike any predecessor for an extraterrestrial mission, has a steering capability. This is a key to the mission's guided entry innovation for added precision in landing. During a crucial portion of descent through the upper atmosphere of Mars, before the back shell deploys its parachute, the center of mass of the spacecraft will be offset from the axis of symmetry (a line through the center of the aeroshell). This offset puts the aeroshell at an angle to its direction of movement, creating lift as the spacecraft interacts with the atmosphere. With lift, the spacecraft can fly like a wing, rather than dropping like a rock. A reaction control system with small thrusters to adjust the orientation of the spacecraft can steer banking turns. A series of turns can shorten the net horizontal distance the spacecraft covers during its descent. Performed in response to sensing how the spacecraft is reacting to unpredictable variability in the atmosphere, the maneuvers counteract the unpredictability and provide a more precise landing.

The heat shield uses a different thermal protection system than used on earlier Mars missions' heat shields, because the unique entry trajectory profile and the mass and size of the vehicle could create external temperatures up to 3,800 degrees Fahrenheit (about 2,100 degrees Celsius). The heat shield is covered with tiles of phenolic impregnated carbon ablator (PICA) material. NASA Ames Research Center, Moffett Field, Calif., invented the PICA material; Fiber Materials Inc., Biddeford, Maine, made the tiles. PICA was first flown as the thermal protection system on the heat shield of NASA's Stardust Sample Return Capsule.

The heat shield carries sensors for collecting data about Mars' atmosphere and the performance of the heat

shield. These are part of the Mars Science Laboratory Entry, Descent and Landing Instrument (MEDLI) Suite, which is described in the Mars Science Laboratory Investigations section of this document.

The back shell, besides making up the upper portion of the capsule protecting the rover during passage through Mars' atmosphere, includes several devices used during the spacecraft's atmospheric entry and descent.

The back shell carries two sets of detachable tungsten weights for altering the spacecraft's center of mass.

Eight small thrusters in the upper half of the back shell are used for the guided entry maneuvers.

A conical structure at the top of the back shell holds the parachute and its deployment mechanism. The parachute is the largest ever built for an extraterrestrial mission. It uses a configuration called disk-gap-band. It has 80 suspension lines, measures 165 feet (50 meters) in length, and opens to a diameter of 51 feet (nearly 16 meters). Most of the orange and white fabric is nylon, though a small disk of heavier polyester is used near the vent in the apex of the canopy due to higher stresses there. The parachute is designed to survive deployment at up to Mach 2.2 in the Martian atmosphere and drag forces of up to 65,000 pounds. Pioneer Aerospace Corp., South Windsor, Conn., made the parachute.

Mounted on the back shell are two antennas — the parachute low-gain antenna and the tilted low-gain antenna — for communicating directly with Earth using X-band frequencies and another antenna — the parachute UHF antenna — for communicating with Mars orbiters using an ultra-high frequency (UHF) band.

**Descent Stage**

The descent stage of the Mars Science Laboratory does its main work during the final few minutes before touchdown on Mars. It provides rocket-powered deceleration and two bands of telecommunications for a phase of the arrival at Mars after the phases using the heat shield and parachute. After reaching a constant vertical velocity, the descent stage lowers the rover on a bridle and continues descent until rover touchdown.

The descent stage uses eight rockets, called Mars lander engines (MLE), positioned around its perimeter in four pairs. These are the first throttleable engines for a Mars landing since the Mars Viking landings in 1976. They were built by Aerojet, in Richmond, Wash., with throttle valve assemblies from Moog Inc., East Aurora, N.Y. Each can provide an adjustable amount of thrust up to about 742 pounds (3,300 newtons). The propulsion system of the descent stage uses pressurized propellant. Three spherical fuel tanks provide a usable propellant load of about 853 pounds (about 387 kilograms) of hydrazine, a propellant that does not require an oxygen source. Two spherical tanks of pressurized helium provide pressure for propellant delivery, moderated by a mechanical regulator.

While the rover is fastened to the descent stage, the two components together are called the powered descent vehicle. The fastenings are pyrotechnic bolts. Firing to release these connections commences the spacecraft's sky crane maneuver.

To perform the sky crane maneuver of lowering the rover on a bridle, the descent stage carries a device called the bridle umbilical and descent rate limiter (BUD). This cone-shaped device is about 2 feet (two-thirds of a meter) long. Three tethers of the bridle, attached to the rover at three points, are spooled around the BUD, with enough length to lower the rover about 25 feet (7.5 meters) below the descent stage during the sky crane maneuver. A slightly longer umbilical, with data and power connections between the rover and the descent stage, is also spooled around the BUD. A descent brake in the device governs the rotation rate as the bridle unspools, hence the speed at which gravity pulls the rover away from the descent stage. The descent brake, made by the Starsys division of SpaceDev Inc. (now Sierra Nevada Corp.), Poway, Calif., uses gear boxes and banks of mechanical resistors engineered to prevent the bridle from spooling out too quickly or too slowly. The cords of the bridle are made of nylon. The BUD also includes springs for quickly retracting the loose bridle and umbilical after they are severed at the rover end when touchdown is detected.

Through the umbilical, the spacecraft's main computer inside the rover controls activities during the entry, descent and landing. After the heat shield drops away, crucial information for determining the timing of events comes to that computer from the terminal descent sensor, a radar system engineered and built specifically for this mission. The radar, mounted on the descent stage, has six disk-shaped antennas oriented at different angles. It measures both vertical and horizontal velocity, as well as altitude.

The descent stage carries an X-band transponder and amplifier and two telecommunication antennas: the descent low-gain antenna for communicating directly with Earth via X-band transmissions and the descent UHF antenna for sending information to Mars orbiters.

**Rover**

The Mars Science Laboratory rover, Curiosity, carries the instruments of the mission's 10 science investigations plus multiple systems that enable the science payload to do its job and send home the results. Key systems include six-wheeled mobility, sample acquisition and handling with a robotic arm, navigation using stereo imaging, a radioisotope power source, avionics, software, telecommunications and thermal control.

The rover's name was suggested by the winning entrant in a national naming contest conducted among U.S. school students. More than 9,000 students, ages 5 through 18, submitted entries in late 2008 and early 2009. An essay by Clara Ma of Lenexa, Kans., a 12-year-old sixth-grader at the time, was selected by NASA in May 2009.

Curiosity is 10 feet (3 meters) long (not counting its arm), 9 feet (2.7 meters) wide and 7 feet (2.2 meters) high at the top of its mast, with a mass of 1,982 pounds (899 kilograms), including 165 pounds (75 kilograms) of science instruments. By comparison, each of the previous generation of Mars rovers, Spirit and Opportunity, is 5.2 feet (1.6 meters) long, 7.5 feet (2.3 meters) wide and 4.9 feet (1.5 meters) high, with a mass of 374 pounds (170 kilograms), including about 20 pounds (9 kilograms) of science instruments.

The science payload is described in the Mars Science Laboratory Science Investigations section of this press kit.

Curiosity's mechanical structure provides the basis for integrating all of the other rover subsystems and payload instruments. The chassis is the core of the rover. With insulated surfaces, it forms the shell of the warm electronics box containing the avionics. The mechanical subsystem provides deployments that bring the rover to its full functionality, including deployments of the remote-sensing mast, robotic arm, antennas and mobility system.

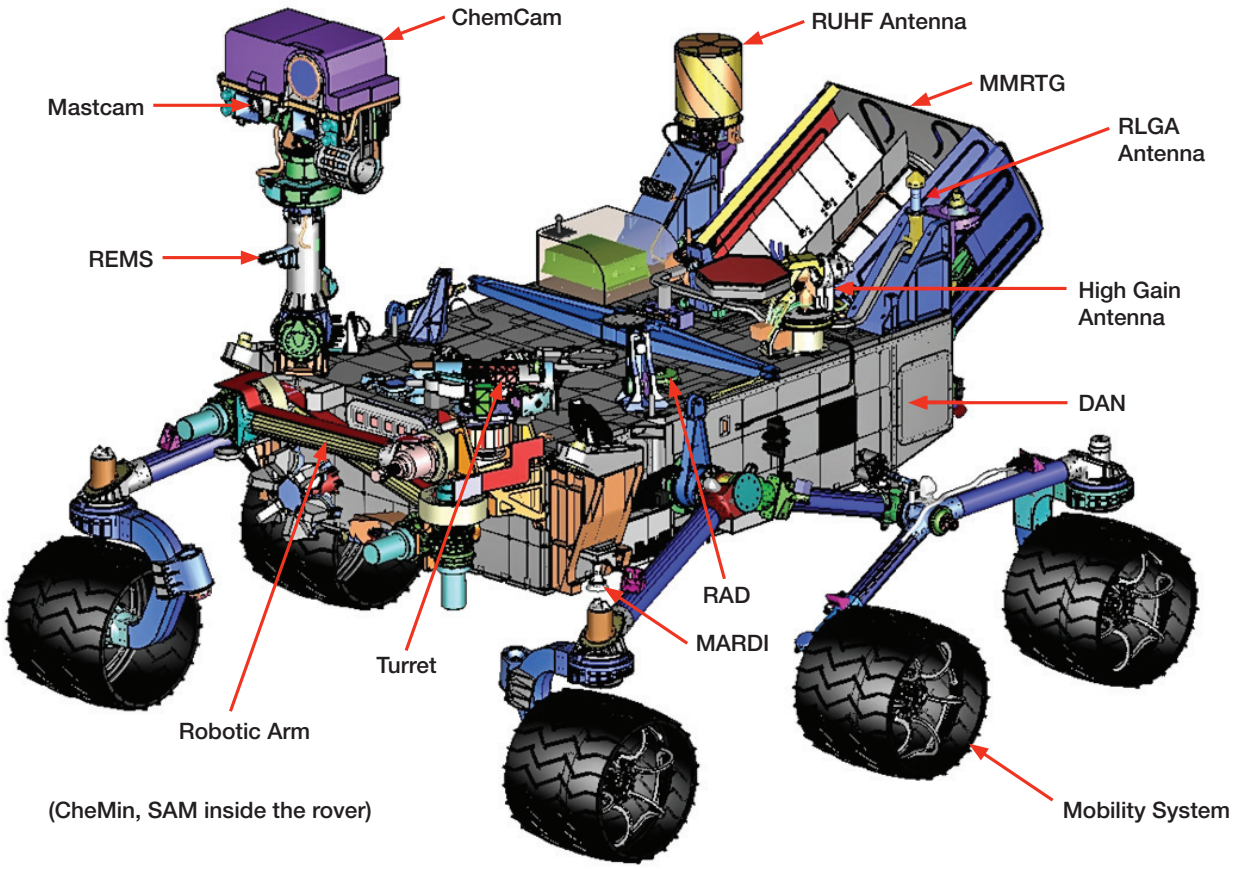
**Rover Mobility**

Curiosity's mobility subsystem is a scaled-up version of what was used on the three earlier Mars rovers: Sojourner, Spirit and Opportunity. Six wheels all have driver motors. The four corner wheels all have steering motors. Each front and rear wheel can be independently steered, allowing the vehicle to turn in place as well as to drive in arcs. The suspension is a rocker-bogie system. Combined with a differential connecting the left and right sides of the mobility system, the rocker-bogie design enables a six-wheel vehicle to keep all its wheels in contact with the ground even on uneven terrain, such as with a wheel going over a rock as big as the wheel. On each side, a bogie connects the middle and rear wheels and provides a pivot point between those wheels. The rocker connects the bogie pivot point to the front wheel. The rocker's pivot point connects to the differential across the rover body to the rocker on the other side.

Curiosity's wheels are aluminum, 20 inches (0.5 meter) in diameter, which is twice the size of the wheels on Spirit and Opportunity. They have cleats for traction and for structural support. Curving titanium spokes give springy support. The wheels were machined by Tapemation, Scotts Valley, Calif. Titanium tubing for the suspension system came from Litespeed Titanium, Chattanooga, Tenn.

The drive actuators — each combining an electric motor and gearbox — are geared for torque, not speed. Aeroflex Inc., Plainview, N.Y., built the cold-tolerant actuators for the wheels and other moving parts of Curiosity. The rover has a top speed on flat, hard ground of about 1.5 inches (4 centimeters) per second. However, under autonomous control with hazard avoidance, the vehicle achieves an average speed of less than half that. The rover was designed and built to be capable of driving more than 12 miles (more than 20 kilometers) during the prime mission. The actual odometry will depend on decisions the science team makes about allocating time for driving and time for investigating sites along the way.

For Curiosity, unlike earlier Mars rovers, the mobility system doubles as a landing system, directly absorbing the force of impacting the Martian surface at touchdown. As on the earlier rovers, the mobility system can also be used for digging beneath the surface by rotating one corner wheel while keeping the other five wheels immobile.



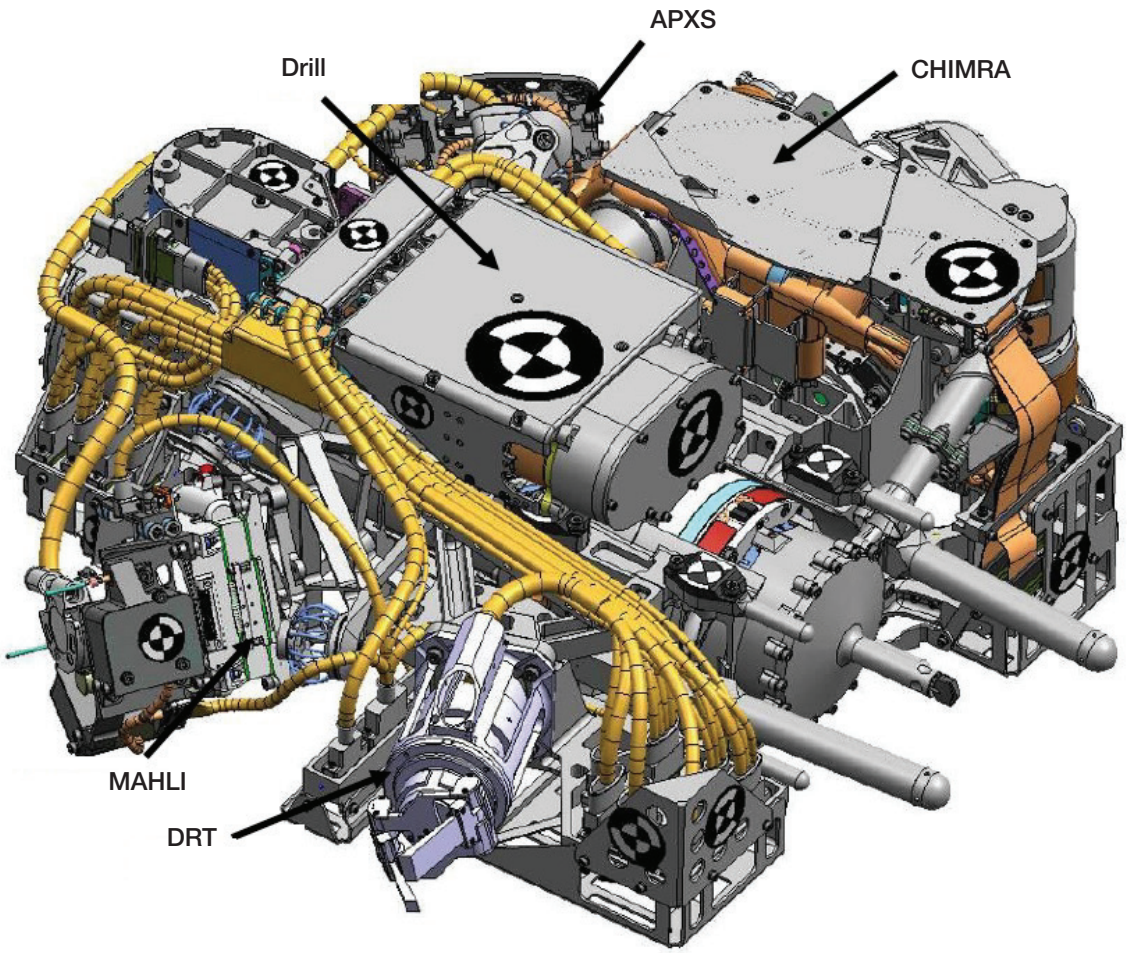

*Curiosity Mars Rover*

*Locations of several science instruments and major subsystems on the NASA Mars rover Curiosity are indicated. These include (clockwise from left): Rover Environmental Monitoring Station (REMS); Mast Camera (Mastcam); Chemistry and Camera (ChemCam); Rover ultra high-frequency (RUHF) antenna; Multi-mission radioisotope thermoelectric generator (MMRTG); Rover low-gain (RLGA) antenna; high-gain antenna; Dynamic Albedo of Neutrons (DAN); mobility system (wheels and suspension); Radiation Assessment Detector (RAD); Mars Descent Imager (MARDI); turret (see larger image for tools on the turret at the end of the robotic arm); and robotic arm. Two science instruments — Chemistry and Mineralogy (CheMin) and Sample Analysis at Mars (SAM) — are inside the body of the rover.*

## Rover Arm and Turret

The turret at the end of the Curiosity's robotic arm holds two science instruments and three other devices. The arm places and holds turret-mounted tools on rock and soil targets and manipulates the sample-processing mechanisms on the turret. It is strong enough to hold the 73-pound (33-kilogram) turret at full extension of the arm. With the arm extended straight forward, the center of the turret is 6.2 feet (1.9 meters) from the front of the rover body. The diameter of the turret, including the tools mounted on it, is nearly 2 feet (60 centimeters).

The arm has five degrees of freedom of movement provided by rotary actuators known as the shoulder azimuth joint, shoulder elevation joint, elbow joint, wrist joint and turret joint. The Space Division of MDA Information Systems Inc. built the arm in Pasadena, Calif.




*Turret of tools at the end of Curiosity's robotic arm*

*Locations of tools on the turret that is mounted on Curiosity's arm are indicated. These include (clockwise from upper left): the drill for acquiring powdered samples from interiors of rocks; the Alpha Particle X-ray Spectrometer (APXS); the sample processing subsystem named Collection and Handling for In-Situ Martian Rock Analysis (CHIMRA), which includes a scoop for acquiring soil samples; the Dust Removal Tool (DRT) for brushing rock surfaces clean; and the Mars Hand Lens Imager (MAHLI).*

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The science instruments on the arm's turret are the Mars Hand Lens Imager (MAHLI) and the Alpha Particle X-ray Spectrometer (APXS). The other tools on the turret are components of the rover's Sample Acquisition/Sample Processing and Handling (SA/SPaH) subsystem: the Powder Acquisition Drill System (PADS), the Dust Removal Tool (DRT), and the Collection and Handling for In-situ Martian Rock Analysis (CHIMRA) device.

The Powder Acquisition Drill System is a rotary percussive drill to acquire samples of rock material for analysis. It can collect a sample from up to 2 inches (5 centimeters) beneath a rock's surface. The diameter of the drilled hole is 0.63 inch (1.6 centimeters). The drill penetrates the rock and powders the sample to the appropriate grain size for use in the two analytical instruments inside the rover: Sample Analysis at Mars (SAM), and Chemistry and Mineralogy (CheMin). The powder travels up an auger in the drill for transfer to sample processing mechanisms. If the drill bit becomes stuck in a rock, the drill can disengage from that bit and replace it with a spare. The arm moves the drill to engage and capture one of two spare bits in bit boxes mounted to the front of the rover.

The Dust Removal Tool, from Honeybee Robotics, N.Y., is a metal-bristle brushing device used to remove the

dust layer from a rock surface or to clean the rover's observation tray.

One portion of the Collection and Handling for In-situ Rock Analysis device is a motorized, clamshell-shaped scoop to collect soil samples from the Martian surface. The other turret-mounted portion of this device has chambers and labyrinths used for sorting, sieving and portioning the samples collected by the drill and the scoop. These functions are carried out by manipulating the orientation of the turret while a vibration device helps move material through the chambers, passages and sieves. Samples can be sieved to screen out particles more than 0.04 inch (1 millimeter) across or to screen out particles more than 0.006 inch (150 microns) across. The vibration device also aids in creating the appropriate portion size and in the delivery action when the device drops material into inlet ports of the analytical instruments. Each of the inlet ports — two for Sample Analysis at Mars and one for Chemistry and Mineralogy — has a cover that can be opened and closed using a motor.

An observation tray on the rover allows the Mars Hand Lens Imager and the Alpha Particle X-ray Spectrometer a place to examine collected and processed samples of soil and powdered rock.

**Rover Power**

Rover power is provided by a multi-mission radioisotope thermoelectric generator (MMRTG) supplied by the U.S. Department of Energy. This generator is essentially a nuclear battery that reliably converts heat into electricity. It consists of two major elements: a heat source that contains plutonium-238 dioxide and a set of solid-state thermocouples that convert the plutonium's heat energy to electricity. It contains 10.6 pounds (4.8 kilograms) of plutonium dioxide as the source of the steady supply of heat used to produce the onboard electricity and to warm the rover's systems during the frigid Martian night.

Radioisotope thermoelectric generators have enabled NASA to explore the solar system for many years. The Apollo missions to the moon, the Viking missions to Mars, and the Pioneer, Voyager, Ulysses, Galileo, Cassini and New Horizons missions to the outer solar system all used radioisotope thermoelectric generators. The multi-mission radioisotope thermoelectric generator is a new generation designed to operate on planetary bodies with an atmosphere, such as Mars, as well as in the vacuum of space. In addition, it is a more flexible modular design capable of meeting the needs of a wider variety of missions as it generates electrical power in smaller increments, slightly over 110 watts. The design goals for the multi-mission radioisotope thermoelectric generator include ensuring a high degree of safety, optimizing power levels over a minimum lifetime of 14 years, and minimizing weight. It is about 25 inches (64 centimeters) in diameter by 26 inches (66 centimeters) long and weighs about 99 pounds (45 kilograms).

Like previous generations of this type of generator, the multi-mission radioisotope thermoelectric generator is built with several layers of protective material designed to contain its plutonium dioxide fuel in a wide range of potential accidents, verified through impact testing. In the unlikely event of a launch accident, it is unlikely that any plutonium would be released or that anyone would be exposed to nuclear material. The type of plutonium used in a radioisotope power system is different from the material used in weapons and cannot explode like a bomb. It is manufactured in a ceramic form that does not become a significant health hazard unless it becomes broken into very fine pieces or vaporized and then inhaled or swallowed. Those people who might be exposed in a Mars Science Laboratory launch accident would receive an average dose of 5 to 10 millirem, equal to about a week of background radiation. The average American receives 360 millirem of radiation each year from natural sources, such as radon and cosmic rays.

The electrical output from the multi-mission radioisotope thermoelectric generator charges two lithium ion rechargeable batteries. This enables the power subsystem to meet peak power demands of rover activities when the demand temporarily exceeds the generator's steady output level. The batteries, each with a capacity of about 42 amp-hours, were made by Yardney Technical Products, Pawcatuck, Conn. They are expected to go through multiple charge-discharge cycles per Martian day.

**Rover Telecommunication**

Curiosity has three antennas for telecommunication. Two are for communications directly with NASA's Deep Space Network antennas on Earth using a radio frequency in the X band (7 to 8 gigahertz). The third is for communications with Mars orbiters, using the ultra-high frequency (UHF) band (about 400 megahertz).

X-band communications use a 15-watt, solid state power amplifier fed by the rover's small deep space transponder, manufactured by General Dynamics Advanced Information Systems, Scottsdale, Ariz. Spain provided the rover's high gain antenna, which is hexagonally shaped, nearly 1 foot (0.3 meter) in diameter and mounted near the left edge of the rover deck. With this antenna, the X-band subsystem is designed to transmit at 160 bits per second or faster to the Deep Space Network's 112-foot-diameter (34-meter-diameter) antennas or at 800 bits per second or faster to the Deep Space Network's 230-foot-diameter (70-meter-diameter) antennas. The high gain antenna, which requires pointing, can be used for either transmitting or receiving. The rover low-gain antenna, which does not require pointing, is designed primarily for receiving communications from the Deep Space Network. X-band reception through the high-gain antenna is anticipated as the typical method for daily uplink of commands to the rover.

The rover UHF antenna, a helix-pattern cylinder mounted high near the right-rear corner of Curiosity is fed by a pair of redundant Electra-Lite radios, which were built through a partnership between NASA's Jet Propulsion Laboratory and L-3 Cincinnati Electronics, Mason, Ohio. These radios are software-defined, enabling them to autonomously adjust their data rate to suit variations in signal strength due to angles and transmission distance. They use standardized communication protocols for interoperability with all the relay orbiters at Mars, and are especially compatible with the adaptive Electra UHF radio on NASA's Mars Reconnaissance Orbiter. The primary method for the rover's transmission of data is anticipated to be UHF relay to the Mars Reconnaissance Orbiter or Mars Odyssey orbiter during two of the opportunities each Martian day when the orbiters pass in the sky above the rover. The European Space Agency's Mars Express orbiter also has the capability to serve as a backup relay.

**Rover Computing**

Curiosity has redundant main computers, or rover compute elements. Of this "A" and "B" pair, it uses one at a time, with the spare held in cold backup. Thus, at a given time, the rover is operating from either its "A" side or its "B" side. Most rover devices can be controlled by either side; a few components, such as the navigation camera, have side-specific redundancy themselves. The computer inside the rover — whichever side is active — also serves as the main computer for the rest of the Mars Science Laboratory spacecraft during the flight from Earth and arrival at Mars.

Each rover compute element contains a radiation-hardened central processor with PowerPC 750 architecture: a BAE RAD 750. This processor operates at up to 200 megahertz speed, compared with 20 megahertz speed of the single RAD6000 central processor in each of the Mars rovers Spirit and Opportunity. Each of Curiosity's redundant computers has 2 gigabytes of flash memory (about eight times as much as Spirit or Opportunity), 256 megabytes of dynamic random access memory and 256 kilobytes of electrically erasable programmable read-only memory.

The Mars Science Laboratory flight software monitors the status and health of the spacecraft during all phases of the mission, checks for the presence of commands to execute, performs communication functions and controls spacecraft activities.

**Rover Navigation**

Two sets of engineering cameras on the rover — Navigation cameras (Navcams) up high and Hazard-avoidance cameras (Hazcams) down low — will inform operational decisions both by Curiosity's onboard autonomy software and by the rover team on Earth. Information from these cameras is used for autonomous navigation, engineers' calculations for maneuvering the robotic arm and scientists' decisions about pointing the remote-sensing science instruments.

Curiosity's Navcams and Hazcams generate grayscale images that cover red wavelengths centered at about 650 nanometers. The cameras themselves are virtually identical to the engineering cameras on Spirit and Opportunity, though Curiosity has redundant cameras and slightly more powerful heaters for the cameras. Curiosity has a total of 12 engineering cameras, each weighing about 9 ounces (250 grams).

Curiosity's Navcams, paired for stereo imaging, are installed next to the science payload's Mast Camera on the remote-sensing mast. Curiosity carries two stereo pairs of navigation cameras, one pair each connected to the rover's two redundant computers. The navigation cameras that are controlled by and feed imagery to the "A" computer are mounted directly above the navigation cameras linked to the "B" computer. That puts the

"A" pair about 6.5 feet (1.99 meters) above the ground when the rover is on hard, flat terrain and the cameras are pointed straight out (slightly lower when pointed downward), and the other pair 2 inches (5 centimeters) lower. The left and right navigation cameras in each pair are about 16.5 inches (42 centimeters) apart, giving them approximately twice as long a stereo baseline as the separation distance of navigation cameras on Spirit and Opportunity.

Each of the Navcams captures a square field of view 45 degrees wide and tall, comparable to the field of view of a 37-millimeter-focal-length lens on a 35-millimeter, single lens reflex camera. The lens focuses the image onto a 1,024-pixel-by-1,024-pixel area of a charge-coupled device (CCD) detector. This yields a resolution of 0.82 milliradians per pixel — for example, 0.8 inch (2 centimeters) per pixel at a distance of 82 feet (25 meters), enough to resolve a golf ball at that distance as a circle about two Navcam pixels wide. The depth of field achieved by the fixed-aperture f/12 Navcams keeps anything in focus from a distance of about 20 inches (0.5 meter) to infinity.

Curiosity has four pairs of Hazcams: two redundant pairs on the front of the chassis and two redundant pairs on the rear. The rover can drive backwards as well as forward, so both the front and rear Hazcams can be used for detecting potential obstacles in the rover's driving direction. The front Hazcams also provide three-dimensional information for planning motions of the rover's robotic arm, such as positioning of the drill or scoop for collecting samples.

Each Hazcam has a fisheye lens providing a square field of view 124 degrees wide and tall. The depth of field in focus spans from about 4 inches (10 centimeters) to infinity. Resolution of the Hazcams is 2.1 milliradians per pixel on the same type of detector as in the Navcams. At a distance of 33 feet (10 meters), the Hazcam resolution is 0.8 inch (2 centimeters) per pixel. A golf ball at that distance would be approximately two Hazcam pixels across.

The redundant pairs of Hazcams are mounted side by side. On the front, each stereo pair has a baseline of 6.54 inches (16.6 centimeters) between the center of its left eye and center of its right eye. Both the pair linked to the rover's "A" computer and the pair linked to the "B" computer are mounted near the bottom center of the front face of the chassis, about 27 inches (68 centimeters) above ground level. The rear stereo pairs each have a baseline of 3.9 inches (10 centimeters), the same as for both the front and rear hazard-identification cameras on Spirit and Opportunity. The rear "A" pair on Curiosity is toward the port side of the rear face of the vehicle (on the left if a viewer were standing behind the rover and looking toward it). The rear "B" pair is on the right, or toward starboard. Both pairs are about 31 inches (78 centimeters) above ground level.

The hazard-avoidance cameras have one-time-removable lens covers to shield them from potential dust raised during the rover's landing. Pyrotechnic devices will remove the lens caps after landing. The navigation cameras gain protection from the stowed position of the remote-sensing mast during the landing; they do not have lens covers.

Different navigation modes for rover drives use images from the engineering cameras in different ways. Techniques include "blind" driving, hazard avoidance and visual odometry. The set of commands developed by rover planners for a single day's drive may include a combination of these modes.

When using the blind-drive mode, rover planners have sufficient local imaging from the engineering cameras or Mast Camera to determine that a safe path exists, free of obstacles or hazards. They command the rover to drive a certain distance in a certain direction. In a blind drive, the rover's computer calculates distance solely from wheel rotation; one full turn of a wheel with no slippage is nearly 25 inches (63 centimeters) of driving. It does not check imagery from the engineering cameras to assess the slippage.

When the rover planners cannot determine that a path is free of obstacles, they can command driving that uses hazard avoidance. Besides using this hazard avoidance in rougher terrain, they might use it for an additional segment of driving beyond a blind drive on the same day. Hazard avoidance requires the rover to stop frequently to acquire new stereo imaging in the drive direction with the engineering cameras and analyze the images for potential hazards. The rover makes decisions based on its analysis of the three-dimensional information provided by the stereo imaging. Rover planners set variables such as how frequently to stop and check, which cameras to use, and what type of decision the rover makes in response to a hazard detection (whether to choose a path around it or stop driving for the day).

Hazard avoidance can be supplemented with visual odometry. Visual odometry uses navigation camera images made with the cameras pointed to the side of the route being driven. By pausing at intervals during the drive to take these images, the rover can compare the before-and-after situation for each segment of the drive. It can recognize features in the images and calculate how far it has actually traveled during the intervening drive segment. Any difference between that distance and the distance indicated from wheel rotation is an indication that the wheels are slipping against the ground. In the day's set of driving commands, rover planners can set the intervals at which the rover pauses for visual-odometry checks, as suited to the type of terrain being traversed. A slip limit can be set so that if the rover calculates that it is slipping in excess of that amount, it will stop driving for the day. The mode of using visual odometry checks at intervals several times the rover's own length is called slip-check, to differentiate it from full-time visual odometry with sideways-looking stops as frequently as a fraction of the rover's length.

Navigation modes differ significantly in the fraction of time spent with wheels in motion versus stopped for imaging and analysis of the images.

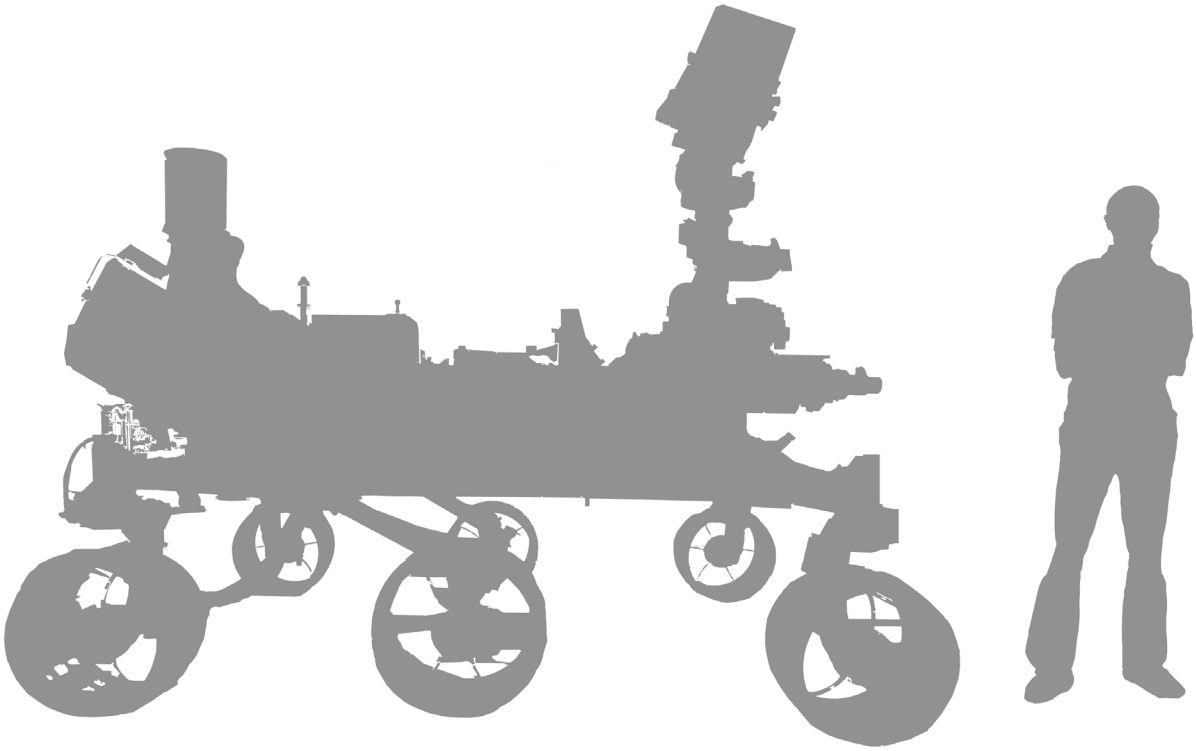
Curiosity can incorporate other safety features in each drive, such as tilt limits. The rover's inertial measurement unit, which incorporates gyroscopes, provides information about changes in tilt. This and other information about the rover's attitude, or orientation, serve in use of the arm and the science instruments, and in pointing the high-gain antenna, as well as in navigation.

**Rover Thermal**

Curiosity's thermal control system was designed to enable the rover to operate far from the equator so that the mission would have a choice of landing sites based on science criteria. In a range of Mars surface temperatures from minus 207 degrees Fahrenheit (minus 133 degrees Celsius) to 81 degrees Fahrenheit (27 degrees Celsius), the temperature-sensitive components inside the rover can be maintained between minus 40 degrees Fahrenheit (minus 40 degrees Celsius) and 122 degrees Fahrenheit (50 degrees Celsius).

The rover's heat rejection system has a pumped-fluid loop that can deliver heat from the multi-mission radioisotope thermoelectric generator when the core electronics need heating and take heat away from the core if the rover is becoming too warm. Pacific Design Technologies Inc., Goleta, Calif., built the pump.

*Rover size, compared with a 5-foot, 8-inch man*



The fluid loop runs through an avionics mounting plate inside the insulated warm electronics box of the rover chassis. The multi-mission radioisotope thermoelectric generator cools passively with its radiator fins when its heat is not needed for warming the rover. For heating needs beyond the circulation of the heat rejection system, the rover uses electrical heaters. These enable flexibility in localizing and timing for the heat they provide. For example, a secondary warm electronics box atop the remote sensing mast uses electrical heating to maintain temperatures there above allowable minimums.

**'Send Your Name to Mars' Chips**

Silicon chips mounted onto Curiosity's deck bear the names of people who participated in the "Send Your Name to Mars" program online. Each chip is about the size of a dime. More than 1.24 million names were submitted online. These names have been etched into silicon using an electron-beam machine used for fabricating microdevices at NASA's Jet Propulsion Laboratory. In addition, more than 20,000 visitors to JPL and NASA's Kennedy Space Center wrote their names on pages that have been scanned and reproduced at microscopic scale on another chip.

# Mars Science Laboratory Landing Site

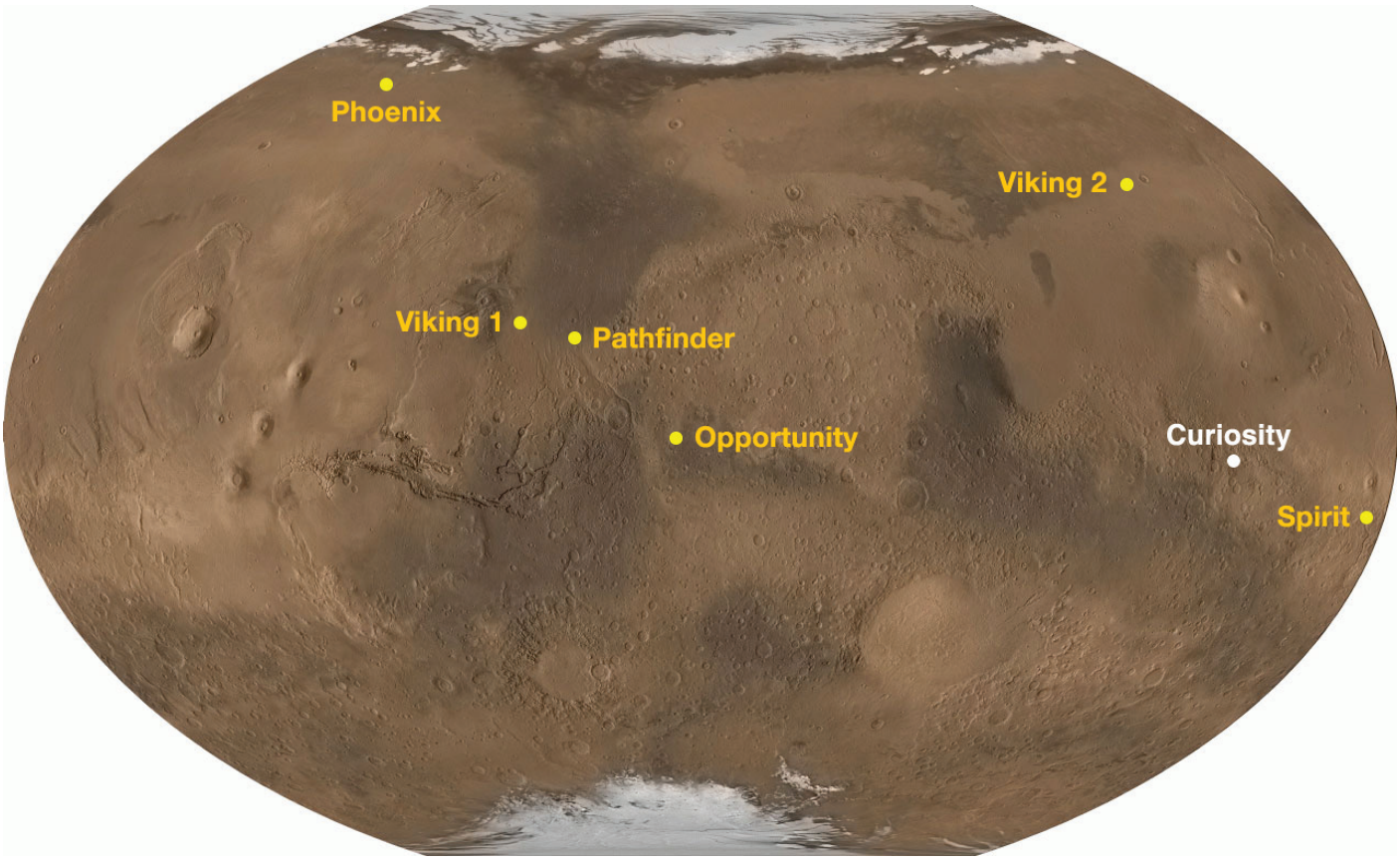
The Mars Science Laboratory mission will place the rover Curiosity at the foot of a mountain of sedimentary strata, or layers, inside Gale Crater. The landing site at 4.5 degrees south latitude, 137.4 degrees east longitude will give the rover access to a field site with science targets both on the crater floor beside the mountain and in the lower layers of the mountain.

Gale Crater spans 96 miles (154 kilometers) in diameter, giving it an area about the equivalent of Connecticut and Rhode Island combined. It holds a mound or mountain rising about 3 miles (5 kilometers) above the crater floor, which is higher than Mt. Rainier rises above Seattle. The slopes of the mountain are gentle enough for Curiosity to climb, though during the prime mission of one Martian year (98 weeks), the rover will probably not go beyond some particularly intriguing layers near the base.

Gale sits at a low elevation relative to most of the surface of Mars, suggesting that if Mars ever had much flowing water, some of it would have pooled inside Gale. Observations from orbit that add evidence of a wet history include water-related clay and sulfate minerals in the lower layers of the mound, and textures higher on the mound where it appears that mineral-saturated groundwater filled fractures and deposited minerals.

Stratification in the mound suggests it is the surviving remnant of an extensive sequence of deposits that were laid down after the impact that excavated the crater more than 3 billion years ago. A geological layer, called a stratum, is formed after the layer beneath it and before the one above it. The stack of layers that forms the mountain inside Gale offers a history book of sequential chapters recording environmental conditions when each stratum was deposited. This is the same principal of geology that makes the strata exposed in Arizona's Grand Canyon a record of environmental history on Earth. For more than 150 years, geologists on

*Locations of landing sites for Curiosity and previous Mars rovers and landers*



Earth have used stacks of strata from globally dispersed locations to piece together a record of Earth history.

In Gale, the stack of layers is much taller than the stack admired in the Grand Canyon. It is a closer match to the amount of layering exposed in Mars' Valles Marineris, the largest canyon in our solar system. Therefore, the Gale mound may offer one of the thickest continuous sequences of strata in the solar system. On Earth, the thickest sequences of strata that also contain a diversity of materials are the best records of Earth's history. Like the most complete copy of an ancient manuscript, they can be used to decode and tie together less complete records from around the globe. It is hoped that the record at Gale will be just such a key reference for deciphering Mars' global history.

Gale Crater was named in 1991 for Australian astronomer Walter F. Gale (1865-1945). The mound inside Gale, when viewed from orbit, resembles the shape of Australia.

NASA's choice of the landing site in Gale Crater in July 2011 followed a five-year process that considered about 60 sites and involved about 150 Mars scientists in a series of public workshops. Four finalist sites identified in 2008 were mapped and examined so extensively from orbit that they have become four of the best-studied places on Mars. The detail in images taken by the High Resolution Imaging Science Experiment camera on NASA's Mars Reconnaissance Orbiter, for example, reveals virtually every individual boulder big enough to spoil a landing. Mineral mapping by the Compact Reconnaissance Imaging Spectrometer on the same orbiter and the OMEGA spectrometer on the European Space Agency's Mars Express identified mineral evidence of wet histories at all four sites. All four finalist sites qualified as safe for landing, so the selection could be made based on the sites' scientific appeal.

The guided entry technology enabling the Mars Science Laboratory to land more precisely than previous Mars missions, coupled with Curiosity's driving capability, meant that, for the first time, the main science destination for a Mars mission could be outside of the area that needed to qualify as safe for landing. The mission's technologies for atmospheric entry, descent and landing give the spacecraft about a 99 percent probability of landing within an ellipse 12.4 miles (20 kilometers) by 15.5 miles (25 kilometers). That is about one-third the size of the landing ellipses for Mars rovers that landed in 2004. Curiosity was designed and built to be able to drive far enough to get outside of its landing ellipse during its prime mission.

The slopes of the mountain inside Gale Crater are too steep for the rover to land safely on the mountain. The science targets initially identified for the rover to investigate are in the lower layers of the mountain, requiring the rover to drive outside the landing ellipse to get to the science targets. Subsequent observations and analysis have identified additional science targets within the landing ellipse. The pace at which Curiosity gets to the features of high science interest inside and outside of the ellipse will depend on findings and decisions made after landing, including the possibility of identifying targets not yet known.

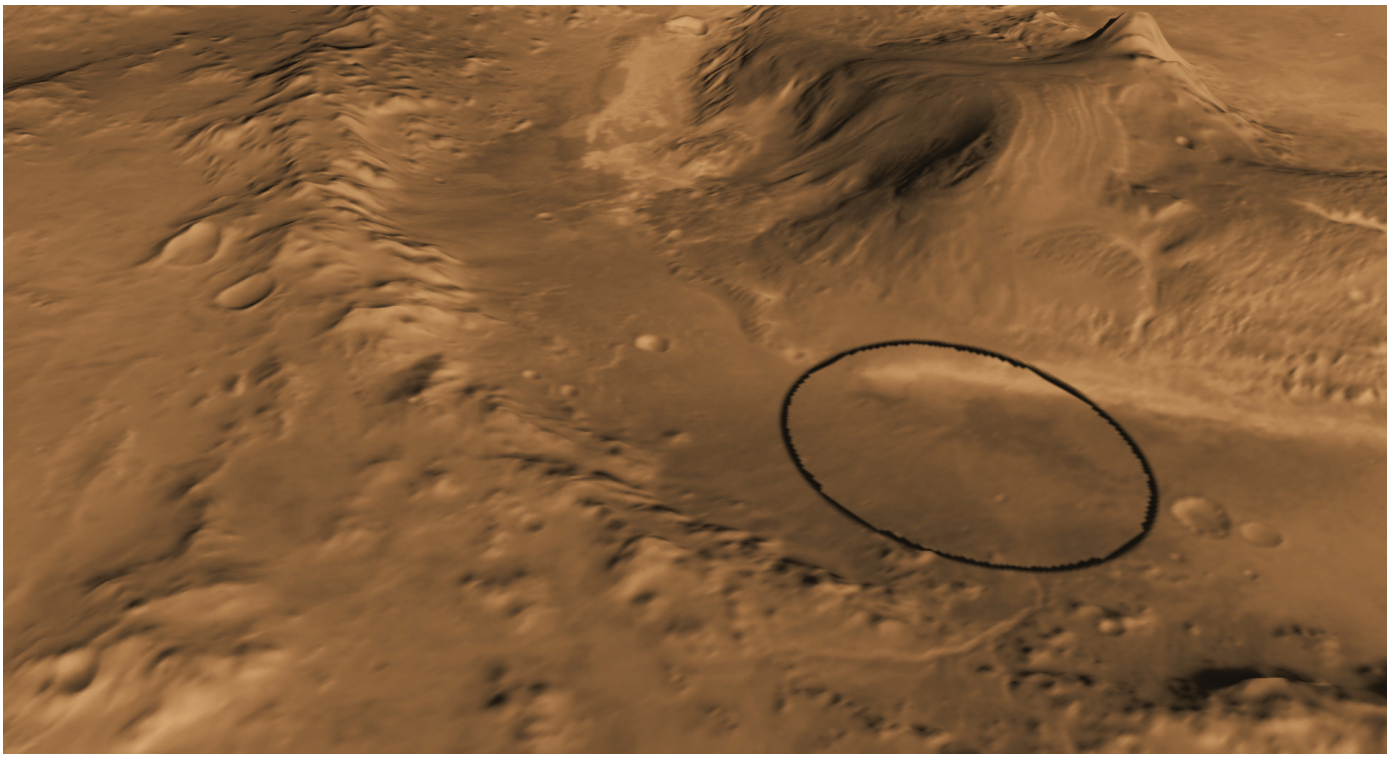
In Curiosity's field site — encompassing accessible areas inside and outside of the landing ellipse — features that make Gale appealing to the science team include:

- An alluvial fan extending into the landing ellipse from the crater wall to the north holds material shed from the crater wall and likely carried by water.

- Down slope, southward, from the alluvial fan lies an exposure of hard, light-toned rock. The mineral composition of this area is unidentified so far. Curiosity could investigate a hypothesis that this exposure is sedimentary rock formed in interaction with water, such as salts left by the drying of a lake. Some relatively fresh, small craters in this part of the crater floor may provide access to material that has not experienced long exposure to the radiation environment affecting chemistry at the Martian surface.

- Among the exposures in the lower portion of Gale's inner mountain are packages of strata that contain clay minerals, strata that contain sulfate salts and strata that contain both. Clays and sulfates both result from wet environments. The differences in mineral composition from one package of strata to the next can provide information about changes in environments that may have been favorable for microbial life.

- Curiosity's analysis of the exposed minerals will provide confirmation of orbiter-based predictions for the distribution and abundance of similar minerals to be present over vast parts of Mars. In this regard, Curiosity will provide important ground truth of hypotheses generated by previous missions.



*Oblique view of Curiosity's landing area and surrounding terrain at Gale Crater, looking toward the southeast*

- The sulfate salts retain trace amounts of water in their mineral structure. Curiosity can monitor how some of that water is released into the atmosphere during warmer hours of the day and reabsorbed by the salts during colder hours. These measurements would provide information about the modern water cycle on Mars.

- Canyons cut into the northern flank of the mountain resulted from flow of water long after the lower layers of the mountain had accumulated. The canyon-cutting environment could have been a separate habitable environment from the environment at the time the clay-containing and sulfate-containing layers formed. Analysis of material deposited at the mouths of the canyons could provide information about that later environment.

- Extensive networks of fractures in the upper parts of the sulfate-bearing strata are filled with minerals that betray circulation of groundwater. These fracture networks would represent yet a different, subsurface habitable environment. The presence of minerals lining these fractures indicates where Curiosity might conduct analyses to look for organic compounds.

One important capability of Curiosity's science payload is to check for the presence of ingredients for life, including the carbon-based building blocks of biology called organic compounds. Long-term preservation of organic compounds requires special conditions.

Clays and sulfate-rich deposits such as the ones Curiosity will investigate in Gale Crater can be good at latching onto organic chemicals and protecting them from oxidation. Another factor in long-term preservation of organics on Mars is protection from natural radiation that is more intense than what reaches Earth's surface. Radiation may gradually destroy organics inside rocks at the surface, but Gale also offers rocks exposed by relatively recent small-crater impacts.

Gale offers these attractive targets at which to check for organic compounds. Finding organics is still a long shot, but this chosen field site also offers records of multiple periods in Mars history, grist for the mission's investigation of environmental changes on Mars, with strong prospects for identifying habitable environments.

Should Curiosity continue to be in working condition following the prime mission, an extended mission could continue the investigation by exploring higher, younger layers of Gale's mountain.

# Recent, Current and Upcoming Missions

Building on scientific discoveries and lessons from past and ongoing missions, NASA's Mars Exploration Program is working to establish a sustained observational presence at Mars. This includes orbiters that view the planet from above and act as telecommunications relays, surface-based mobile laboratories, robots that probe below the planet's surface, and, ultimately, missions that return soil and rock samples to Earth and prepare for human landing.

With international cooperation, the long-term program is guided by compelling questions about Mars and developing technologies to make missions possible with available resources. The program's strategy is to seek to uncover profound insights into Mars' past and present environments, the roles and abundance of water, and the potential for past or present habitats suitable for the existence of life.

The following are the most recently completed, ongoing and near-term future Mars missions of exploration by NASA and its international partners:

**Mars Pathfinder** *(December 1996 – March 1998):* The first completed mission in NASA's Discovery Program of low-cost planetary missions with highly focused scientific goals, Mars Pathfinder set ambitious objectives and surpassed them. This lander released its Sojourner rover on the Martian surface and returned 2.3 billion bits of information from instruments on the lander and the rover. The information included more than 17,000 images, more than 15 chemical analyses of rocks and soil, and extensive data on winds and other aspects of weather. The observations suggest that early Mars may have been more Earth-like with liquid water on its surface and a thicker atmosphere than it has today. The mission functioned on the Martian surface for about three months, well beyond the planned lifetimes of 30 days for the lander and seven days for the rover.

**Mars Global Surveyor** ***(November 1996 – November 2006):*** During its primary mapping mission from March 1999 through January 2001, NASA's Mars Global Surveyor collected more information than any previous Mars project. The orbiter continued to examine Mars' surface and monitor its global weather patterns through three mission extensions, successfully operating longer than any previous spacecraft sent to Mars. It had begun a fourth extension and was five days shy of the 10th anniversary of its launch when it last communicated with Earth. Mars Global Surveyor returned more than 240,000 camera images, 206 million spectrometer measurements and 671 million laser-altimeter shots. Some of the mission's most significant findings include: discovering extensive layering of the planet's crust; discovering ancient deltas; discovering channels, a few of which exhibit modern activity suggesting modern liquid water; identifying concentrations of a mineral that often forms under wet conditions, leading to selection of one large deposit as the landing area for NASA's Mars Exploration Rover Opportunity; laser-altimeter observations producing a nearly global map of the planet's topography, quantifying altitudes and slopes, and characterizing myriad craters, including many eroded or buried craters too subtle for previous observation; compiling extensive evidence for the role of dust in reshaping the recent Martian environment; and detecting localized remnant magnetic fields, proof that Mars once had a global magnetic field like Earth's, shielding the surface from deadly cosmic rays and slowing loss of volatiles to space. This orbiter provided details used to evaluate the risks and attractions of potential landing sites for the Phoenix Mars Lander and the two Mars Exploration Rovers. It also served as a communications relay for the Mars Exploration Rovers during and after their landings.

**Mars Odyssey** ***(April 2001 – present):*** This NASA orbiter's prime mapping mission began in March 2002. Its suite of gamma-ray spectrometer instruments soon provided strong evidence for large quantities of frozen water mixed into the top layer of soil in the 20 percent of the planet near its north and south poles. Subsequently, a site in this permafrost terrain became the destination for the Phoenix Mars Lander. Odyssey's camera system, which examines the planet in both visible-light and infrared wavelengths, has identified minerals in rocks and soils and has compiled the highest-resolution global map of Mars. Nighttime infrared imaging provides information about how quickly or slowly surface features cool off after sunset, which gives an indication of where the surface is rocky and where it is dusty. Odyssey's instruments have monitored the Mars atmosphere for more than a decade, including the tracking of non-condensable gases such as argon as tracers of atmospheric transport. Odyssey has also monitored high-energy radiation at orbital altitudes to help characterize the en-

vironment that future missions, including possible human ones, will experience. Odyssey's observations helped evaluate potential landing sites for the Mars Exploration Rovers, Phoenix and Curiosity. Relays via this orbiter have been the main way for the rovers and Phoenix to send information to Earth; more than 95 percent of rover data has been returned via this communications workhorse. Odyssey is now the longest working spacecraft ever sent to Mars. It will continue to map the planet while providing relay support for Curiosity

**Mars Exploration Rover Spirit** ***(June 2003 – March 2010):*** The first of NASA's twin Mars Exploration Rovers to land on Mars, Spirit was a mobile robotic field geologist sent to examine clues about the planet's environmental history — particularly the history of water — at a carefully selected site. Each rover's mission was planned to run for three months on Mars, but each rover worked for years. Spirit explored inside Gusev Crater, a highly eroded crater 95 miles (150 kilometers) in diameter. Orbital images suggested Gusev may have once held a lake fed by inflow from a large valley network funneling into the crater from highlands to the south. Spirit landed Jan. 4, 2004, on a flat volcanic flood-plain pocked with small craters and strewn with loose rocks. There, the rover found basaltic rocks only slightly altered by exposure to moisture. By June 2004, well into its first extended mission, Spirit had driven to a range named the Columbia Hills, about 1.6 miles (2.6 kilometers) from the landing site, in a quest to find exposed bedrock. Exploring in the hills, Spirit discovered a profusion of rocks and soils bearing evidence of extensive exposure to water, including the iron-oxide-hydroxide mineral goethite and hydrated sulfate salts. It found an outcrop rich in carbonate, evidence for wet conditions that were not acidic. Textures and compositions of materials at a low plateau between hills indicated an early era on Mars when water and hot rocks interacted in explosive volcanism. By driving with one immobile wheel whose motor had worn out after three years on Mars, Spirit serendipitously plowed up a hidden deposit of nearly pure silica. This discovery indicates that the site once had hot springs or steam vents, which are environments that, on Earth, teem with microbial life. In June 2009, Spirit became embedded in a patch of fine-grained material and was unable to extract itself after a second wheel stopped working. Prevented from parking itself in a position favorable for its solar array to generate energy, Spirit was apparently unable to survive the long southern winter, as no further communications were received.

**Mars Exploration Rover Opportunity** ***(July 2003 - present):*** This rover was sent to a flat region named Meridiani Planum, where the spectrometer on Mars Global Surveyor had discovered a large exposure of the mineral hematite — which often forms in the presence of water. On Jan. 25, 2004, Opportunity landed inside a crater only 72 feet (22 meters) in diameter and immediately saw exposed bedrock in the crater's inner slope. During the next few weeks, the rover's examination of that outcrop settled the long-running debate about whether Mars ever had sustained liquid water on its surface. Composition and textures showed that the rocks not only had been saturated with water, but had actually been laid down under gently flowing surface water. For six months beginning in June 2004, Opportunity examined deeper layers of rock inside a stadium-size crater, Endurance, about half a mile (700 meters) from the landing site. The wall-rock layers had all soaked in water, but textures in some showed that periods of dry, wind-blown deposition alternated with periods when water covered the surface. After examining its own jettisoned heat shield and a nickel-iron meteorite near this crater, Opportunity drove more than 4 miles (6 kilometers) southward to reach an even larger and deeper crater, Victoria. Here, it examined geological evidence of similar environmental conditions from a greater span of time. The presence of sulfur-rich material throughout Opportunity's study area indicates acidic watery environments. In mid-2008, Opportunity set off toward a crater 14 miles (22 kilometers) in diameter, Endeavour, where orbital observations have detected water-related clay minerals, different from any Opportunity has seen so far and indicative of less-acidic watery environments. In August 2011, with a total driving odometry of more than 21 miles (34 kilometers), the rover reached the rim of Endeavour Crater to start a new phase of its exploration of Mars, demonstrating once more the value of mobility and longevity.

**Mars Express** ***(June 2003 – present):*** This is a European Space Agency orbiter with NASA participation in two of its seven investigations: a ground-penetrating radar, and a tool for studying how the solar wind removes water vapor from Mars' outer atmosphere. The spacecraft has been returning color stereo images and other data since January 2004 after entering orbit in late December 2003. Its spectrometer for visible and near-infrared wavelengths found deposits of clay minerals indicating a long-ago wet environment that was less acidic than the one that produced the minerals studied by Opportunity. Scientists working with this and similar data from the Mars Reconnaissance Orbiter

have proposed a sequence of globally distributed water environments very early in Mars' history, moving from less to more acidic environments. Meanwhile, scientists working with data from a thermal infrared spectrometer found indications of methane in Mars' atmosphere by averaging millions of spectra to improve signal-to-noise ratio. Scientists presently believe that this gas would break down too rapidly to be detectable unless there is an active source, either biological or non-biological, maintaining its concentration in the atmosphere. These discoveries have important implications for the habitability of Mars, past and present. Since deployment of the radar antenna in June 2005, the spacecraft has examined ice-rich layered deposits covering the polar regions.

**Mars Reconnaissance Orbiter** ***(August 2005 – present):*** This multipurpose spacecraft is examining the surface, subsurface and atmosphere of Mars in unprecedented detail. It began its primary science investigations in November 2006, following 426 carefully planned dips into the top of Mars' atmosphere to adjust the size and shape of its orbit after arriving at Mars in March 2006. Specifically engineered to return the vast volumes of data generated by the high spatial resolution of its imaging cameras and spectrometer, the orbiter has returned more than three times as much data as the combined total from all other space missions that have traveled farther than the moon. NASA's Deep Space Network antennas received more than 130 terabytes of data — including more than 70,000 images — from the six science instruments on Mars Reconnaissance Orbiter during the mission's first five years at Mars. The mission has illuminated three very different periods of Mars' history. Its observations show that different types of watery environments formed extensive deposits of water-related minerals — including clays, sulfates and carbonates — across the planet early in Mars' history. In more recent times, water appears to have cycled as a gas between polar ice deposits and lower-latitude deposits of ice and snow. Radar observations reveal internal, episodic patterns of layering probably connected to cyclical variations in the tilt of the planet's rotation axis and the elliptical nature of its orbit. These cycles modulate the solar heating of the poles to a much larger degree than occurs for Earth, with its ice ages, over periods of thousands to a few million years. Radar has also revealed a thick deposit of carbon-dioxide ice buried in the south polar cap, which, if released into the atmosphere, would nearly double the amount of gas in the atmosphere today. With observations of new craters, avalanches and dust storms occurring even now, the orbiter has shown that modern Mars is still a dynamic world. The orbiter's observations have identified sites with high potential for future scientific discovery. In addition, the orbiter's high-resolution cameras can reveal hazards to landing and roving spacecraft, such as rocks and steep slopes, while its atmospheric monitors characterize the environment that can be encountered during landing and operations on the surface. Observations by the Mars Reconnaissance Orbiter enabled the Phoenix mission to choose a landing site less rocky than one previously considered. The orbiter has examined potential landing sites for Mars Science Laboratory and will serve as a relay asset during the landing and surface operations of Curiosity.

**Phoenix Mars Lander** ***(August 2007 – November 2008):*** In 2001, NASA announced a new program of competitively proposed and selected missions to Mars: Mars Scout missions. The Phoenix Mars Lander proposal, submitted by a team led by Peter Smith of the University of Arizona, Tucson, was selected out of 25 proposals in 2003 to be the one developed for launch in 2007. The mission sent a stationary lander with a robotic digging arm and suite of science instruments to study the summer environment in a far-northern zone. Phoenix confirmed and examined deposits of underground water ice detected from orbit by Mars Odyssey. It identified a mineral called calcium carbonate that suggested occasional presence of thawed water. The lander also found soil chemistry with significant implications for life and observed falling snow. The mission's biggest surprise was the discovery of perchlorate, an oxidizing chemical on Earth that is food for some microbes and potentially toxic for others, and which can lower the freezing point of liquid water by tens of degrees. It completed its planned three months of operation on Mars and worked two extra months before the anticipated seasonal decline in solar energy at its high latitude ended the mission.

**Mars Atmosphere and Volatile Evolution Mission, or MAVEN** *(for launch in 2013):* The second Mars Scout mission, selected from 26 competitive proposals in 2007, will explore the planet's upper atmosphere, ionosphere and interactions with the sun and solar wind. Various evidence suggests that Mars was a wetter planet early in its history. Where has that water gone? Scientists will use MAVEN data to determine the role that loss of volatile compounds, such as carbon dioxide and water, from the Mars atmosphere to space has played through time, giving insight into the history of Mars' atmosphere and climate, liquid water, and planetary habitability. The principal investigator is Bruce Jakosky, University of Colorado, Boulder.

**ExoMars Trace Gas Orbiter** ***(for launch in 2016):*** NASA and the European Space Agency (ESA) have embarked on a joint program to explore Mars. The ExoMars Trace Gas Orbiter will be the first in a series of planned joint robotic missions. It will study the chemical makeup of the Martian atmosphere with a 1,000-fold increase in sensitivity over previous Mars orbiters. The mission will focus on trace gases, including methane, which could be potentially geochemical or biological in origin and be indicators for the existence of life on Mars today. The mission also will serve as an additional communications relay for Mars surface missions beginning in 2018. NASA and ESA selected five science investigations for ExoMars Trace Gas Orbiter in 2010. The mission will also carry a European-built small lander demonstrator.

**InSight** ***(in consideration for launch in 2016):*** One of three competing proposals selected as finalists for a 2016 launch as part of NASA's Discovery Program would study Mars. If chosen to fly, the proposed mission would investigate the structure and composition of the interior of Mars and advance understanding of the formation and evolution of rocky planets. It would carry a seismometer and a subsurface thermal probe, and it would use radio tracking of tiny variations in Mars' motions to provide information about the planet's core. The principal investigator is Bruce Banerdt at JPL.

**Beyond 2016:** NASA is collaborating with the European Space Agency to gain further understanding of Mars, including whether Mars has supported life. This international partnership is in the early stages of creating a joint rover mission that would access and analyze subsurface materials, and characterize and prepare samples for possible analysis by Earth-based laboratories. Concepts for a program to return samples from Mars to Earth envision a campaign of multiple missions performing different steps in that challenge.

# Mars Science: A Story of Changes

As the world in 1965 eagerly awaited results of the first spacecraft flyby of Mars, everything we knew about the Red Planet was based on what sparse details could be gleaned by peering at it from telescopes on Earth. Since the early 1900s, popular culture had been enlivened by the notion of a habitable neighboring world crisscrossed by canals and, possibly, inhabited by advanced life forms that might have built them — whether friendly or not. Astronomers were highly skeptical about the canals, which looked more dubious the closer they looked. About the only hard information they had on Mars was that they could see it had seasons with ice caps that waxed and waned, along with seasonally changing surface markings. By breaking down the light from Mars into colors, they learned that its atmosphere was thin and dominated by an unbreathable gas, carbon dioxide.

The past four decades have revolutionized that view. First, hopes of a lush, Earth-like world were deflated when Mariner 4's flyby on July 15, 1965, revealed large impact craters, like craters that cover Earth's barren, lifeless moon. Those holding out for Martians were further discouraged when NASA's two Viking landers were sent to the surface in 1976 equipped with a suite of chemistry experiments that turned up no conclusive sign of biological activity. Mars as we came to know it was cold, nearly airless and bombarded by hostile radiation from both the sun and from deep space.

Since then, however, new possibilities of a more hospitable Martian past have emerged. Mars is a much more complex body than Earth's moon. Scientists scrutinizing pictures from the orbiters of the 1970s detected surface features potentially shaped by liquid water, perhaps even the shoreline of an ancient ocean. Eight successful Mars missions since the mid-1990s have advanced the story. Accumulated evidence shows that the surface of Mars appears to be shaped by flowing water in hundreds of places; that some Mars rocks formed in water; that significant amounts of water as ice and in hydrated minerals still make up a fraction of the top surface layer of Mars in many areas; and that water may, even today, occasionally emerge from the ground to flow briefly before freezing or evaporating.

Although it appears unlikely that complex organisms similar to advanced life on Earth could have existed on Mars' comparatively hostile surface, scientists are intrigued by the possibility that life in some form — perhaps very simple microbes — may have gained a foothold in ancient times when Mars was wetter, if not warmer. It is not unthinkable that life in some form could persist today in underground springs warmed by heat vents around smoldering volcanoes, or even beneath the thick ice caps. To investigate those possibilities, NASA's productive strategy has been to learn more about the history of water on Mars: How much was there? How long did it last? Where are formerly wet environments that make the best destinations for seeking evidence of past life? Where might there be wet environments capable of sustaining life today?

The consensus strategy for answering those questions uses a balance of examining selected sites in great detail while also conducting planet-wide surveys to provide context for interpreting the selected sites. This enables researchers to extrapolate from the intensively investigated sites to regional and global patterns, and to identify which specific sites make the best candidates for targeted examination.

One way this balance works is in the combination punch of orbital and surface missions. Mineral mapping by NASA's orbiting Mars Global Surveyor identified a hematite deposit that made Meridiani Planum the selected landing site for NASA's Mars Exploration Rover Opportunity. The hematite suggested a possible water history. Opportunity's examination of the composition and fine structure of rocks where it landed confirmed that the site had had surface and underground water, and added details about the acidity of the water and the alternation of wet and dry periods at the site. Meanwhile, halfway around the planet at Gusev Crater, the Spirit rover found evidence of materials altered in an ancient hydrothermal system. This "ground truthing" by the rover improves interpretation of current orbiters' observations of the surrounding region. Conversely, orbiters' observations add context for understanding how the environment that landing-site rocks reveal about a particular place and time fits into a broader history.

Similarly, the Phoenix Mars Lander investigated a site with intriguing characteristics discovered from orbit. Spectrometers on NASA's Mars Odyssey orbiter found evidence of copious water ice within the top 3 feet (1 meter) of the surface in high-latitude and some mid-

latitude regions. Phoenix landed at a far-northern site and confirmed the presence of plentiful water ice just beneath the surface. In the soil above the ice, Phoenix found a chemical called perchlorate, which could serve as an energy source for microbes and as a potent anti-freeze enabling water to be liquid at low temperature.

As another example of the synergy among Mars spacecraft, NASA's Mars Reconnaissance Orbiter, which reached Mars in 2006, found a less rocky, safer landing site for Phoenix. The orbiter also examined more than 30 potential landing sites for the Mars Science Laboratory. Four finalist sites were examined in thorough detail to identify specific mineral deposits of interest and potential landing hazards down to the scale of individual rocks before Gale Crater was chosen as the landing site.

The Mars Science Laboratory is NASA's first astrobiology mission to Mars since the Viking landers. One goal of NASA's Astrobiology Program is to determine the history of any environment having liquid water, other chemical ingredients of life, and energy sources that might have sustained living systems. Astrobiology's investment in Mars exploration is geared toward identifying, categorizing and understanding locations on Mars that may have once supported habitable environments. This includes developing tools and techniques for identifying mineralogical and physical signs of liquid water, biosignatures and chemical evidence of ancient habitats.

**Myths and Reality**

Mars caught public fancy in the late 1870s, when Italian astronomer Giovanni Schiaparelli reported using a telescope to observe "canali," or channels, on Mars. A possible mistranslation of this word as "canals" may have fired the imagination of Percival Lowell, an American businessman with an interest in astronomy. Lowell founded an observatory in Arizona, where his observations of Mars convinced him that the canals were dug by intelligent beings — a view that he energetically promoted for many years.

By the turn of the last century, popular songs envisioned sending messages between worlds by way of huge signal mirrors. On the dark side, H.G. Wells' 1898 novel "The War of the Worlds" portrayed an invasion of Earth by technologically superior Martians desperate for water. In the early 1900s novelist Edgar Rice Burroughs, known for the "Tarzan" series, also entertained young readers with tales of adventures among the exotic inhabitants of Mars, which he called Barsoom.

Fact began to turn against such imaginings when the first robotic spacecraft were sent to Mars in the 1960s. Pictures from the 1965 flyby of Mariner 4 and the 1969 flybys of Mariner 6 and 7 showed a desolate world, pocked with impact craters similar to those seen on Earth's moon. Mariner 9 arrived in 1971 to orbit Mars for the first time, but showed up just after an enormous dust storm had engulfed the entire planet. When the storm died down, Mariner 9 revealed a world that, while partly crater-pocked like Earth's moon, was much more geologically complex, complete with gigantic canyons, volcanoes, dune fields and polar ice caps. This first wave of Mars exploration culminated in the Viking mission, which sent two orbiters and two landers to the planet in 1975. The landers carried a suite of experiments that conducted chemical tests to detect life. Most scientists interpreted the results of these tests as negative, deflating hopes of identifying another world where life might be or have been widespread. However, Viking left a huge legacy of information about Mars that fed a hungry science community for two decades.

The science community had many other reasons for being interested in Mars, apart from the direct search for life. The next mission on the drawing boards concentrated on a study of the planet's geology and climate using advanced orbital reconnaissance. Over the next 20 years, however, new findings in laboratories and in extreme environments on Earth came to change the way that scientists thought about life and Mars.

One was the 1996 announcement by a team from Stanford University and NASA's Johnson Space Center that a meteorite believed to have originated on Mars contained what might be the fossils of ancient bacteria. This rock and other Mars meteorites discovered on several continents on Earth appear to have been blasted off Mars by asteroid or comet impacts. The evidence that they are from Mars comes from gases trapped in them that unmistakably match the composition of Mars' atmosphere as measured by the Viking landers. Many scientists have questioned the conclusions of the team announcing the discovery of possible life in one Martian meteorite, but if nothing else, the mere presence of organic compounds in the meteorites increases the odds of life forming at an earlier time on a wetter Mars. The debate has also focused attention on what types of experiments would be most useful for assessing

whether an extraterrestrial site or sample has ever held anything alive.

Another development shaping ideas about extraterrestrial life was a string of spectacular findings on how and where life thrives on Earth. The fundamental requirements for life as we know it today are liquid water, organic compounds and an energy source for synthesizing complex organic molecules. In recent years, it has become increasingly clear that life can thrive in settings much harsher than what we as humans can experience.

In the 1980s and 1990s, biologists found that microbial life has an amazing flexibility for surviving in extreme environments — niches that by turn are extraordinarily hot, or cold, or dry, or under immense pressures — that would be completely inhospitable to humans or complex animals. Some scientists even deduce that life on Earth may have begun at hot vents far under the ocean's surface.

This in turn had its effect on how scientists thought about Mars. Martian life might not be so widespread that it would be readily found at the foot of a lander spacecraft, but it may have thrived billions of years ago in an underground thermal spring or other hospitable environment. Or it might still exist in some form in niches below the currently frigid, dry, windswept surface, perhaps shielded in ice or in liquid water aquifers.

Each successful Mars mission uncovers more pages of the planet's story. After years of studying pictures from the Mariner 9 and Viking orbiters, scientists gradually came to conclude that many features they saw suggested that Mars may have been warm and wet in an earlier era.

Two decades after Viking, NASA's Mars Pathfinder observed rounded pebbles and sockets in larger rocks, suggesting conglomerates that formed in running water. Mars Global Surveyor's camera detected possible evidence for recent liquid water in many settings, including hundreds of hillside gullies. That orbiter's longevity even allowed before-and-after imaging that showed fresh gully-flow deposits in 2005 that had not been present earlier in the mission. Observations by Global Surveyor and Odyssey have also been interpreted as evidence that Mars is still adjusting from a recent ice age as part of a repeating cycle of global climate change. The cycle results from changes in the tilt of the rotational axis of Mars on time scales of hundreds of thousands to a few million years. Mars' tilt varies much more than Earth's.

NASA's Mars Exploration Rover Opportunity established that rocks in at least one part of Mars were formed under flowing surface water billions of years ago. Minerals present indicate the ancient water was very acidic. Halfway around the planet, Opportunity's twin, Spirit, found a carbonate deposit offering evidence for a wet environment that was less acidic and found a nearly pure silica deposit formed by a hot spring or steam vent. Either of those long-ago environments deduced from Spirit's observations could have been even more favorable for microbial life than the conditions that left the clues found by Opportunity.

The European Space Agency's Mars Express has identified exposures of clay minerals that probably formed in long-lasting, less-acidic wet conditions even earlier in Mars history than the conditions that produced the minerals examined by Opportunity through 2010. Mars Express and telescopic studies from Earth have found traces of atmospheric methane at Mars that might come from volcanic or biological sources. A radar instrument co-sponsored by NASA and the Italian Space Agency on the European orbiter has assessed the thickness and water content of icy layers covering Mars' south polar region, yielding an estimate that the quantity of water frozen into those icy layers is equivalent to a 36-foot-thick (11-meter-thick) coating of the whole planet.

Since 2006, NASA's Mars Reconnaissance Orbiter has radically expanded our knowledge of the Red Planet. Observing the planet at the highest spatial resolutions yet achieved from orbit, this mission has provided copious information about ancient environments, ice-age-scale climate cycles and present-day changes on Mars. It has mapped water-related mineral deposits, including multiple types of clay minerals, in hundreds of locations, and carbonates in several locales, confirming a story of alteration by water in a diversity of environments early in Martian history and a dramatic change to very acidic water in many areas after an era of more neutral conditions.

With regard to recent Mars history, the Mars Reconnaissance Orbiter has added evidence of ongoing climate-change cycles linked to how changes in the tilt of the planet's rotation axis alter intensity of sunlight near the poles. This evidence includes radar observations of episodic layering within the polar ice caps and of debris-covered ice deposits. Other observations have revealed water ice just below the surface in middle latitudes, exposed in small craters formed by fresh impacts identified in before-and-after observations. These findings and their implications for ongoing cycles of climate change

put water ice closer to the equator on modern Mars, including possibly beneath the Viking 2 Lander, than most researchers imagined a few years ago.

Orbital studies in recent years have also revealed some processes on Mars very unlike those on Earth related to temperatures low enough to freeze some of the carbon-dioxide gas out of the planet's thin atmosphere, which is mostly that gas. Carbon-dioxide ice blankets the ground around whichever pole is in winter. In the spring, sunlight penetrates the translucent ice, heating it from below. As the carbon dioxide thaws back into gas, it triggers geyser-like eruptions in some areas and fresh flows of sand on slopes in other areas.

The surface pressure of the Mars atmosphere varies over the year as the seasonal carbon-dioxide frost forms and then sublimes at each pole in turn. A major finding by the radar on Mars Reconnaissance Orbiter is a thick, hidden layer of carbon-dioxide ice deep in the water ice that forms the bulk of the south polar ice cap. This deposit may contain nearly as much carbon-dioxide as today's Martian atmosphere. This implies that the total mass of the atmosphere on Mars can change several fold on time scales of hundreds of thousands of years or less. Computer modeling indicates that during larger tilt, when summertime solar heating at the poles is more intense, most of the frozen carbon-dioxide rejoins the atmosphere, and that during smaller tilt, most of the atmosphere freezes out.

Modern Mars is a more dynamic planet today than we realized before the advent of frequent, high-resolution imaging. Hundreds of sets of before-and-after images from Mars Global Surveyor and Mars Reconnaissance Orbiter document soil flowing down gullies, rocks bouncing down hills, dunes migrating, craters forming, icy layers receding and dust blowing. Cameras in orbit have even caught avalanches and tall whirlwinds as they happen. Image sequences from Spirit show the motions of dust devils dancing across the landscape and clouds scooting across the sky. Thus, the Martian landscape, which has changed dramatically in the past, continues to change today.

**Three Ages of Mars**

Based on what they have learned from spacecraft missions, scientists view Mars as the "in-between" planet of the inner solar system. Small rocky planetary bodies such as Mercury and Earth's moon apparently did not have enough internal heat to drive the motion of tectonic plates, so their crusts grew cold and static relatively soon after they formed when the solar system condensed into planets about 4.6 billion years ago. Devoid of atmospheres, they are riddled with craters that are relics of impacts from a period of bombardment when the inner planets were sweeping up remnants of small rocky bodies that failed to "make it as planets" in the solar system's early times.

Earth and Venus, by contrast, are larger planets with substantial internal heat sources and significant atmospheres. Earth's surface is continually reshaped by tectonic plates sliding under and against each other and by materials spouting forth from active volcanoes where plates are ripped apart. Both Earth and Venus have been paved over so recently that both lack any discernible record of cratering from the era of bombardment in the early solar system.

On the basis of current yet evolving knowledge, Mars appears to stand between those sets of worlds. Like Earth and Venus, it possesses many volcanoes, although they probably did not remain active as long as counterparts on Earth and Venus. On Earth, a single "hot spot" or plume might form a chain of middling-size islands, such as the Hawaiian Islands, as a tectonic plate slowly slides over it. On Mars, there are apparently no such tectonic plates, at least as far as we know today, so when volcanoes formed in place they had the time to become much more enormous than the rapidly moving volcanoes on Earth. Overall, Mars appears to be neither as dead as Mercury and our moon, nor as active as Earth and Venus. As one scientist quips, "Mars is a warm corpse, if not a fire-breathing dragon." Thanks to the ongoing observations by current missions, however, this view of Mars is still evolving.

Mars almost resembles two different worlds that have been glued together. From latitudes around the equator to the south are ancient highlands pockmarked with craters from the solar system's early era, yet riddled with channels that attest to the flow of water. The northern third of the planet, however, overall is sunken and much smoother at mile (kilometer) scales. Analysis of subsurface densities by their gravitational effect on orbiters supports a theory that an impactor almost big enough to be a planet itself bashed Mars early in Martian history, excavating the largest crater in the solar system. If that happened, it was long-enough ago that it would not explain the smoothness of the northern plains. Theories for that range from proposing that the plains are the floor

of an ancient sea to proposing that the smoothness is merely the end product of innumerable lava flows.

Scientists today view Mars as having had three broad ages, each named for a geographic area that typifies it:

• **The Noachian Era** is the name given to the time spanning roughly the first billion years of Mars' existence after the planet was formed 4.6 billion years ago. In this era, scientists suspect that Mars was quite active with periods of warm and wet environments, erupting volcanoes and some degree of tectonic activity. The planet may have had a thicker atmosphere to support flowing water, and it may have rained and snowed.

• **In the Hesperian Era,** which lasted for about the next 500 million to 1.5 billion years, geologic activity was slowing down and near-surface water perhaps was freezing to form surface and buried ice masses. Despite plunging temperatures, water pooled underground erupted when heated by impacts in catastrophic floods that surged across vast stretches of the surface — floods so powerful that they unleashed the force of thousands of Mississippi Rivers. Eventually, water became locked up as permafrost or subsurface ice, or was partially lost into outer space.

• **The Amazonian Era** is the current age that began around 2 billion to 3 billion years ago. The planet is now a dry, desiccating environment with only a modest atmosphere in relation to Earth. In fact, the atmosphere is so thin that pure water exposed to it can be stable only as a solid or a gas, not as a liquid. The climate and perhaps the stability of water at the surface may vary on scales of thousands to millions of years as the tilt of the planet and its distance from the sun waver cyclically.

Apart from that broad outline, there is lively debate and disagreement on the details of Mars' history. How wet was the planet, and how long ago? What eventually happened to all of the water? That is all a story that is still being written.

Even if we ultimately learn that Mars never harbored life as we know it here on Earth, scientific exploration of the Red Planet can assist in understanding the history and evolution of life on our own world. Much if not all of the evidence for the origin of life here on Earth has been obliterated by the rapid pace of weathering and global tectonics that have operated over billions of years. Mars, by comparison, is a composite world with some regions that may have histories similar to Earth's ancient crust, while others are a frozen gallery of the solar system's early days.

Thus, even if life never developed on Mars — something that we cannot answer just yet —scientific exploration of the planet may yield critical information unobtainable by any other means about the pre-biotic chemistry that led to life on Earth. Mars as a fossil graveyard of the chemical conditions that fostered life on Earth is an intriguing possibility.

# Historical Mars Missions

***Mission: Country, Launch Date, Purpose, Results***

**Marsnik 1:** USSR, 10/10/60, Mars flyby, did not reach Earth orbit

**Marsnik 2:** USSR, 10/14/60, Mars flyby, did not reach Earth orbit

**Sputnik 22:** USSR, 10/24/62, Mars flyby, achieved Earth orbit only

**Mars 1:** USSR, 11/1/62, Mars flyby, radio failed at 65.9 million miles (106 million kilometers)

**Sputnik 24:** USSR, 11/4/62, Mars flyby, achieved Earth orbit only

**Mariner 3:** U.S., 11/5/64, Mars flyby, shroud failed to jettison

**Mariner 4:** U.S. 11/28/64, first successful Mars flyby 7/14/65, returned 21 photos

**Zond 2:** USSR, 11/30/64, Mars flyby, passed Mars but radio failed, returned no planetary data

**Mariner 6:** U.S., 2/24/69, Mars flyby 7/31/69, returned 75 photos

**Mariner 7:** U.S., 3/27/69, Mars flyby 8/5/69, returned 126 photos

**Mars 1969A:** USSR, 3/27/69, Mars orbiter, did not reach Earth orbit

**Mars 1969B:** USSR, 4/2/69, Mars orbiter, failed during launch

**Mariner 8:** U.S., 5/8/71, Mars orbiter, failed during launch

**Kosmos 419:** USSR, 5/10/71, Mars lander, achieved Earth orbit only

**Mars 2:** USSR, 5/19/71, Mars orbiter/lander arrived 11/27/71, no useful data, lander burned up due to steep entry

**Mars 3:** USSR, 5/28/71, Mars orbiter/lander, arrived 12/3/71, lander operated on surface for 20 seconds before failing

**Mariner 9:** U.S., 5/30/71, Mars orbiter, operated in orbit 11/13/71 to 10/27/72, returned 7,329 photos

**Mars 4:** USSR, 7/21/73, failed Mars orbiter, flew past Mars 2/10/74

**Mars 5:** USSR, 7/25/73, Mars orbiter, arrived 2/12/74, lasted a few days

**Mars 6:** USSR, 8/5/73, Mars flyby module and lander, arrived 3/12/74, lander failed due to fast impact

**Mars 7:** USSR, 8/9/73, Mars flyby module and lander, arrived 3/9/74, lander missed the planet

**Viking 1:** U.S., 8/20/75, Mars orbiter/lander, orbit 6/19/76-1980, lander 7/20/76-1982

**Viking 2:** U.S., 9/9/75, Mars orbiter/lander, orbit 8/7/76-1987, lander 9/3/76-1980; combined, the Viking orbiters and landers returned more than 50,000 photos

**Phobos 1:** USSR, 7/7/88, Mars orbiter and Phobos lander, lost 8/88 en route to Mars

**Phobos 2:** USSR, 7/12/88, Mars orbiter and Phobos lander, lost 3/89 near Phobos

**Mars Observer:** U.S., 9/25/92, Mars orbiter, lost just before Mars arrival 8/21/93

**Mars Global Surveyor:** U.S., 11/7/96, Mars orbiter, arrived 9/12/97, high-detail mapping through 1/00, third extended mission completed 9/06, last communication 11/2/06

**Mars 96:** Russia, 1/16/96, orbiter/two landers/two penetrators, launch vehicle failed

**Mars Pathfinder:** U.S., 12/4/96, Mars lander/rover, landed 7/4/97, completed prime mission and began extended mission 8/3/97, last transmission 9/27/97

**Nozomi:** Japan, 7/4/98, Mars orbiter, failed to enter orbit 12/03

**Mars Climate Orbiter:** U.S., 12/11/98, lost upon arrival 9/23/99

**Mars Polar Lander/Deep Space 2:** U.S., 1/3/99, lander/two penetrators, lost on arrival 12/3/99

**Mars Odyssey:** U.S., 3/7/01, Mars orbiter, arrived 10/24/01, completed prime mission 8/25/04, currently conducting extended mission of science and communication relay

**Mars Express/Beagle 2:** European Space Agency, 6/2/03, Mars orbiter/lander, orbiter completed prime mission 11/05, currently in extended mission; lander lost on arrival 12/25/03

**Mars Exploration Rover Spirit:** U.S., 6/10/03, Mars rover, landed 1/4/04 for three-month prime mission inside Gusev Crater, completed several extended missions, last communication 3/22/10

**Mars Exploration Rover Opportunity:** U.S., 7/7/03, Mars rover, landed 1/25/04 for three-month prime mission in Meridiani Planum region, currently conducting extended mission

**Mars Reconnaissance Orbiter:** U.S., 8/12/05, Mars orbiter, arrived 3/12/06, completed prime mission 9/26/10, currently conducting extended mission of science and communication relay

**Phoenix Mars Lander:** U.S., 8/4/07, Mars lander, landed 5/25/08, completed prime mission and began extended mission 8/26/08, last communication 11/2/08

# Program Project Management

The Mars Science Laboratory Project is managed by the Jet Propulsion Laboratory, Pasadena, Calif., for NASA's Science Mission Directorate, Washington. JPL is a division of the California Institute of Technology in Pasadena.

At NASA Headquarters, Washington, the Mars Exploration Program is managed by the Science Mission Directorate. Edward Weiler is associate administrator for the Science Mission Directorate and Charles Gay is deputy associate administrator. Douglas McCuistion is director of the Mars Exploration Program.

Michael Meyer is lead scientist for the Mars Exploration Program and program scientist for the Mars Science Laboratory. Mary Voytek is deputy program scientist for the Mars Science Laboratory. David Lavery is program executive for the Mars Science Laboratory.

At JPL, Fuk Li is Mars Program manager and Roger Gibbs is deputy manager. Richard Zurek and David Beaty are Mars chief scientists. Peter Theisinger is Mars Science Laboratory project manager and Richard Cook is deputy project manager. John Grotzinger, of Caltech, is Mars Science Laboratory project scientist, and Joy Crisp and Ashwin Vasavada are deputy project scientists.