

A Comprehensive book on
Planetary Rovers

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Chapter- 1

Planetary Rover



Two different Mars rover designs

A **rover** (or sometimes **planetary rover**) is a space exploration vehicle designed to move across the surface of a planet or other astronomical body. Some rovers have been designed to transport members of a human spaceflight crew; others have been partially or fully autonomous robots. Rovers usually arrive at the planetary surface on a lander-style spacecraft.

Comparison with space probes of other types

Rovers have several advantages over stationary landers: they examine more territory, they can be directed to interesting features, they can place themselves in sunny positions to weather winter months if they are solar powered and they can advance the knowledge

of how to perform very remote robotic vehicle control which is necessarily semi-autonomous due to the finite speed of light.

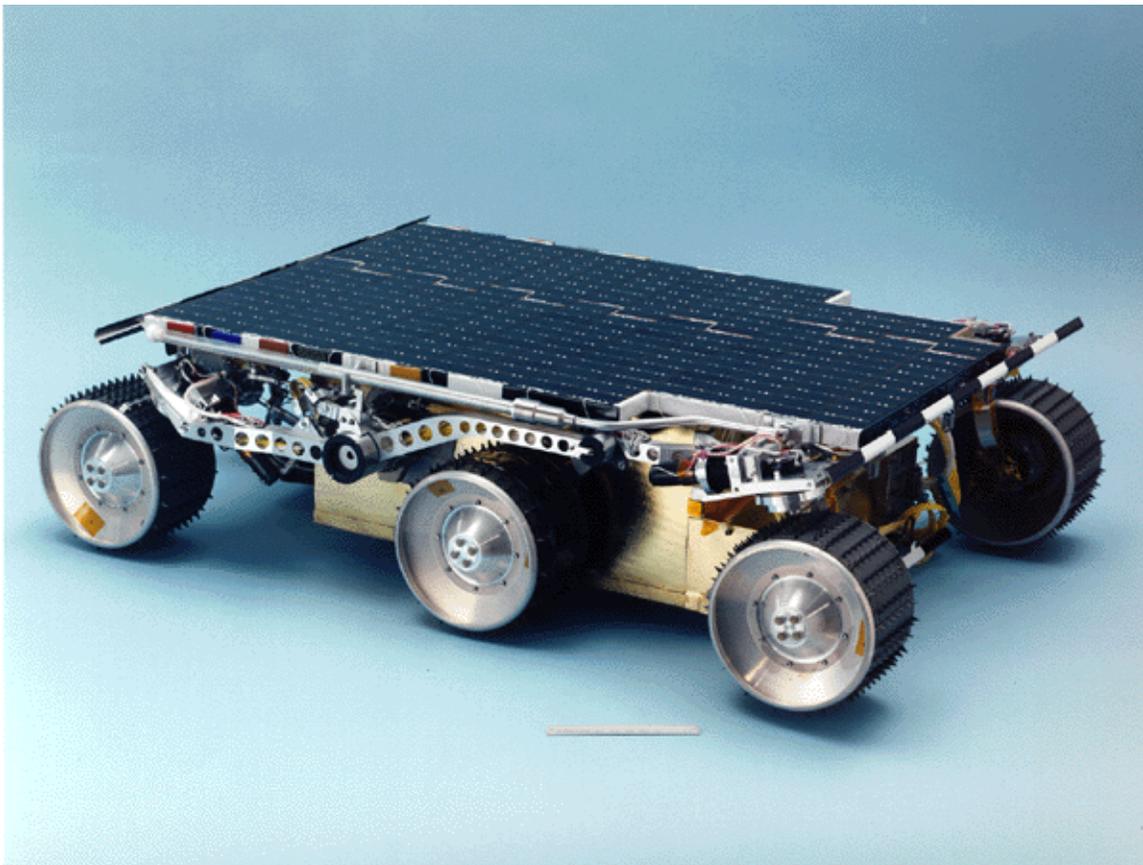
Their advantages over orbiting spacecraft are that they can make observations to a microscopic level and can conduct physical experimentation. Disadvantages of rovers compared to orbiters are the higher chance of failure, due to landing and other risks, and that they are limited to a small area around a landing site which itself is only approximately anticipated.

Features

Rovers arrive on spacecrafts and are used in conditions very distinct from those on the Earth, which makes some demands on their design.

Reliability

Rovers have to withstand high levels of acceleration, high and low temperatures, pressure, dust, corrosion, cosmic rays, remaining functional without repair for a needed period of time.



Mars rover Sojourner in cruise configuration

Compactness

Rovers are usually packed for placing in a spacecraft, because it has limited capacity, and have to be deployed. They are also attached to a spacecraft, so devices for removing these connections are installed.

Autonomy

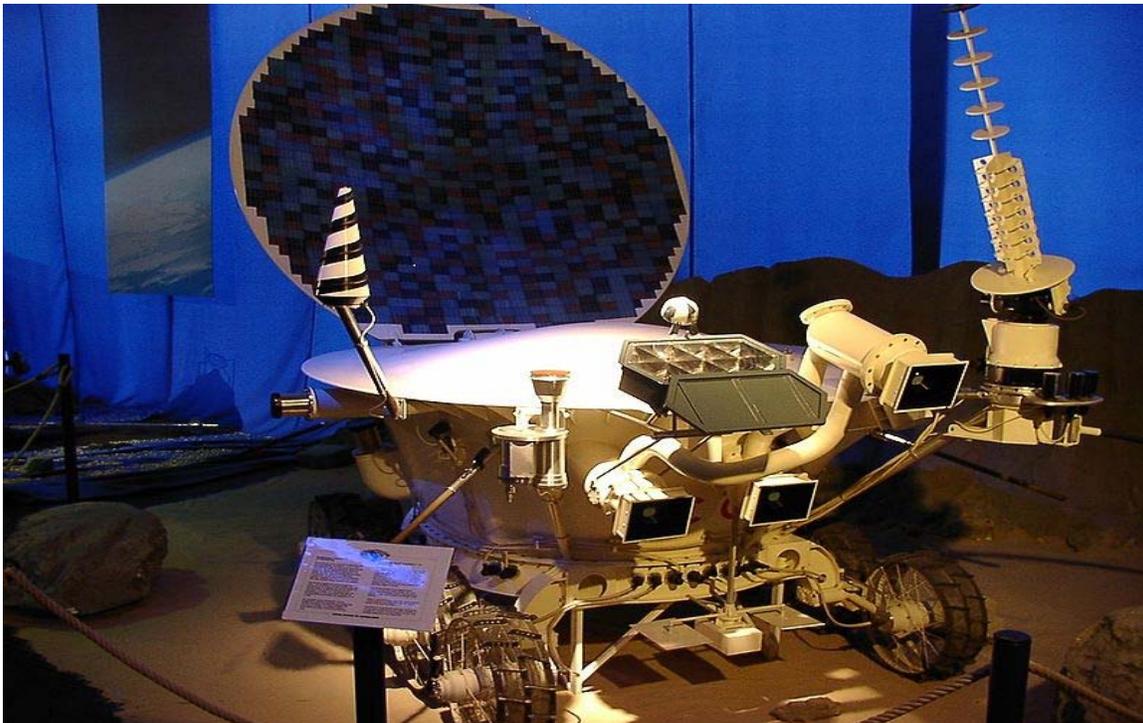
Rovers which land on celestial bodies far from the Earth, such as the Mars Exploration Rovers, cannot be remotely controlled in real-time since the speed at which radio signals travel is far too slow for *real time* or *near-real time* communication. These rovers are thus capable of operating autonomously with little assistance from ground control as far as navigation and data acquisition are concerned although they still require human input for identifying promising targets to drive to in the distance and determining how to position itself to maximize solar energy if it depends on solar panels for power.

History

Lunokhod 1A

The Soviet rover intended to be a first roving remote-controlled robot on the Moon but crashed during failed start of launcher 19 February 1969.

Lunokhod 2



The Lunokhod 2 Lunar Rover

The Lunokhod 2 was the second of two unmanned lunar rovers landed on the Moon by the Soviet Union as part of the Lunokhod program. The rover became operational on the Moon on 16 January 1973. It was the second roving remote-controlled robot to land on any celestial body. The Soviet Union launched Lunokhod 2 aboard the Luna 21 spacecraft on January 8, 1973, and it entered lunar orbit on January 12. The spacecraft soft-landed in the eastern edge of the Mare Serenitatis region on January 15. Lunokhod 2 descended from the lander's dual ramps to the lunar surface at 01:14 UT on 16 January. Lunokhod 2 operated for about 4 months, covered 37 km (23 miles) of terrain sending back 86 panoramic images and over 80,000 TV pictures. It also analyzed the lunar soil.

Lunokhod 3

The built but unlaunched Soviet rover was intended to be the third roving remote-controlled robot on the Moon in 1977. The mission was canceled due to lack of launcher availability and funding.

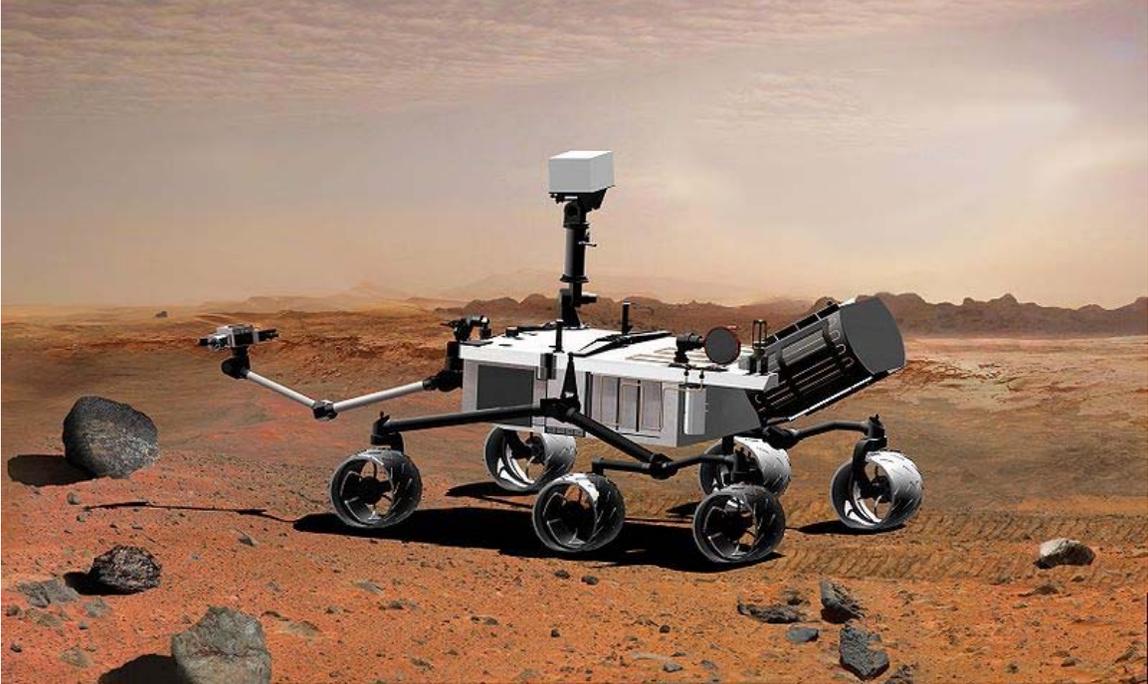
Marsokhod

The unrealised heavy Soviet remote-controlled and automatic rover for Mars by Mars 4NM project planned to be launched (after 1973 according to plans of 1970) aboard on N1 superrocket that never flew successfully.

Planned rover missions

ExoMars Rover

The European Space Agency (ESA) is currently designing and carrying out early prototyping and testing of the ExoMars Rover which is scheduled for launch in 2018.



Mars Science Laboratory

Chang'e 3

Chang'e 3 is a Chinese lunar rover scheduled for launch in 2013. It will be China's first lunar rover, part of the second phase of the Chinese Lunar Exploration Program undertaken by China National Space Administration (CNSA).

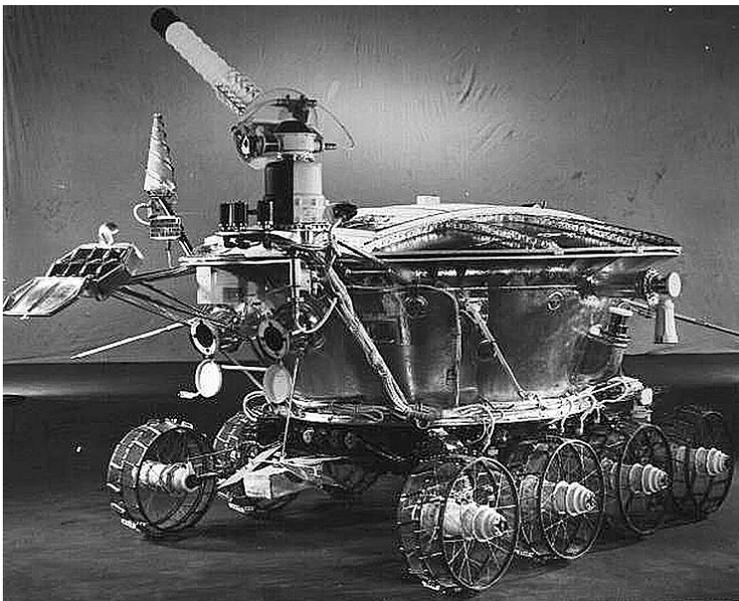
Future lunar missions

NASA's plans for future moon missions call for rovers that have a far longer range than the Apollo rovers.

Chapter- 2

Lunokhod 1

Lunokhod 1



Lunokhod series Soviet Moon exploration robot vehicle

Operator	Soviet Union
Mission type	Rover
Orbital insertion date	Landed on November 17, 1970 at 03:47:00 UTC
Launch date	November 10, 1970
Launch vehicle	Proton
Mission duration	ended on October 4, 1971
COSPAR ID	1970-095A
Homepage	Lunar and Planetary Department

Moscow University Lunokhod 1

page

Mass 5600 kg (rover itself 756 kg)

Power 180 W solar panel

Planetary landing

Coordinates 38°19'30"N 36°59'42"W /

38.32507°N 36.9949°W

Lunokhod 1 (**Луноход**, *moon walker* in Russian; *Annapam 8EJI № 203*, *vehicle 8EJI№203*) was the first of two unmanned lunar rovers landed on the Moon by the Soviet Union as part of its Lunokhod program. The spacecraft which carried Lunokhod 1 was named Luna 17. Lunokhod was the first roving remote-controlled robot to land on another celestial body.

Rover description

Lunokhod 1 was a lunar vehicle formed of a tub-like compartment with a large convex lid on eight independently powered wheels. Its length was 2.3 metres. Lunokhod was equipped with a cone-shaped antenna, a highly directional helical antenna, four television cameras, and special extendable devices to impact the lunar soil for soil density and mechanical property tests. An X-ray spectrometer, an X-ray telescope, cosmic ray detectors, and a laser device were also included. The vehicle was powered by batteries which were recharged during the lunar day by a solar cell array mounted on the underside of the lid. To be able to work in vacuum a special fluoride based lubricant was used for the mechanical parts and the electric motors (one in each wheel hub) were enclosed in pressurised containers. During the lunar nights, the lid was closed and a polonium-210 radioisotope heater unit kept the internal components at operating temperature. Lunokhod was intended to operate through three lunar days (approximately 3 Earth months) but actually operated for eleven lunar days.

Launch and lunar orbit

Luna 17 was launched on November 10, 1970 at 14:44:01 UTC. After reaching earth parking orbit, the final stage of Luna 17's launching rocket fired to place it into a trajectory towards the Moon (1970-11-10 at 14:54 UTC). After two course correction maneuvers (on November 12 and 14), it entered lunar orbit on November 15, 1970 at 22:00 UTC.

Landing and surface operations

The spacecraft soft-landed on the Moon in the Sea of Rains on November 17 at 03:47 UTC. The lander had dual ramps from which the payload, Lunokhod 1, could descend to the lunar surface. At 06:28 UT the rover moved onto the moon's surface.

The rover would run during the lunar day, stopping occasionally to recharge its batteries via the solar panels. At night the rover hibernated until the next sunrise, heated by the radioactive source.

1970:

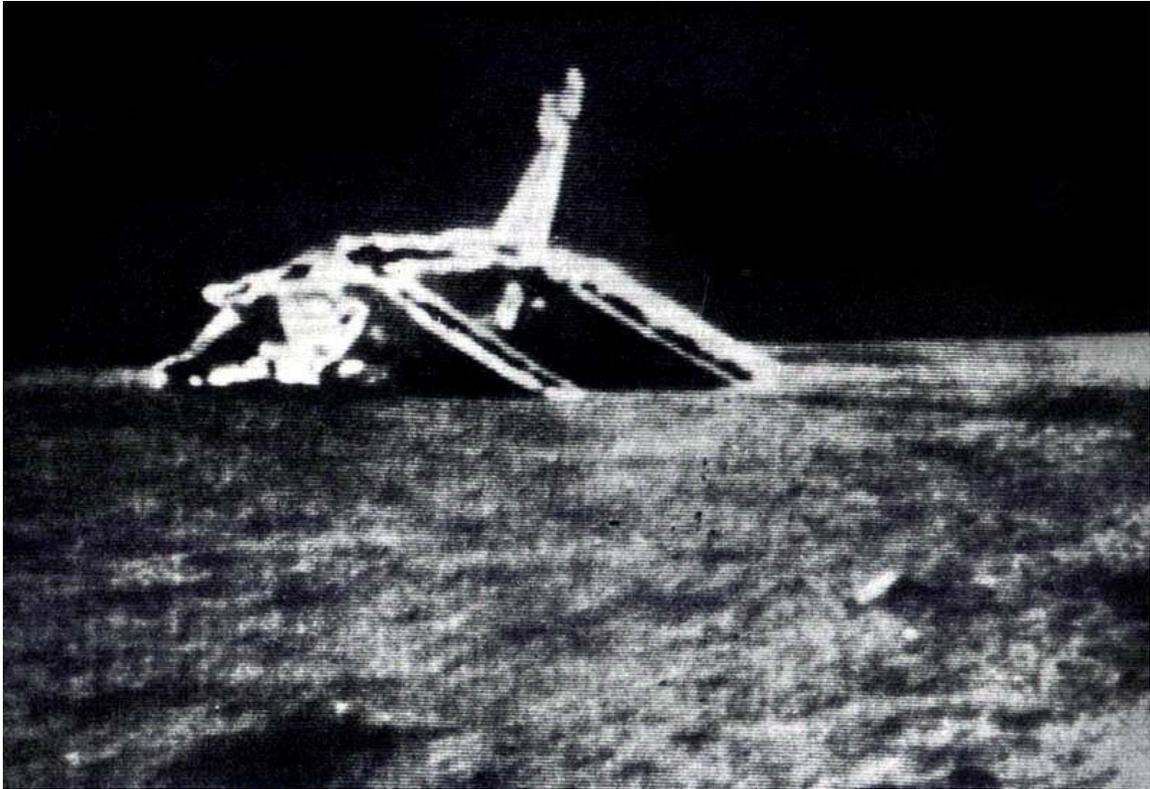
- November 17 - November 22: The rover drives 197 m, returns 14 close up pictures of the Moon and 12 panoramic views, during 10 communication sessions. It also conducts analyses of the lunar soil.
- December 9 - December 22: 1,522 m

1971:

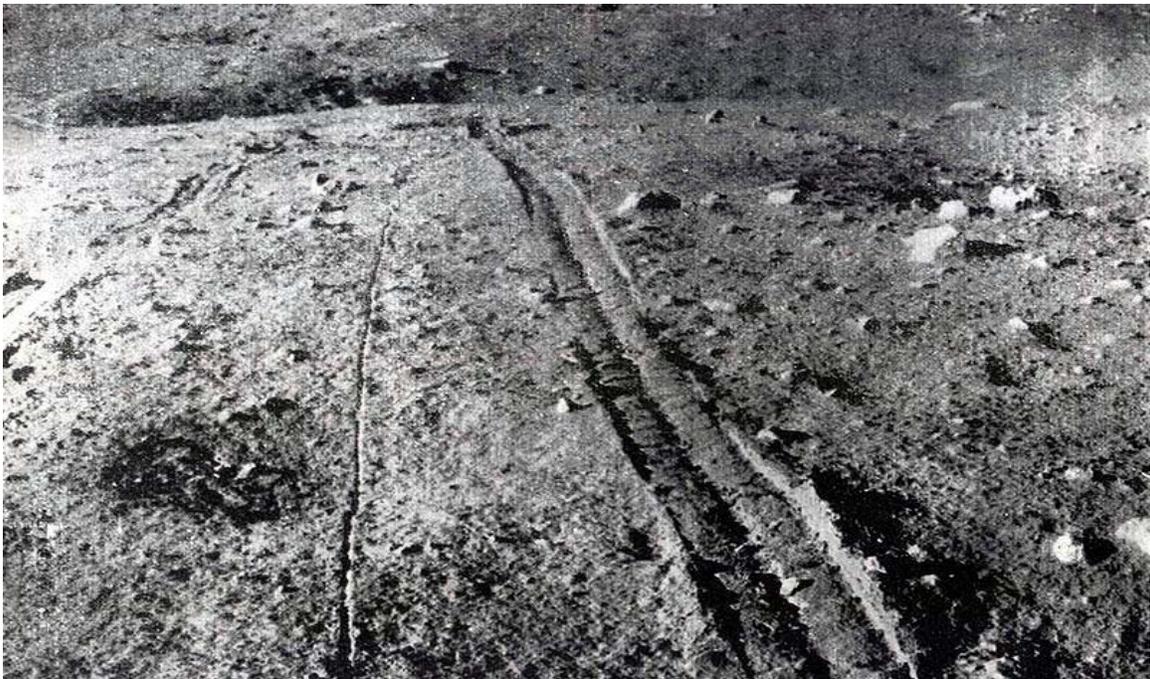
- January 8 - January 20: 1,936 m
- February 8 - February 19: 1,573 m
- March 9 - March 20: 2,004 m
- April 8 - April 20: 1,029 m
- May 7 - May 20: 197 m
- June 5 - June 18: 1,559 m
- July 4 - July 17: 220 m
- August 3 - August 16: 215 m
- August 31 - September 14: 88 m



A panorama shot from Lunokhod 1



A photo from Lunokhod 1 showing the Luna 17 lander

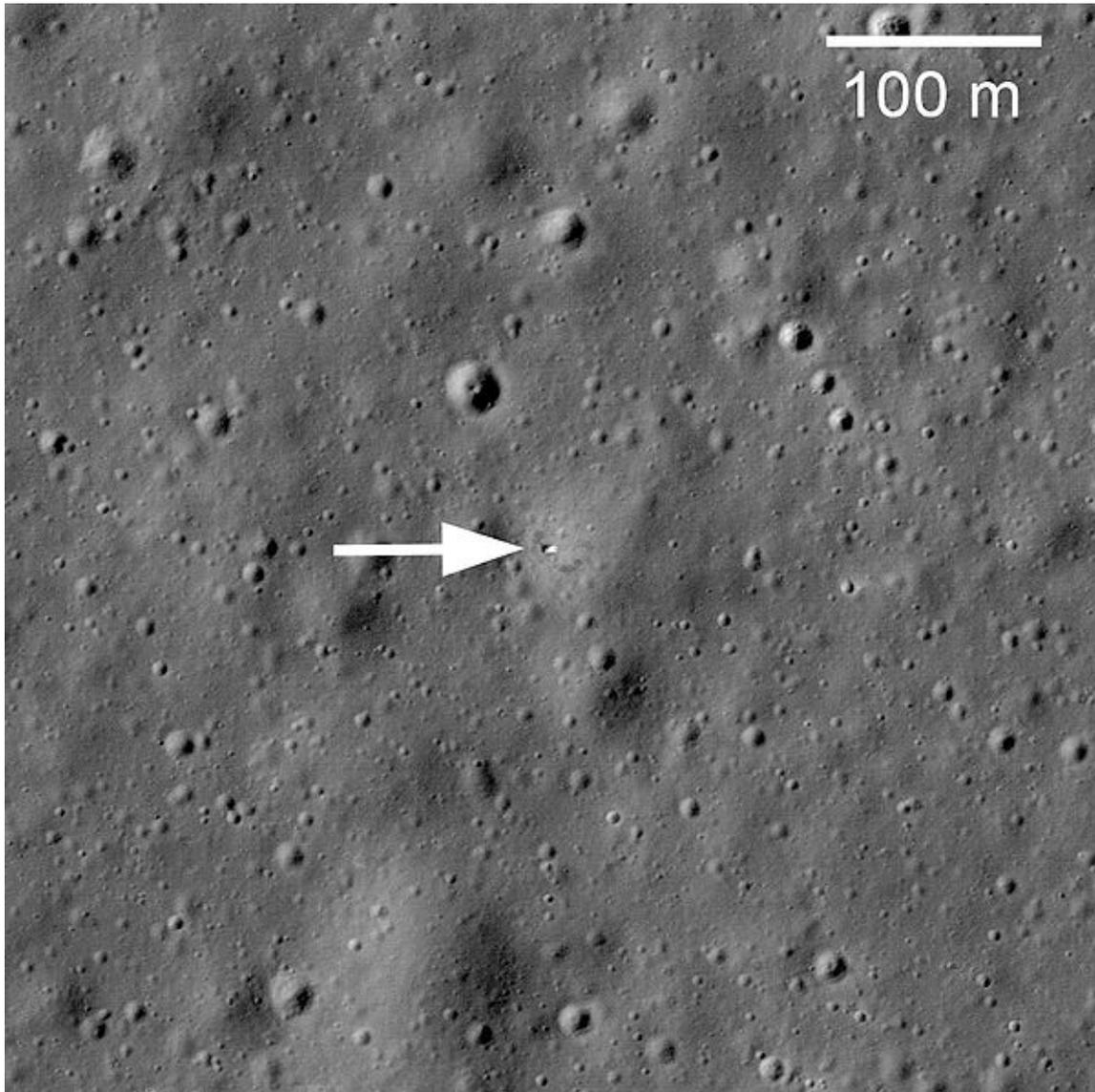


The tracks of Lunokhod showing the "little wheel" in the center that was used for odometry.

End of mission and results

Controllers finished the last communications session with Lunokhod 1 at 13:05 UT on September 14, 1971. Attempts to reestablish contact were finally discontinued and the operations of Lunokhod 1 officially ceased on October 4, 1971, the anniversary of Sputnik 1. During its 322 Earth days of operations, Lunokhod traveled 10,540 metres and returned more than 20,000 TV images and 206 high-resolution panoramas. In addition, it performed 25 lunar soil analyses with its RIFMA x-ray fluorescence spectrometer and used its penetrometer at 500 different locations.

Current location



LRO image from 2010

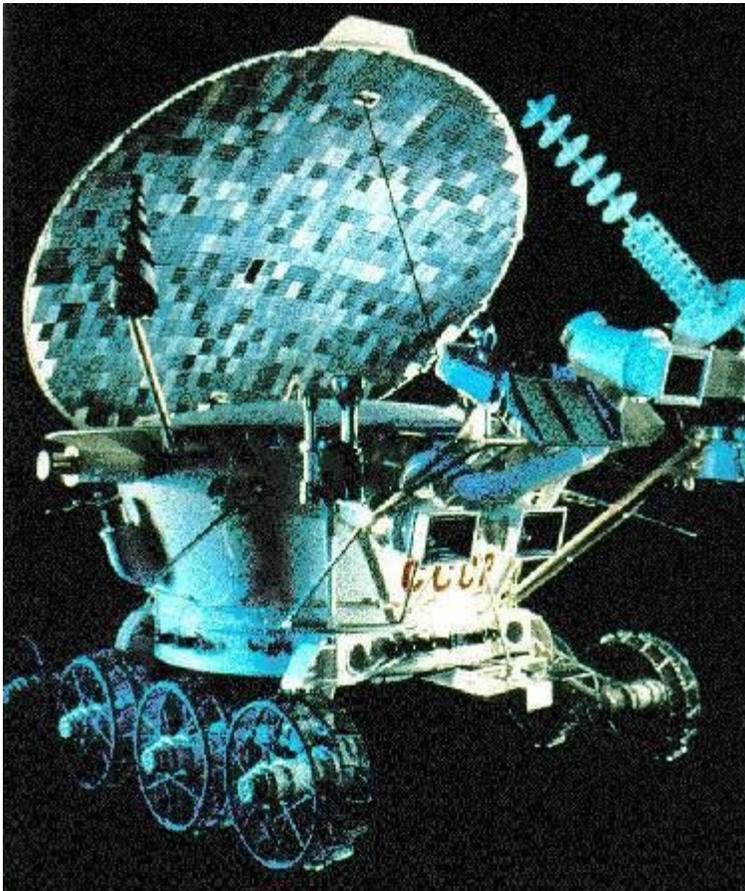
The final location of Lunokhod 1 was uncertain until 2010, as lunar laser ranging experiments had failed to detect a return signal from it since 1971. In April 2010, the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) team from the University of California at San Diego used images from NASA's Lunar Reconnaissance Orbiter to locate the orbiter closely enough for laser range (distance) measurements. On April 22, 2010 and days following, the team successfully measured the distance several times. The intersection of the spheres described by the measured distances then pinpoint the current location of Lunokhod 1 to within 1 meter. APOLLO is now using Lunokhod 1's reflector for experiments, as they discovered, to their surprise, that it was returning much more light than other reflectors on the moon. According to a NASA press release, APOLLO researcher Tom Murphy said, "We got about 2,000 photons from Lunokhod 1 on our first try. After almost 40 years of silence, this rover still has a lot to say."

By fall of 2010, the location of the rover had been determined to about a centimeter. The location near the limb of the moon, combined with the ability to range the rover even when it is in sunlight, promises to be particularly useful for determining aspects of the Earth-Moon system.

Chapter- 3

Lunokhod 2

Lunokhod 2



Lunokhod series Soviet Moon exploration robot vehicle

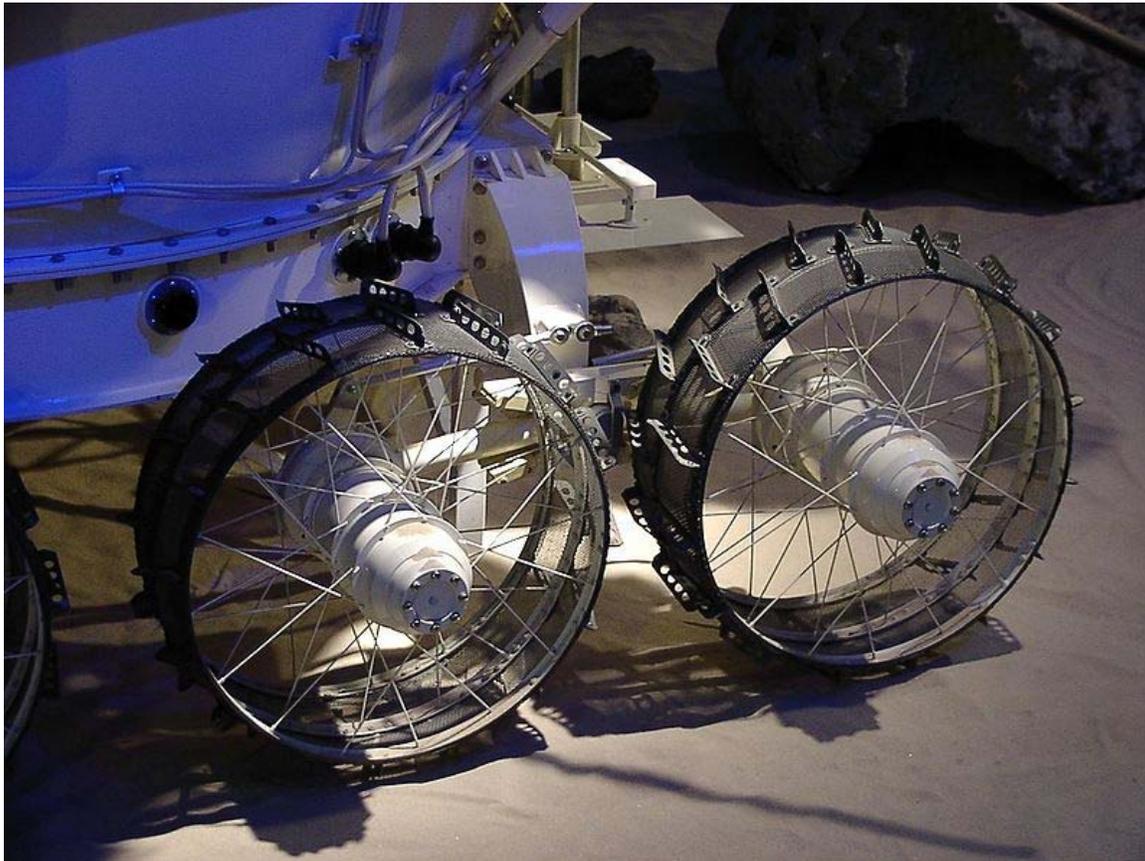
Operator	Soviet Union
Mission type	Rover
Orbital insertion date	Landed on January 15, 1973
Launch date	January 11, 1973 at 06:55:38 UTC

Launch vehicle	Proton
Mission duration	ended on June 4, 1973
COSPAR ID	1973-001A
Mass	840 kg (rover)
Power	solar panel

Lunokhod 2 (Луноход, *moon walker* in Russian) was the second of two unmanned lunar rovers landed on the Moon by the Soviet Union as part of the Lunokhod program.

The Luna 21 spacecraft landed on the Moon and deployed the second Soviet lunar rover (Lunokhod 2). The primary objectives of the mission were to collect images of the lunar surface, examine ambient light levels to determine the feasibility of astronomical observations from the Moon, perform laser ranging experiments from Earth, observe solar X-rays, measure local magnetic fields, and study the soil mechanics of the lunar surface material.

Lunokhod 2 rover and subsystems



Detail of Lunokhod's wheels

The rover stood 135 cm (4 ft 5 in) high and had a mass of 840 kg (1,850 lb). It was about 170 cm (5 ft 7 in) long and 160 cm (5 ft 3 in) wide and had 8 wheels each with an independent suspension, electric motor and brake. The rover had two speeds, ~1 km/h and ~2 km/h (0.6 mph and 1.2 mph). Lunokhod 2 was equipped with three television cameras, one mounted high on the rover for navigation, which could return high resolution images at different frame rates—3.2, 5.7, 10.9 or 21.1 seconds per frame. These images were used by a five-man team of controllers on Earth who sent driving commands to the rover in real time. Power was supplied by a solar panel on the inside of a round hinged lid which covered the instrument bay, which would charge the batteries when opened. A polonium-210 radioisotope heater unit was used to keep the rover warm during the long lunar nights. There were four panoramic cameras mounted on the rover. Scientific instruments included a soil mechanics tester, solar X-ray experiment, an astrophotometer to measure visible and ultraviolet light levels, a magnetometer deployed in front of the rover on the end of a 2.5 m (8 ft 2 in) boom, a radiometer, a photodetector (Rubin-1) for laser detection experiments, and a French-supplied laser corner reflector. The lander carried a bas relief of Lenin and the Soviet coat of arms. The lander and rover together massed 1814 kg.

Mission profile

The SL-12/D-1-e launcher put the spacecraft into Earth parking orbit followed by translunar injection. On January 12, 1973 Luna 21 was braked into a 90 by 100 km (56 by 62 mile) lunar orbit. On January 13 and January 14, the perilune was lowered to 16 km (10 mi) altitude.

Landing and surface operations

On January 15 after 40 orbits, the braking rocket was fired at 16 km (10 mi) altitude, and the craft went into free fall. At an altitude of 750 m (2,460 ft) the main thrusters began firing, slowing the fall until a height of 22 m (72 ft) was reached. At this point the main thrusters shut down and the secondary thrusters ignited, slowing the fall until the lander was 1.5 m (5 ft) above the surface, where the engine was switched off. Landing occurred at 23:35 UT in Le Monnier crater at 25.85 degrees N, 30.45 degrees E.

After landing, the Lunokhod 2 took TV images of the surrounding area, then rolled down a ramp to the surface at 01:14 UT on January 16 and took pictures of the Luna 21 lander and landing site, driving for 30 metres. After a period of charging up its batteries, it took more pictures of the site and the lander, and then set off to explore the moon.

The rover would run during the lunar day, stopping occasionally to recharge its batteries with the solar panels. At night the rover hibernated until the next sunrise, heated by the radioactive source.

- January 18, 1973 to January 24, 1973: The rover drives 1,260 metres
- February 8, 1973 to February 23, 1973: The rover drives 9,086 metres further

- March 11, 1973 to March 23, 1973: The rover drives 16,533 metres further
- April 9, 1973 to April 22, 1973: The rover drives 8,600 metres further
- May 8, 1973 to June 3, 1973: The rover drives 880 metres further

End of mission

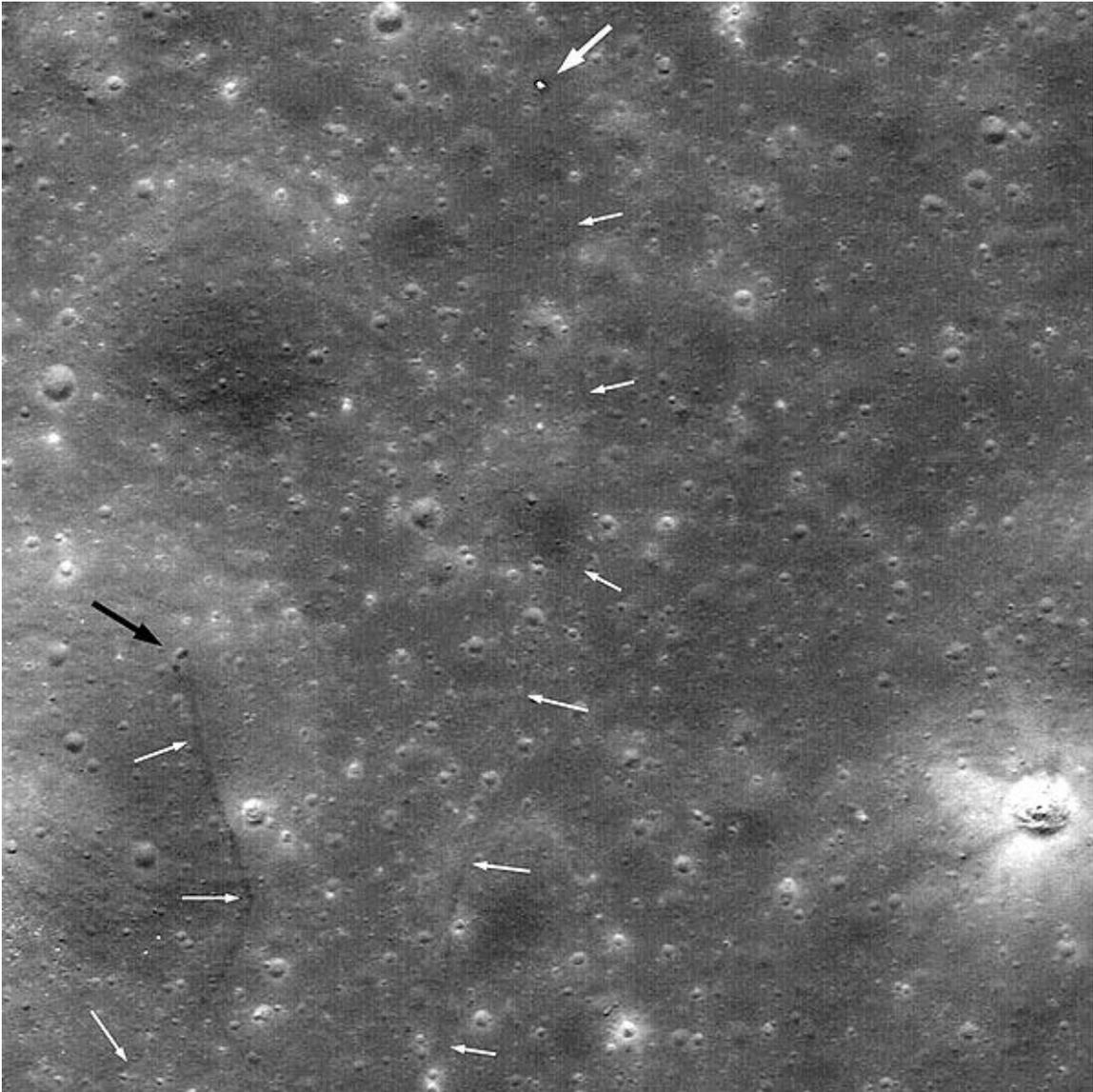
On June 4, 1973 it was announced that the program was completed, leading to speculation that the vehicle probably failed in mid-May or could not be revived after the lunar night of May-June.

More recently, Alexander Basilevsky related an account where on May 9, 1973, the rover's open lid touched a crater wall and became covered with dust. When the lid was closed for the lunar night, this dust (a very good insulator) was dumped on to the radiators. The following lunar day, controllers saw the internal temperature of the Lunokhod climb as it was unable to cool itself, eventually rendering the rover inoperable.

Results

Lunokhod 2 operated for about 4 months, covered 37 km (23 miles) of terrain, including hilly upland areas and rilles, and sent back 86 panoramic images and over 80,000 TV pictures. At the time, the journey was the longest any robotic rover had ever been driven on another celestial body. Many mechanical tests of the surface, laser ranging measurements, and other experiments were completed during this time.

Current status



Lunar Reconnaissance Orbiter image of Lunokhod 2 and its tracks. The large white arrow indicates the rover, the smaller white arrows indicate its tracks, and the black arrow indicates the crater where it picked up its fatal load of lunar dust.

Lunokhod 2 continues to be detected by lunar laser ranging experiments and its position is known to sub-meter accuracy. On March 17, 2010 Phil Stooke, a professor at the University of Western Ontario announced that he had located Lunokhod 2's final resting place in photographs made by the Lunar Reconnaissance Orbiter.

Present ownership

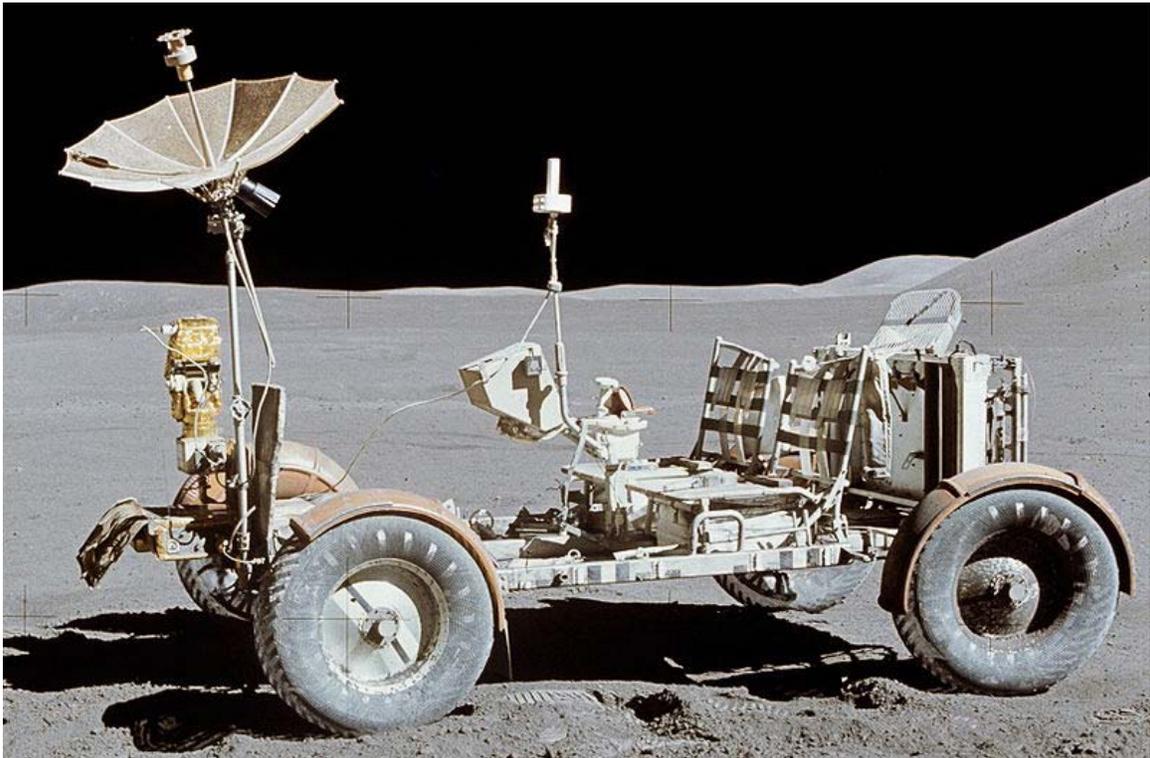
Ownership of Lunokhod 2 and the Luna 21 lander was sold by the Lavochkin Association for \$68,500 in December 1993 at a Sotheby's auction in New York. (The catalog incorrectly lists lot 68A as Luna 17/Lunokhod 1).

The buyer was computer gaming entrepreneur and astronaut's son Richard Garriott (also known as Lord British), who stated in a 2001 interview with Computer Games Magazine's Cindy Yans that:

I purchased Lunakod 21 [sic] from the Russians. I am now the world's only private owner of an object on a foreign celestial body. Though there are international treaties that say, no government shall lay claim to geography off planet earth, I am not a government. Summarily, I claim the moon in the name of Lord British!

Chapter- 4

Lunar Rover (Apollo)

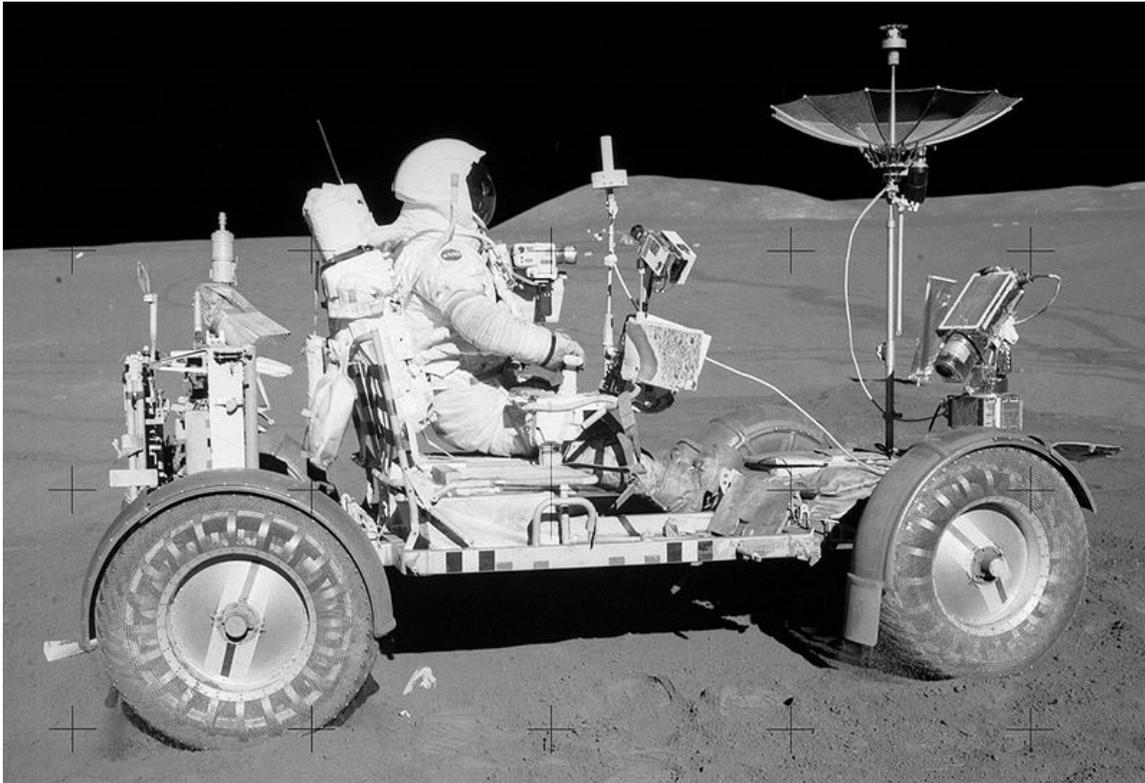


The U.S. Apollo Lunar Roving Vehicle from Apollo 15 on the moon in 1971

The **Lunar Roving Vehicle (LRV)** or **lunar rover** was a battery-powered four-wheeled rover used on the Moon during the last three missions of the American Apollo program (15, 16, and 17) during 1971 and 72. It was popularly known as the **moon buggy**, a play on the phrase "dune buggy".

The LRV could carry one or two astronauts, their equipment, and lunar samples.

History



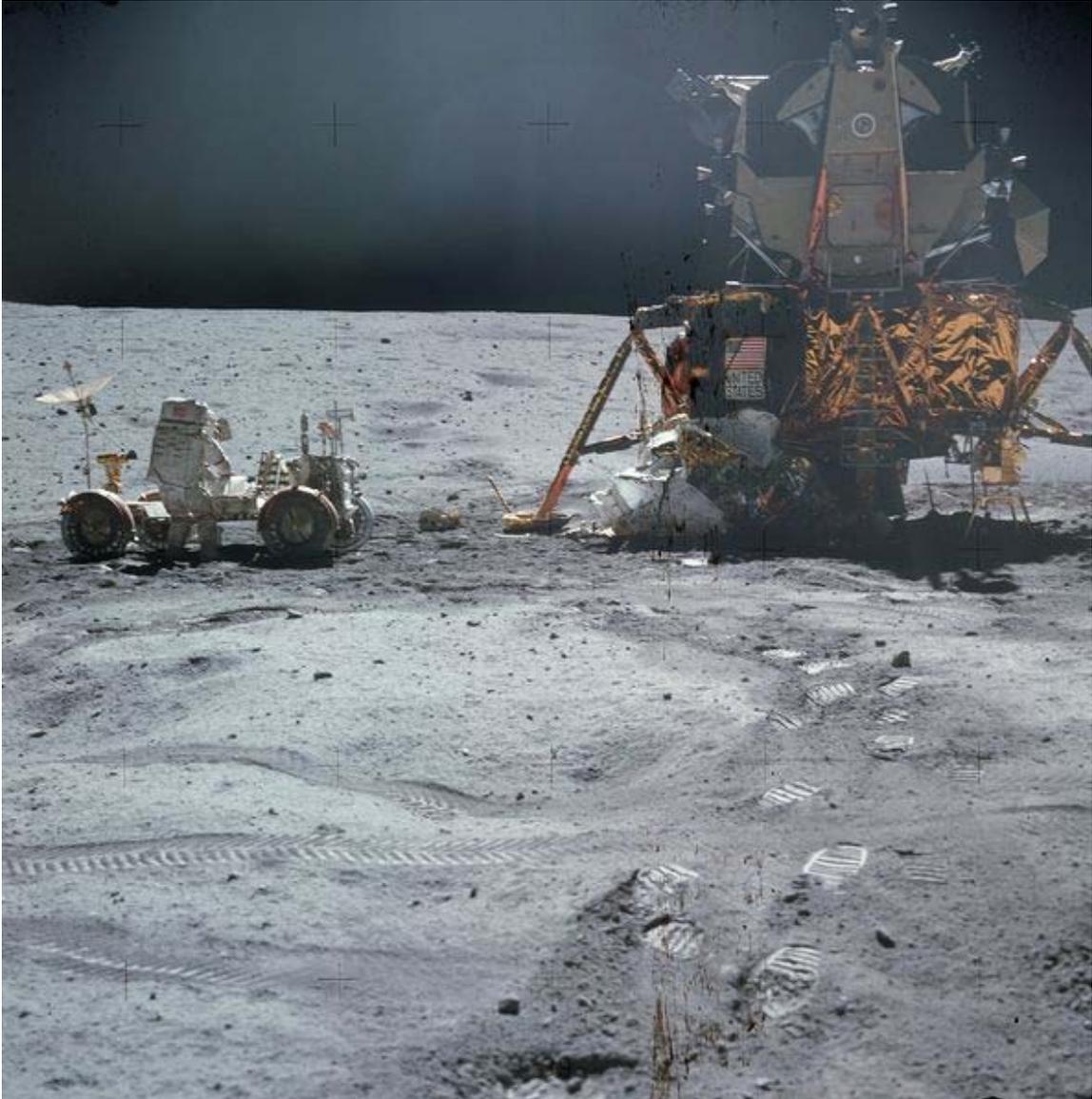
Apollo 15 LRV

The concept of a lunar rover predated Apollo, with a 1950s series in *Collier's Weekly* magazine by Wernher Von Braun and others, "Man Will Conquer Space Soon!", describing a six week stay on the moon, featuring ten-ton tractor trailers for moving supplies. In the February 1964 issue of *Popular Science*, Von Braun, then director of NASA's Marshall Space Flight Center, discussed the need for a lunar surface vehicle. In anticipation of this as-yet unfunded project, NASA officially changed the name of the lunar lander from Lunar Excursion Module to simply Lunar Module in an effort to make clear that the capability for powered lunar surface mobility ("excursions" away from the lunar lander base) did not yet exist.

The author of the general idea, design and form of the LRV was engineer Mieczyslaw G. Bekker. The final lightweight design, the new tires, and the folding mechanism of the assembly were the inventions of engineer Ferenc Pavlics.

The first cost-plus-incentive-fee contract to Boeing (with Delco Electronics as a major sub-contractor) was for \$19,000,000 and called for delivery of the first LRV by April 1, 1971, but cost overruns led to a final cost of \$38,000,000. Four lunar rovers were built, one each for Apollo missions 15, 16, and 17; and one used for spare parts after the cancellation of further Apollo missions. There were other LRV models built: a static model to assist with human factors design, an engineering model to design and integrate the subsystems, two one-sixth gravity models for testing the deployment mechanism, a

one-gravity trainer to give the astronauts instruction in the operation of the rover and allow them to practice driving it, a mass model to test the effect of the rover on the Apollo Lunar Module (LM) structure, balance and handling, a vibration test unit to study the LRV's durability and handling of launch stresses, and a qualification test unit to study integration of all LRV subsystems.



John Young works at the LRV near the LM *Orion* on Apollo 16 in April 1972

LRVs were used for greater surface mobility during the Apollo J-class missions (*Apollo 15*, *Apollo 16*, and *Apollo 17*). The rover was first used on July 31, 1971, during the *Apollo 15* mission. This greatly expanded the range of the lunar explorers. Previous teams of astronauts were restricted to short walking distances around the landing site due to the bulky space suit equipment required to sustain life in the lunar environment. The range, however, was operationally restricted to remain within walking distance of the

lunar module, in case the rover broke down at any point. The rovers had a top speed of about 8 mph (13 km/h), although Gene Cernan recorded a maximum speed of 11.2 mph (18.0 km/h), giving him the (unofficial) lunar land speed record.

The LRV was developed in only 17 months and yet performed all its functions on the Moon with no major anomalies. Harrison Schmitt of Apollo 17 said, "....the Lunar Rover proved to be the reliable, safe and flexible lunar exploration vehicle we expected it to be. Without it, the major scientific discoveries of Apollo 15, 16, and 17 would not have been possible; and our current understanding of lunar evolution would not have been possible."

The LRVs did experience some minor problems. The rear fender extension on the Apollo 16 LRV was lost during the mission's second EVA (extra-vehicular activity) at station 8 when Young bumped into it while going to assist Duke. The dust thrown up from the wheel covered the crew, the console and the communications equipment. High battery temperatures and resulting high power consumption ensued. No repair attempt was mentioned. The fender extension on the Apollo 17 LRV broke when accidentally bumped by Eugene Cernan with a hammer handle. The crew taped the extension back in place, but due to the dusty surfaces, the tape did not adhere and the extension was lost after about one hour of driving, causing the astronauts to be covered with dust. For the second EVA, a replacement "fender" was made with some EVA maps, duct tape, and a pair of clamps from inside the Lunar Module - nominally intended for the moveable overhead light. This repair was later undone so that the clamps could be brought back inside for launch. The maps were brought back and are now on display at the National Air and Space Museum. The abrasion from the dust is evident on some portions of the makeshift fender.



Lunar rover on Space Achievement Decade Issue of 1971

The color television camera mounted on the front of the LRV could be remotely operated by Mission Control in two axes: pan and tilt. This allowed far better television coverage of the EVA than the earlier missions. On each mission, at the conclusion of the astronauts' stay on the surface, the commander drove the LRV to a position away from the Lunar Module so that the camera could record the ascent stage launch. The camera operator in Mission Control experienced difficulty in timing the various delays so that the

LM ascent stage was in frame through the launch. On the third and final attempt (Apollo 17), the launch and ascent were successfully tracked.

NASA's rovers, left behind, are among the artificial objects on the Moon; as are the Soviet Union's unmanned rovers, Lunokhod 1 and Lunokhod 2.

Features and specifications



Eugene Cernan test drives the Apollo 17 lunar rover shortly after unloading it from the LM

The Apollo Lunar Roving Vehicle was an electric vehicle designed to operate in the low-gravity vacuum of the Moon and to be capable of traversing the lunar surface, allowing the Apollo astronauts to extend the range of their surface extravehicular activities. Three LRVs were used on the Moon, one on Apollo 15 by astronauts David Scott and Jim

Irwin, one on Apollo 16 by John Young and Charles Duke, and one on Apollo 17 by Gene Cernan and Harrison Schmitt. The mission Commanders served as the drivers, occupying the left-hand seats of LRVs.

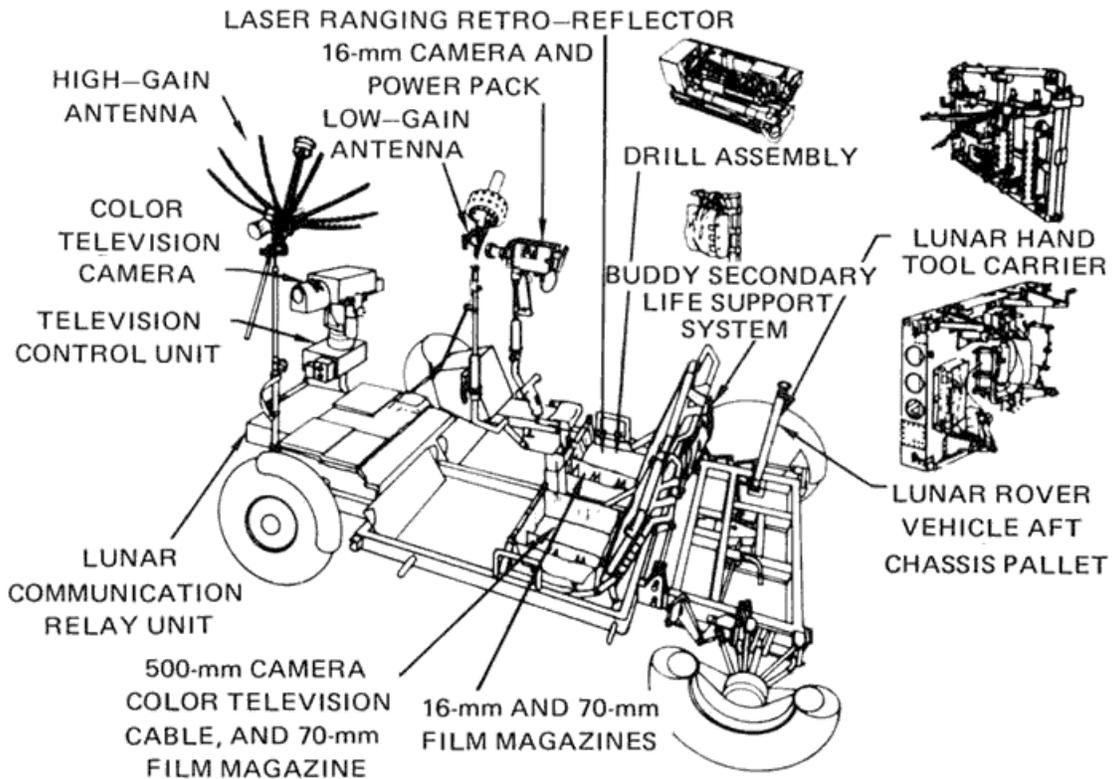
Mass and payload

The Lunar Roving Vehicle had a weight of 463 lbs (210 kg) and was designed to hold a payload of an additional 1,080 lbs (490 kg) on the lunar surface. The frame was 10 feet (3 m) long with a wheelbase of 7.5 feet (2.3 m). The height of the vehicle was 3.6 ft (1.1 m). The frame was made of aluminum alloy 2219 tubing welded assemblies and consisted of a three-part chassis which was hinged in the center so it could be folded up and hung in the Lunar Module quad 1 bay. It had two side-by-side foldable seats made of tubular aluminum with nylon webbing and aluminum floor panels. An armrest was mounted between the seats, and each seat had adjustable footrests and a Velcro seat belt. A large mesh dish antenna was mounted on a mast on the front center of the rover. The suspension consisted of a double horizontal wishbone with upper and lower torsion bars and a damper unit between the chassis and upper wishbone. Fully loaded the LAV had a ground clearance of 14 inches (35 cm).

Wheels and power

The wheels were manufactured by General Motors Defense Research Laboratories. They consisted of a spun aluminum hub and a 32 inches (81 cm) diameter, 9 inches (23 cm) wide tire made of zinc coated woven 0.033 inches (0.84 mm) diameter steel strands attached to the rim and discs of formed aluminum. Titanium chevrons covered 50 percent of the contact area to provide traction. Inside the tire was a 25.5 inches (65 cm) diameter bump stop frame to protect the hub. Dust guards were mounted above the wheels. Each wheel had its own electric drive made by Delco, DC series wound motor capable of 0.25 horsepower (190 W) @ 10,000 rpm, attached to the wheel via an 80:1 harmonic drive, and a mechanical brake unit. Maneuvering capability was provided through the use of front and rear steering motors. Each series wound DC steering motor was capable of 0.1 horsepower (75 W). Both sets of wheels would turn in opposite directions, giving a steering radius of 10 feet (3 m), or could be decoupled so only one set would be used for steering. They could also free-wheel in case of drive failure. Power was provided by two 36-volt silver-zinc potassium hydroxide non-rechargeable batteries with a capacity of 121 A·h each (a total of 242 A·h), translating into a range of 57 mi (92 km). These were used to power the drive and steering motors and also a 36 volt utility outlet mounted on front of the LRV to power the communications relay unit or the TV camera. LRV batteries and electronics were passively cooled, using reflective, upward-facing radiating surfaces mounted atop each battery unit. While driving, radiators were covered with mylar blankets to minimize dust accumulation. When stopped, the astronauts would open the blankets, and manually removed dust from the cooling surfaces with hand brushes.

Control and navigation



Lunar Rover diagram. (NASA)

A T-shaped hand controller situated between the two seats controlled the four drive motors, two steering motors and brakes. Moving the stick forward powered the LRV forward, left and right turned the vehicle left or right, pulling backwards activated the brakes. Activating a switch on the handle before pulling back would put the LRV into reverse. Pulling the handle all the way back activated a parking brake. The control and display modules were situated in front of the handle and gave information on the speed, heading, pitch, and power and temperature levels.

Navigation was based on continuously recording direction and distance through use of a directional gyro and odometer and feeding this data to a computer which would keep track of the overall direction and distance back to the LM. There was also a Sun-shadow device which could give a manual heading based on the direction of the Sun, using the fact that the Sun moved very slowly in the sky.

Usage

Each rover was used on three traverses, one per day over the three day course of each mission, with the individual performances logged as follows:

mission	total distance	total time	longest single traverse	maximum range from the LM
Apollo 15 (LRV-001)	17.25 miles (27.76 km)	3h 02 m	7.75 miles (12.47 km)	3.1 miles (5.0 km)
Apollo 16 (LRV-002)	16.50 miles (26.55 km)	3h 26 m	7.20 miles (11.59 km)	2.8 miles (4.5 km)
Apollo 17 (LRV-003)	22.30 miles (35.89 km)	4h 26 m	12.50 miles (20.12 km)	4.7 miles (7.6 km)

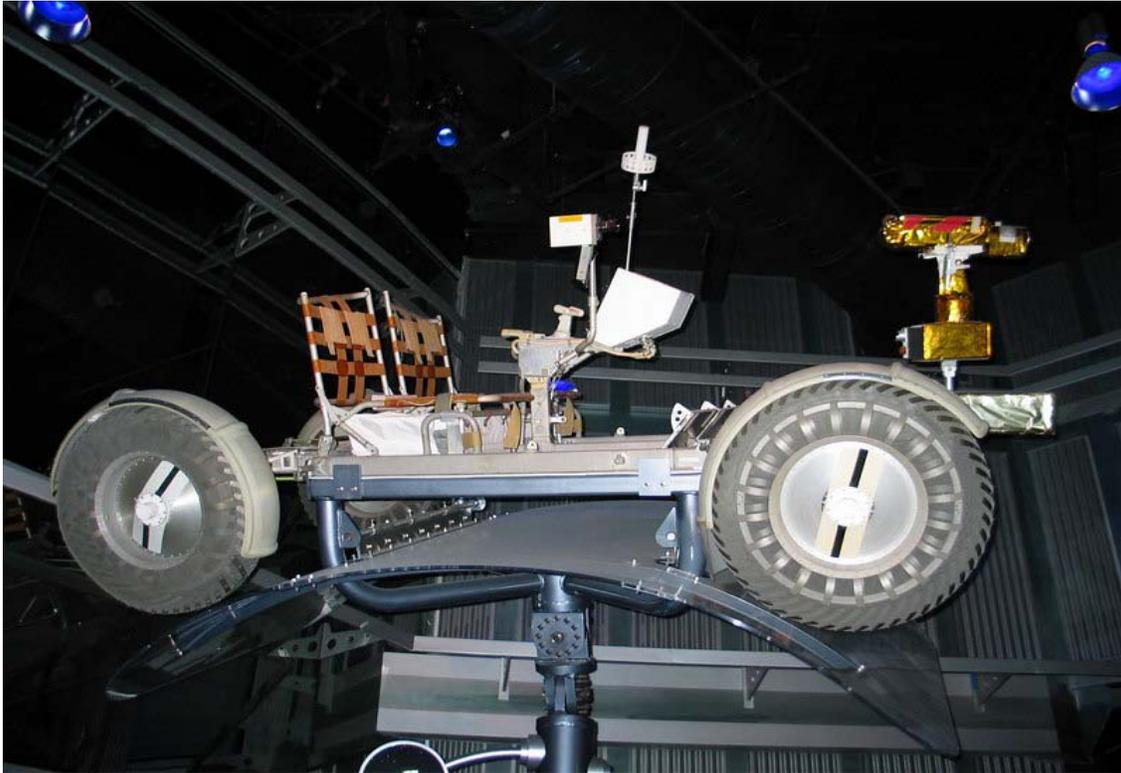
An operational constraint on the use of the LRV was that the astronauts must be able to walk back to the LM if the LRV were to fail at any time during the EVA (called the "Walkback Limit"). Thus, the traverses were limited in the distance they could go at the start and at any time later in the EVA. Therefore, they went to the farthest point away from the LM and worked their way back to it so that, as the life support consumables were depleted, their remaining walk back distance was equally diminished. This constraint was relaxed during the longest traverse on Apollo 17, based on the demonstrated reliability of the LRV and spacesuits on previous missions.

Deployment

Deployment of the LRV from the LM quad 1 by the astronauts was achieved with a system of pulleys and braked reels using ropes and cloth tapes. The rover was folded and stored in quad 1 with the underside of the chassis facing out. One astronaut would climb the egress ladder on the LM and release the rover, which would then be slowly tilted out by the second astronaut on the ground through the use of reels and tapes. As the rover was let down from the bay most of the deployment was automatic. The rear wheels folded out and locked in place and when they touched the ground the front of the rover could be unfolded, the wheels deployed, and the entire frame let down to the surface by pulleys.

The rover components locked into place upon opening. Cabling, pins and tripods would then be removed and the seats and footrests raised. After switching on all the electronics the vehicle was ready to back away from the LM.

Current locations



Rover replica on display at Epcot

Several rovers were created for testing, training or validation purposes. The engineering mockup is on display at the Museum of Flight in Seattle, Washington. The Qualification Test Unit is on display at the National Air and Space Museum in Washington D.C. The rover used for vibration testing is on display in the Davidson Saturn V Center at the Marshall Space Flight Center in Huntsville, Alabama. Additional test units are on display at the Johnson Space Center in Houston, Texas and the Kennedy Space Center Visitors Complex in Cape Canaveral, Florida.

Replicas of rovers are on display at the National Museum of Naval Aviation in Pensacola, Florida, the Evergreen Aviation & Space Museum in McMinnville, Oregon and the Kansas Cosmosphere and Space Center in Hutchinson, Kansas. A replica on loan from the Smithsonian Institution is on display at the Mission: Space attraction at Epcot at the Walt Disney World Resort near Orlando, Florida.

Four flight-ready rovers were manufactured. Three of them were carried to the Moon on Apollo 15, 16, and 17, and left there. After Apollo 18 was canceled, the other lunar rover was used for spare parts for the Apollo 15 to 17 missions. The only lunar rovers on display are test vehicles, trainers, and models. The rover used on Apollo 15 was left on the lunar surface at Hadley-Apennine (26.10 N, 3.65 E). The rover used on Apollo 16 was left on the lunar surface at Descartes (8.99 S, 15.51 E). The rover used on Apollo 17 was left on the lunar surface at Taurus-Littrow (20.16 N, 30.76 E).

Chapter- 5

Mars Pathfinder

Mars Pathfinder

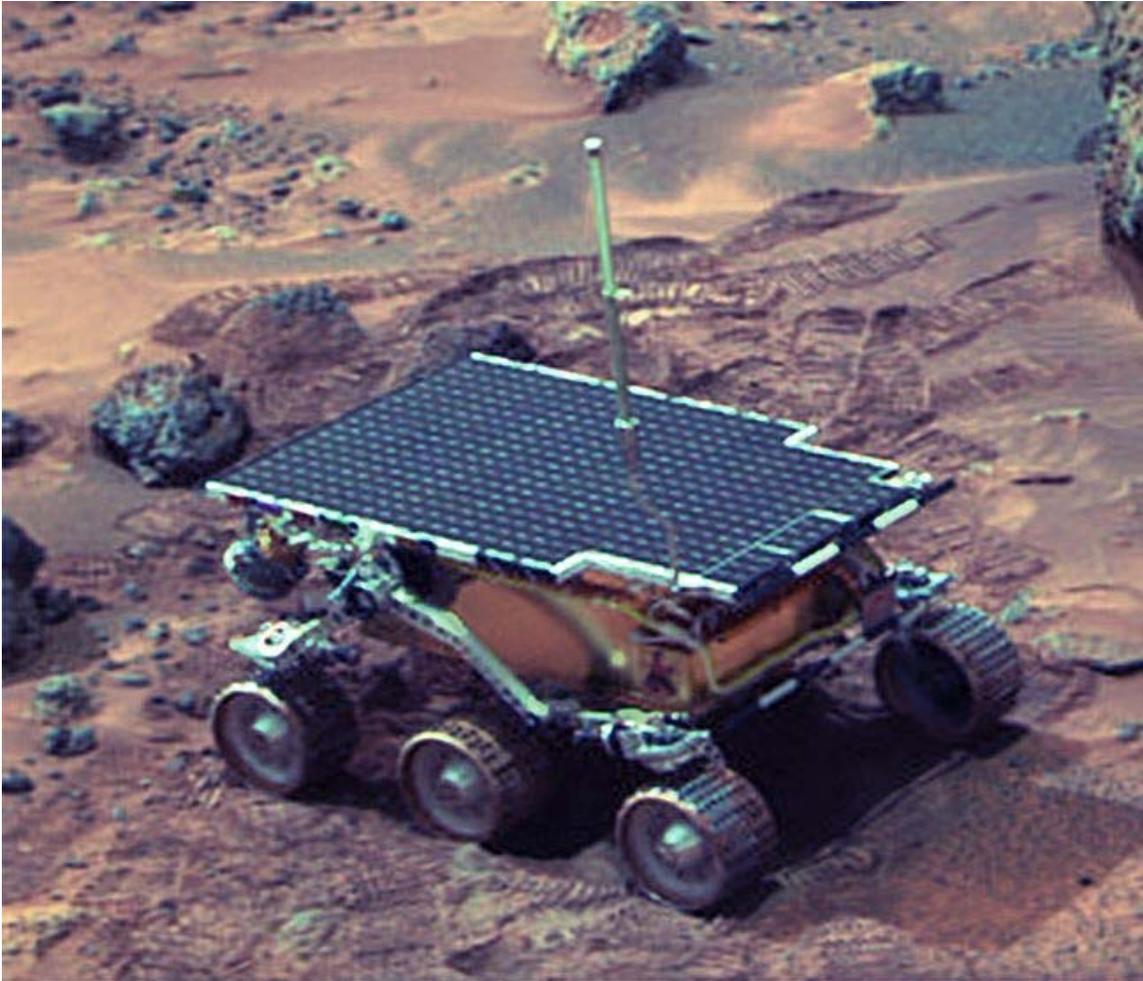


Operator	NASA – JPL
Mission type	Lander, rover
Orbital insertion date	Landed July 4, 1997 UT 16:57
Launch date	December 4, 1996 at 06:58:07 UTC from ESMC Launch Complex 17B
Launch vehicle	Delta 7925 (#D240)
COSPAR ID	1996-068A
Mass	264 kg (lander), 10.5 kg (rover)
Power	35 W (lander) 13 W (rover)

The **Mars Pathfinder (MESUR Pathfinder)**, later renamed the **Carl Sagan Memorial Station**, is an American spacecraft that landed the first roving probe deployed on another

planet. It consisted of a lander and a lightweight (10.6 kilograms/23 pounds) wheeled robotic rover named *Sojourner*.

Launched on December 4, 1996 by NASA aboard a Delta II booster a month after the Mars Global Surveyor was launched, it landed on July 4, 1997 on Mars' Ares Vallis, in a region called Chryse Planitia in the Oxia Palus quadrangle. The lander then opened, exposing the rover that would go on to conduct many experiments on the Martian surface.



Sojourner rover

The mission carried a series of scientific instruments to analyze the Martian atmosphere, climate, geology and the composition of its rocks and soil. It was the second project from NASA's Discovery Program, which promotes the use of low-cost spacecraft and frequent launches under the motto "cheaper, faster and better" promoted by the then administrator, Daniel Goldin. The mission was directed by the Jet Propulsion Laboratory (JPL), a division of the California Institute of Technology, responsible for NASA's Mars Exploration Program. The project manager was JPL's Tony Spear.

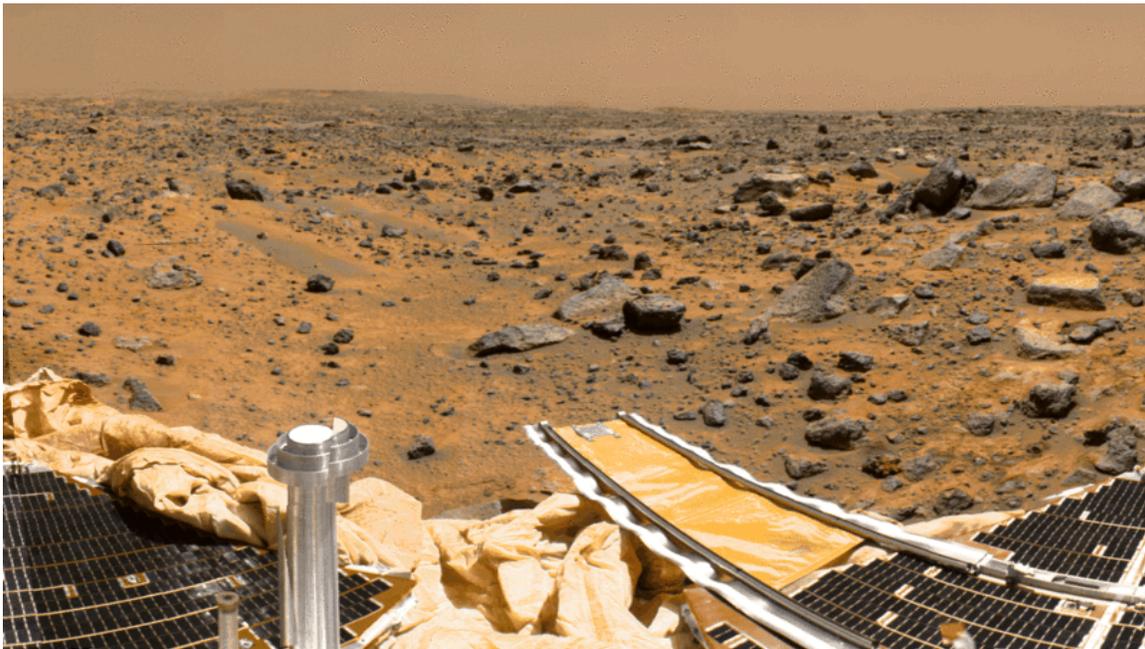
This mission, besides being the first of a series of missions to Mars that included rovers (robotic exploration vehicles), was the most important since the *Vikings* landed on the red planet in 1976. Although the Soviet Union successfully sent rovers to the Moon as part of the Lunokhod program in the 1970s, its two attempts to send rovers in its Mars probe program failed.

In addition to scientific objectives, the Mars Pathfinder mission was also a "proof-of-concept" for various technologies, such as airbag-mediated touchdown and automated obstacle avoidance, both later exploited by the Mars Exploration Rovers. The Mars Pathfinder was also remarkable for its extremely low price relative to other unmanned space missions to Mars. Originally, the mission was conceived as the first of the Mars Environmental Survey (MESUR) program.

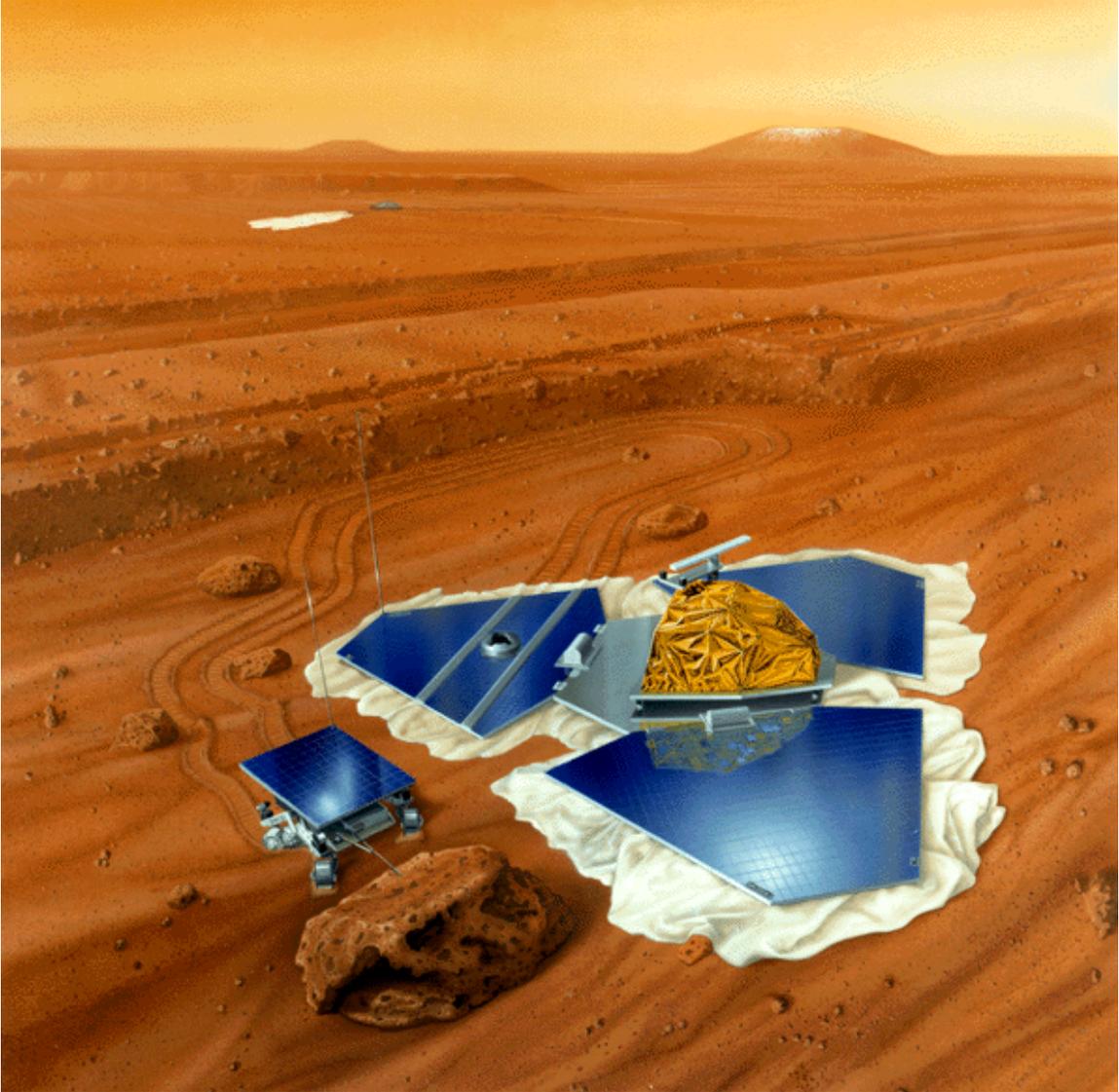
Mission objectives

- To prove that the development of "faster, better and cheaper" spacecraft is possible (with three years for development and a cost under \$150 million).
- To show that it is possible to send a load of scientific instruments to another planet with a simple system and at one fifteenth the cost of a Viking mission. (For comparison, the Viking missions cost \$935 million in 1974 or \$3.5 billion in 1997 dollars)
- To demonstrate NASA's commitment to low-cost planetary exploration by finishing the mission with a total expenditure of \$280 million, including the launch vehicle and mission operations.

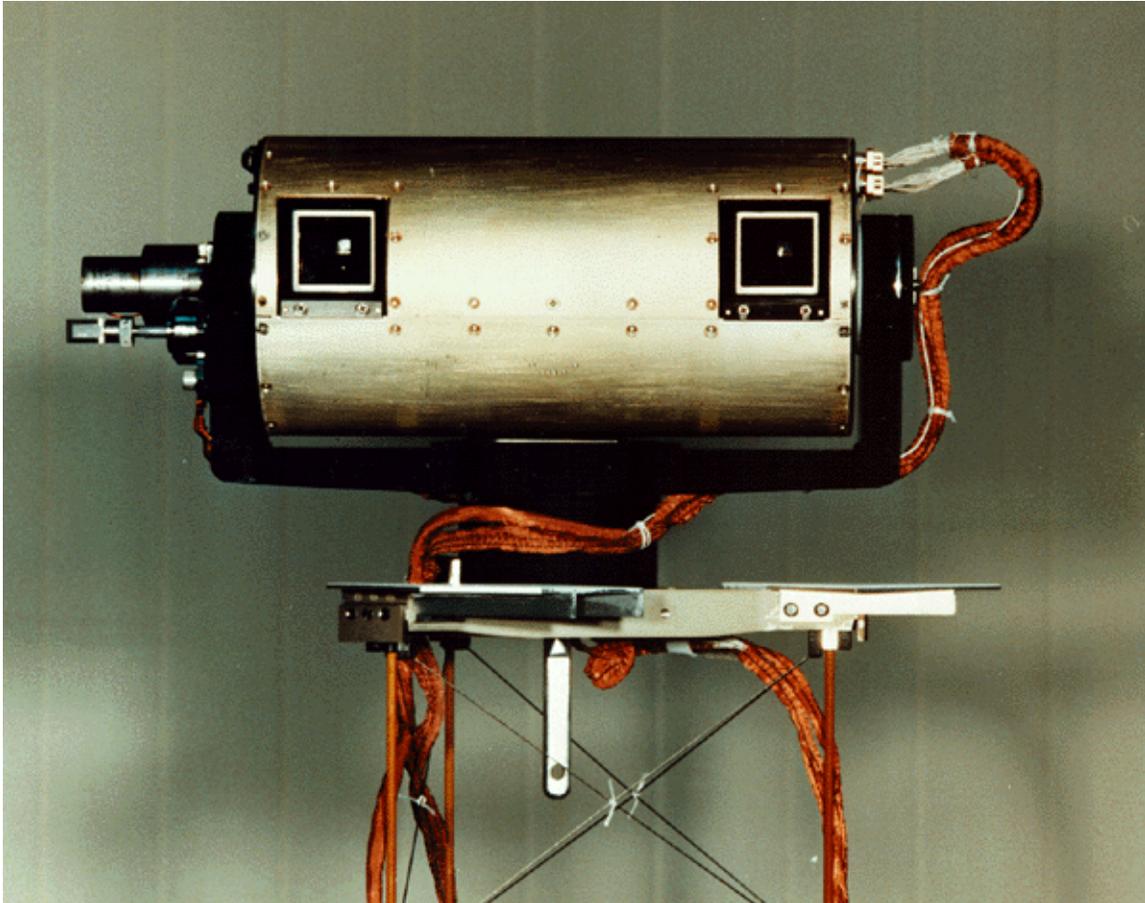
Science experiments



1997 image from the IMP after landing on Mars



1990s concept illustration of lander and rover



Mars Pathfinder lander IMP

The Mars Pathfinder conducted different investigations on the Martian soil using three scientific instruments. The lander contained a stereoscopic camera with spatial filters on an expandable pole called *Imager for Mars Pathfinder* (IMP), and the *Atmospheric Structure Instrument/Meteorology Package* (ASI /MET) which acts as a Mars meteorological station, collecting data about pressure, temperature, and winds. The MET structure included three windsocks mounted at three heights on a pole, the topmost at about one meter (yard) and generally registered winds from the West.

The *Sojourner* rover had a *Alpha Proton X-ray Spectrometer* (APXS), which was used to analyze the components of the rocks and soil. The rover also had two black and white cameras and a color one. These instruments could make investigations of the geology of the Martian surface from just a few millimeters to many hundreds of meters, the geochemistry and evolutionary history of the rocks and surface, the magnetic and mechanical properties of the land, as well as the magnetic properties of the dust, atmosphere and the rotational and orbital dynamics of the planet.

Pathfinder lander

1. Imager for Mars Pathfinder (IMP), (includes magnetometer and anemometer)

2. Atmospheric and meteorological sensors (ASI/MET)

Sojourner rover

1. Imaging system (three cameras: front B&W stereo, 1 rear color)
2. Laser striping hazard detection system
3. Alpha Proton X-ray Spectrometer (APXS)
4. Wheel Abrasion Experiment
5. Material Adherence Experiment
6. Accelerometers
7. Potentiometers

Landing site



Close-up of Mars sky at sunset, showing more color variation, as imaged by Mars Pathfinder

The landing site was an ancient flood plain in Mars's northern hemisphere called "Ares Vallis" ("the valley of Ares," the ancient Greek equivalent of the ancient Roman deity Mars) and is among the rockiest parts of Mars. Scientists chose it because they found it to be a relatively safe surface to land on and one that contained a wide variety of rocks deposited during a catastrophic flood. After the landing, at 19°08'N 33°13'W / 19.13°N 33.22°WCoordinates: 19°08'N 33°13'W / 19.13°N 33.22°W, succeeded, the landing site received the name *The Carl Sagan Memorial Station* in honor of the late astronomer and leader in the field of robotic spacecraft missions.

Entry, descent and landing

Mars Pathfinder entered the Martian atmosphere and landed using an innovative system involving an entry capsule, a supersonic parachute, followed by solid rockets and large airbags to cushion the impact.

Mars Pathfinder directly entered Mars atmosphere in a retrograde direction from a hyperbolic trajectory at 6.1 km/s using an atmospheric entry aeroshell (capsule) that was derived from the original Viking Mars lander design. The aeroshell consisted of a back shell and a specially designed ablative heatshield to slow to 370 m/s (830 MPH) where a supersonic disk-gap-band parachute was inflated to slow its descent through the thin Martian atmosphere to 68 m/s (about 160 MPH). The lander's on-board computer used redundant on-board accelerometers to determine the timing of the parachute inflation. Twenty seconds later the heatshield was pyrotechnically released. Another twenty seconds later the lander was separated and lowered from the backshell on a 20 m bridle (tether). When the lander reached 1.6 km above the surface, a radar was used by the on-board computer to determine altitude and descent velocity. This information was used by the computer to determine the precise timing the landing events that followed.



The Pathfinder air bags are tested in June 1995

Once the lander was 355 m above the ground, airbags were inflated in less than a second using three catalytically cooled solid rocket motors that served as gas generators. The airbags were made of 4 inter-connected multi-layer vectran bags that surrounded the tetrahedron lander. They were designed and tested to accommodate grazing angle impacts as high as 28 m/s. However, as the airbags were designed for no more than about 15 m/s vertical impacts, three solid retrorockets were mounted above the lander in the backshell. These were fired at 98 m above the ground. The lander's on-board computer estimated the best time to fire the rockets and cut the bridle so that the lander velocity would be reduced to about 0 m/s between 15 and 25 m above the ground. After 2.3 seconds, while the rockets were still firing, the lander cut the bridle loose about 21.5 m above the ground

and fell to the ground. The rockets flew up and away with the backshell and parachute (they have since been sighted by orbital images). The lander impacted at 14 m/s and limited the impact to only 18 G of deceleration. The first bounce was 15.7 m high and continued bouncing for at least 15 additional bounces (accelerometer data recording did not continue through all of the bounces).

The entire entry, descent and landing (EDL) process was completed in 4 minutes.

Once the lander stopped rolling, the airbags deflated and retracted toward the lander using four winches mounted on the lander "petals". Designed to right itself from any initial orientation, the lander happened to roll right side up onto its base petal. 74 minutes after landing, the petals were deployed with Sojourner rover and the solar panels attached on the inside.

The lander arrived at night at 2:56:55 Mars local solar time (16:56:55 UTC) on July 4, 1997. The lander had to wait until sunrise to send its first digital signals and images to Earth. The landing site was located at 19.30° north latitude and 33.52° west longitude in Ares Vallis, only 19 kilometres southwest of the center of the 200 km wide landing site ellipse. During Sol 1 –or martian days– the lander took pictures and made some meteorologic measurements. Once the data was received, the engineers realized that one of the airbags hadn't fully deflated and could be a problem for the forthcoming traverse of Sojourner's descent ramp. To solve the problem, they sent commands to the lander to raise one of its petals and perform additional retraction to flatten the airbag. The procedure was a success and on Sol 2, Sojourner was released, stood up and backed down one of two ramps.



Mars Pathfinder panorama of landing site taken by IMP

The Mars Pathfinder entry descent and landing system design was used (with some modification) on the Mars Exploration Rover mission. Likewise, many design aspects of the *Sojourner* rover (e.g. the rocker-bogie mobility architecture and the navigation algorithms) were also successfully used on the Mars Exploration Rover mission.

Rover operations

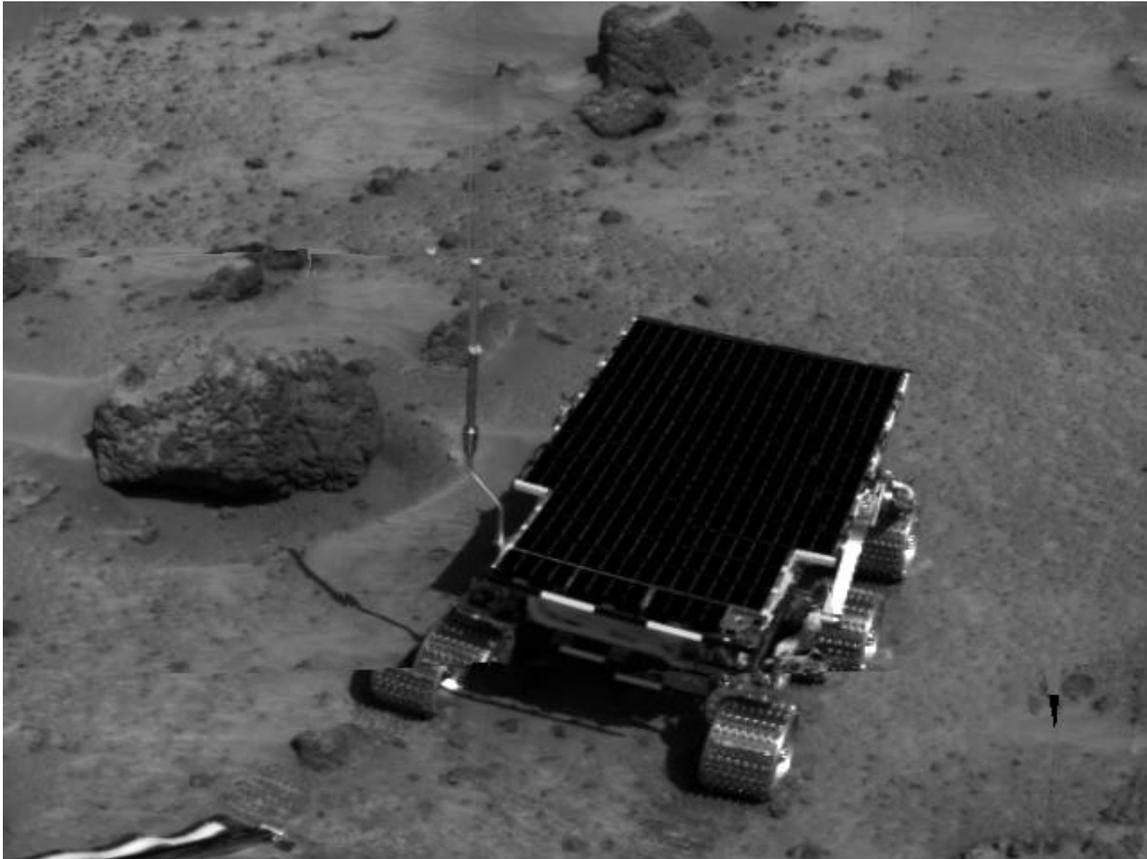
Sojourner deployment

The *Sojourner* rover was the second space exploration rover to reach another planet, and the first to be deployed. *Sojourner's* exit from the lander occurred on Sol 2, after its landing on July 4, 1997. As the next sols progressed it approached some rocks which

were named (by the scientists) "Barnacle Bill", "Yogi", and "Scooby Doo", after famous cartoon characters. The rover made measurements of the elements found in those rocks and in the martian soil, while the lander took pictures of the *Sojourner* and the surrounding terrain, besides making climate observations.

The *Sojourner* is a six-wheeled 65 cm long vehicle, 48 cm wide, 30 cm tall and weighs 10.5 kg. When operating, it could move about 500 meters from the lander and its maximum speed reached one centimeter per second. During its 83 sols of operation, it sent 550 photographs to Earth and analyzed the chemical properties of 16 locations near the lander.

Sojourner's rock analysis



Sojourner next to the rock "Barnacle Bill"

The first analysis on a rock started on Sol 3 with Barnacle Bill. The *Alpha Proton X-ray Spectrometer* (APXS) was used to determine its composition, the spectrometer taking ten hours to make a full scan of the sample. It found all the elements except hydrogen, which constitutes just 0.1 percent of the rock's or soil's mass.

The APXS works by irradiating rocks and soil samples with alpha particles (helium nuclei, which consist of two protons and two neutrons). The results indicated that "Barnacle Bill" is much like Earth's andesites, confirming past volcanic activity. The

discovery of andesites shows that some Martian rocks have been remelted and reprocessed. On Earth, Andesite forms when magma sits in pockets of rock while some of the iron and magnesium settle out. Consequently, the final rock contains less iron and magnesiums and more silica. Volcanic rocks are usually classified by comparing the relative amount of alkalis (Na_2O and K_2O) with the amount of silica (SiO_2). Andesite is different than the rocks found in meteorites that have come from Mars.

Analysis of the Yogi rock again using the APXS showed that it was a basaltic rock, more primitive than Barnacle Bill. Yogi's shape and texture show that it was probably deposited there by a flood.

Another rock, named "Moe", was found to have certain marks on its surface, demonstrating erosion caused by the wind. Most rocks analyzed showed a high content of silicon. In another region known as Rock Garden, *Sojourner* encountered crescent moon-shaped dunes, which are similar to crescentic dunes on Earth.

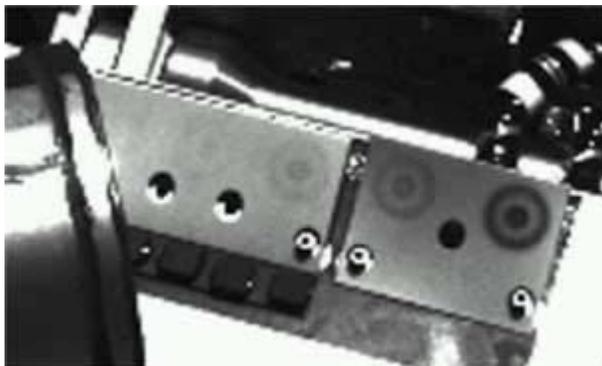
By the time that final results of the mission were described in a series of articles in the journal *Science* (December 5, 1997), it was believed that the rock Yogi contained a coating of dust, but was similar to the rock Barnacle Bill. Calculations suggest that the two rocks contain mostly the minerals orthopyroxene (magnesium-iron silicate), feldspars (aluminum silicates of potassium, sodium, and calcium), quartz (silicon dioxide), with smaller amounts of magnetite, ilmenite, iron sulfide, and calcium phosphate.

The lander, on the other hand, sent more than 16,500 pictures and made 8.5 million measurements of the atmospheric pressure, temperature and wind speed.

On-board computer

The embedded computer on board the *Sojourner* rover was based around the 100 kHz Intel 80C85 CPU with 512 KB of RAM and 176 KB of flash memory solid-state storage.

Results from Pathfinder

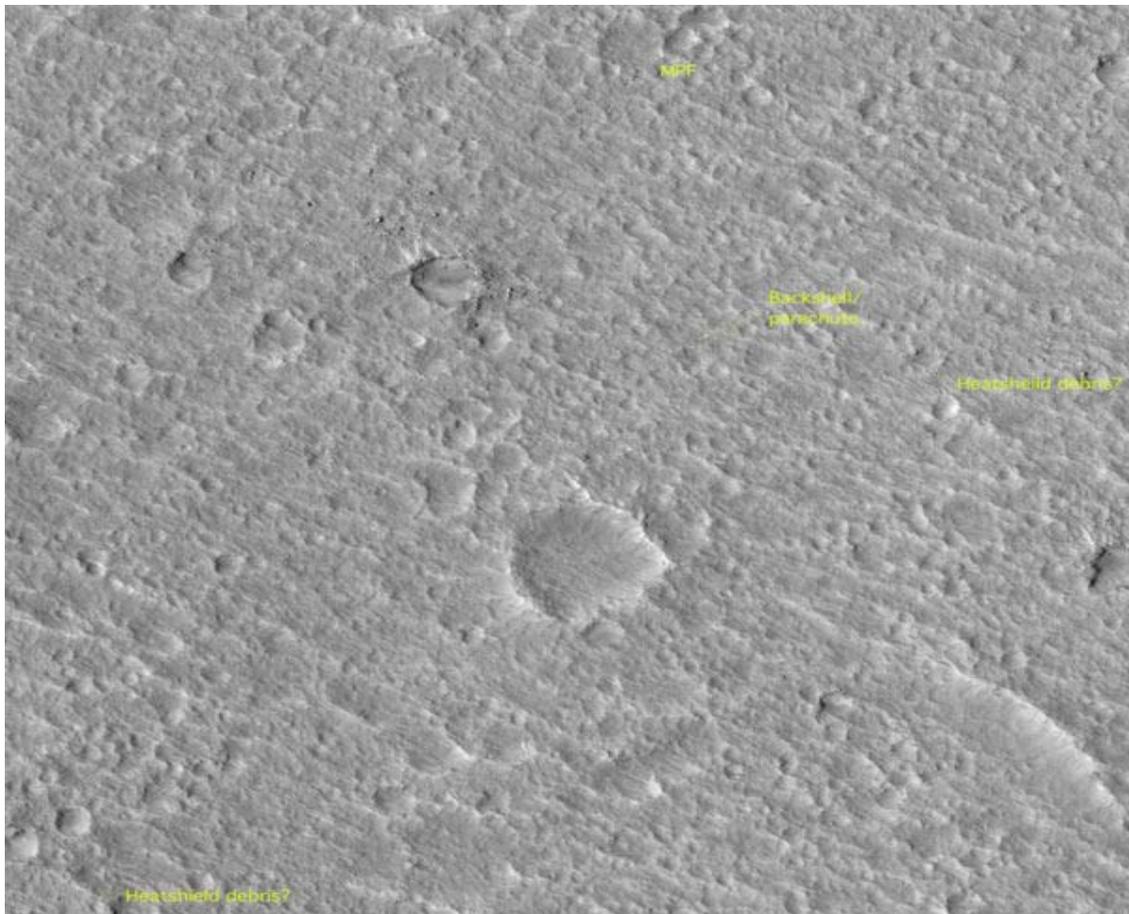


The magnet array experiment Pathfinder was developed by the Niels Bohr Institute led by Jens Martin Knudsen.

By taking multiple images of the sky at different distances from the sun, scientists were able to determine that the size of the particles in the pink haze was about 1 micrometer in radius. The color of some soils was similar to that of an iron oxyhydroxide phase which would support the theory of a warmer and wetter climate in the past. Pathfinder carried a series of magnets to examine the magnetic component of the dust. Eventually, all but one of the magnets developed a coating of dust. Since the weakest magnet did not attract any soil, it was concluded that the airborne dust did not contain pure magnetite or just one type of maghemite. The dust probably was an aggregate possibly cemented with ferric oxide (Fe_2O_3). Using much more sophisticated instruments, Mars Spirit Rover found that magnetite could explain the magnetic nature of the dust and soil on Mars. Magnetite was found in the soil and that the most magnetic part of the soil was dark. Magnetite is very dark.

Using Doppler tracking and two-way ranging, scientists added earlier measurements from the Viking landers to determine that the non-hydrostatic component of the polar moment of inertia is due to the Tharsis bulge and that the interior is not melted. The central metallic core is between 1300 km and 2000 km in radius.

End of mission



Mars Pathfinder seen from space by the MRO HiRISE

Although the mission was programmed to last a week to a month, it eventually lasted for almost three months. The final contact with the Pathfinder was at 10:23 UTC on September 27, 1997. Although the mission planners tried to restore contact during the following five months, the successful mission was terminated on March 10, 1998. After the landing, the Pathfinder was renamed as the *Sagan Memorial Station* in honor of astronomer and planetologist Carl Sagan. The mission had exceeded its goals in the first month.

Mars Reconnaissance Orbiter have spotted Pathfinder in January 2007 (right).

Naming the rover



Sojourner takes its Alpha Proton X-ray Spectrometer measurement of the Yogi Rock

The name Sojourner was chosen for the Mars Pathfinder rover after a year-long, worldwide competition in which students up to 18 years old were invited to select a heroine and submit an essay about her historical accomplishments. The students were asked to address in their essays how a planetary rover named for their heroine would translate these accomplishments to the Martian environment.

Initiated in March 1994 by The Planetary Society of Pasadena, California, in cooperation with NASA's Jet Propulsion Laboratory (JPL), the contest got under way with an announcement in the January 1995 issue of the National Science Teachers Association's magazine *Science and Children*, circulated to 20,000 teachers and schools across the nation.

Valerie Ambrose, 12, of Bridgeport, Connecticut, submitted the winning essay about Sojourner Truth, an African-American reformist who lived during the Civil War era. An abolitionist and champion of women's rights, Sojourner Truth, whose legal name was

Isabella Van Wagener, made it her mission to "travel up and down the land," advocating the rights of all people to be free and the rights of women to participate fully in society. The name *Sojourner* was selected because it means "traveler." JPL scientists and engineers working on the Mars Pathfinder project and Planetary Society staff members reviewed the 3,500 total entries received from all over the world, including essays from students living in Canada, India, Israel, Japan, Mexico, Poland and Russia. Nearly 1,700 of the essays were submitted by students aged 5 to 18 years old.

The selection of winners from this group by representatives from JPL and NASA Headquarters was based on several factors: the quality and creativity of the essay, taking into consideration the age of each contestant, the appropriateness of the name for a Mars rover, and the knowledge of the heroine, and the understanding of the Pathfinder rover's mission conveyed in the essay.

The second place prize winner was Deepti Rohatgi, 18, of Rockville, Maryland, who proposed naming the rover after Marie Curie, a Polish-born chemist who won the Nobel Prize in 1911 for her discovery of the elements radium and polonium. The test model identical to *Sojourner* used on earth was named Marie Curie. The third place prize went to Adam Sheedy, 16, of Round Rock, Texas, who chose the late astronaut Judith Resnik as his namesake for the new rover.

Honors



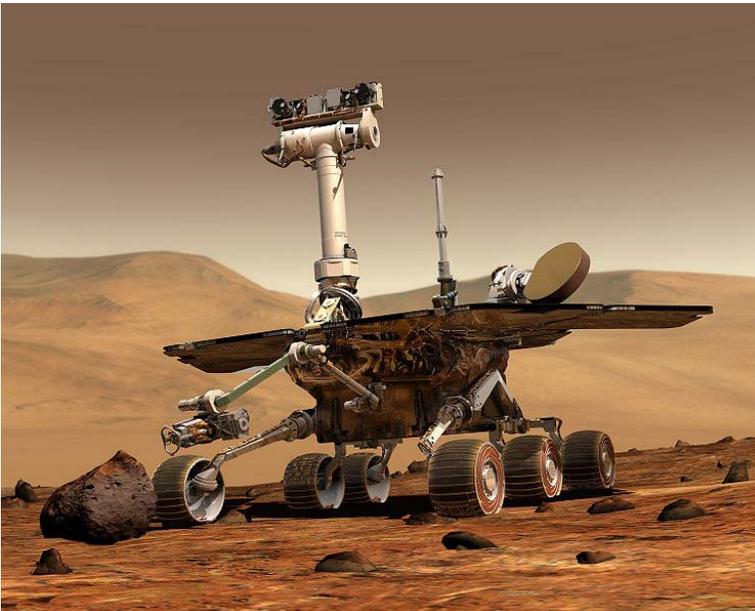
Wheel size comparison: *Sojourner*, Mars Exploration Rover, Mars Science Laboratory

- On October 21, 1997, at the Geological Society of America's annual meeting in Salt Lake City, Utah, *Sojourner* was awarded honorary membership in the Planetary Geology Division of the society.
- In 2003, *Sojourner* was inducted into the Robot Hall of Fame.
- Images of *Sojourner* approaching Yogi Rock were used in the opening credits of the *Star Trek: Enterprise* science fiction television program, the first historical use in a science fiction film or television program of video taken on the surface of another planet.

Chapter- 6

Spirit Rover

Spirit rover (MER-A)



Artist's Concept of Rover on Mars

Operator	NASA
Mission type	Rover
Orbital insertion date	Landed on January 4, 2004
Launch date	June 10, 2003
Launch vehicle	Delta II 7925 9.5 rocket
Mission duration	Planned: 90 Martian solar days (~92 Earth days) Current: 2567 Earth days since landing (1944 Earth days of mobility from

	landing to final embedding)
COSPAR ID	2003-027A
Homepage	JPL's Mars Exploration Rover home page
Mass	185 kg (408 lb)
Power	Solar panels
Batteries	Rechargeable lithium ion batteries



The launch patch for *Spirit*, featuring Marvin the Martian

Spirit, mission designation **MER-A (Mars Exploration Rover - A)**, is the first of the two rovers of NASA's ongoing Mars Exploration Rover Mission. It landed successfully on Mars at 04:35 Ground UTC on January 4, 2004, three weeks before its twin, *Opportunity* (MER-B), landed on the other side of the planet. Its name was chosen through a NASA-sponsored student essay competition.

The rover completed its planned 90-sol mission. Aided by cleaning events that resulted in higher power from its solar panels, *Spirit* went on to function effectively over twenty times longer than NASA planners expected following mission completion. *Spirit* also logged about 10 kilometers of driving instead of the planned 1 km, allowing more extensive geological analysis of Martian rocks and planetary surface features. Initial scientific results from the first phase of the mission (the 90-sol prime mission) were published in a special issue of the journal *Science*.

On May 1, 2009 (5 years, 3 months, 27 Earth days after landing; 21.6 times the planned mission duration), *Spirit* became stuck in soft soil. This was not the first of the mission's

"embedding events" and for the following eight months NASA carefully analyzed the situation, running Earth-based theoretical and practical simulations, and finally programming the rover to make extrication drives in an attempt to free itself. These efforts continued until January 26, 2010 (6 years and 22 days after landing; 24.6 times the planned mission duration), when NASA officials announced that the rover was likely irrecoverably obstructed by its location in soft soil, though it will continue to perform scientific research from its current location.

There has been no communication with Spirit since sol 2210 (March 22, 2010) and there is some concern that the rover was not able to survive the Martian winter. However, the rover team plans to continue to attempt to contact the lander, which may be hibernating while increasing solar levels charge its batteries, until at least summer solstice at Spirit's location in March 2011.

The Jet Propulsion Laboratory (JPL), a division of the California Institute of Technology in Pasadena, manages the Mars Exploration Rover project for NASA's Office of Space Science, Washington.

Objectives



Delta II Heavy lifting off with MER-A on June 10, 2003

The scientific objectives of the Mars Exploration Rover mission are to:

- Search for and characterize a variety of rocks and soils that hold clues to past water activity. In particular, samples sought will include those that have minerals deposited by water-related processes such as precipitation, evaporation, sedimentary cementation or hydrothermal activity.
- Determine the distribution and composition of minerals, rocks, and soils surrounding the landing sites.
- Determine what geologic processes have shaped the local terrain and influenced the chemistry. Such processes could include water or wind erosion, sedimentation, hydrothermal mechanisms, volcanism, and cratering.
- Perform calibration and validation of surface observations made by Mars Reconnaissance Orbiter instruments. This will help determine the accuracy and effectiveness of various instruments that survey Martian geology from orbit.
- Search for iron-containing minerals, identify and quantify relative amounts of specific mineral types that contain water or were formed in water, such as iron-bearing carbonates.
- Characterize the mineralogy and textures of rocks and soils and determine the processes that created them.
- Search for geological clues to the environmental conditions that existed when liquid water was present.
- Assess whether those environments were conducive to life.

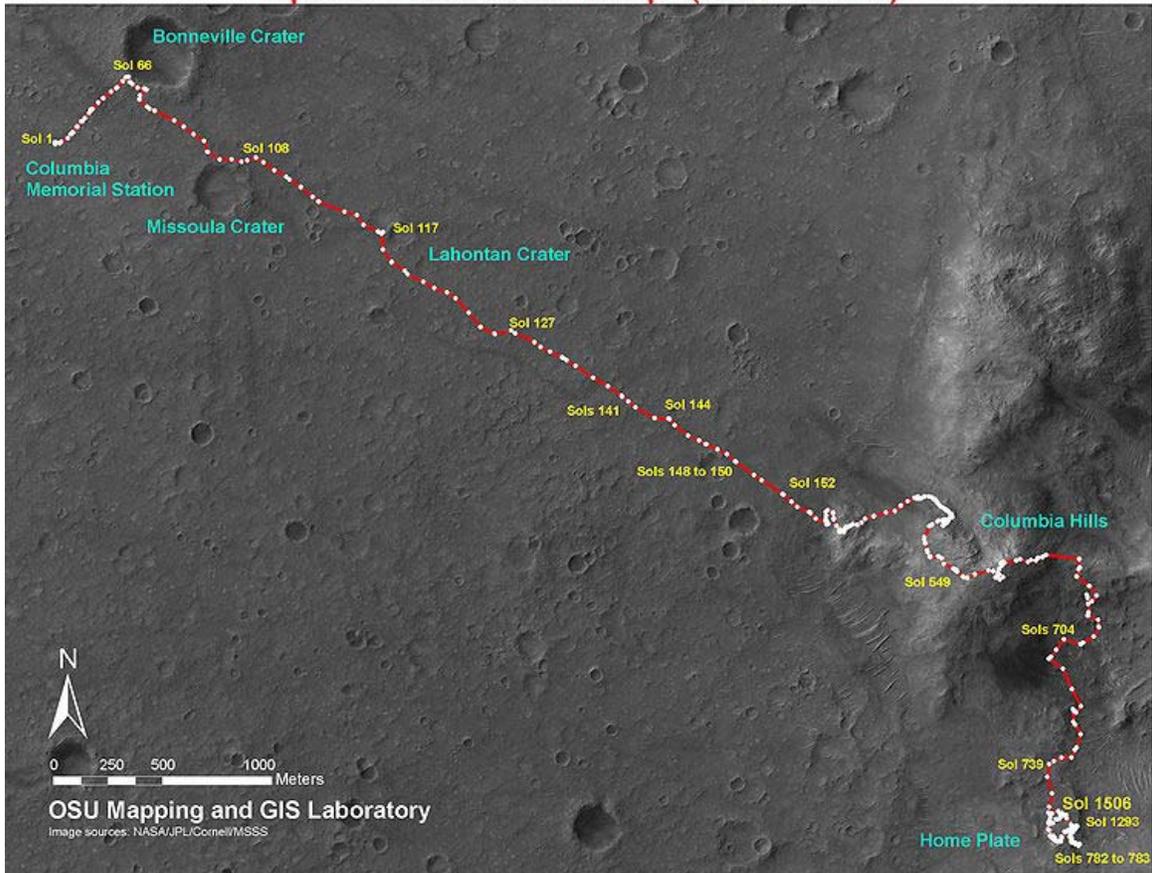
During the next two decades, NASA will continue to conduct missions to address whether life ever arose on Mars. The search begins with determining whether the Martian environment was ever suitable for life. Life, as we understand it, requires water, so the history of water on Mars is critical to finding out if the Martian environment was ever conducive to life. Although the Mars Exploration Rovers do not have the ability to detect life directly, they are offering very important information on the habitability of the environment during the planet's history.

Design and construction

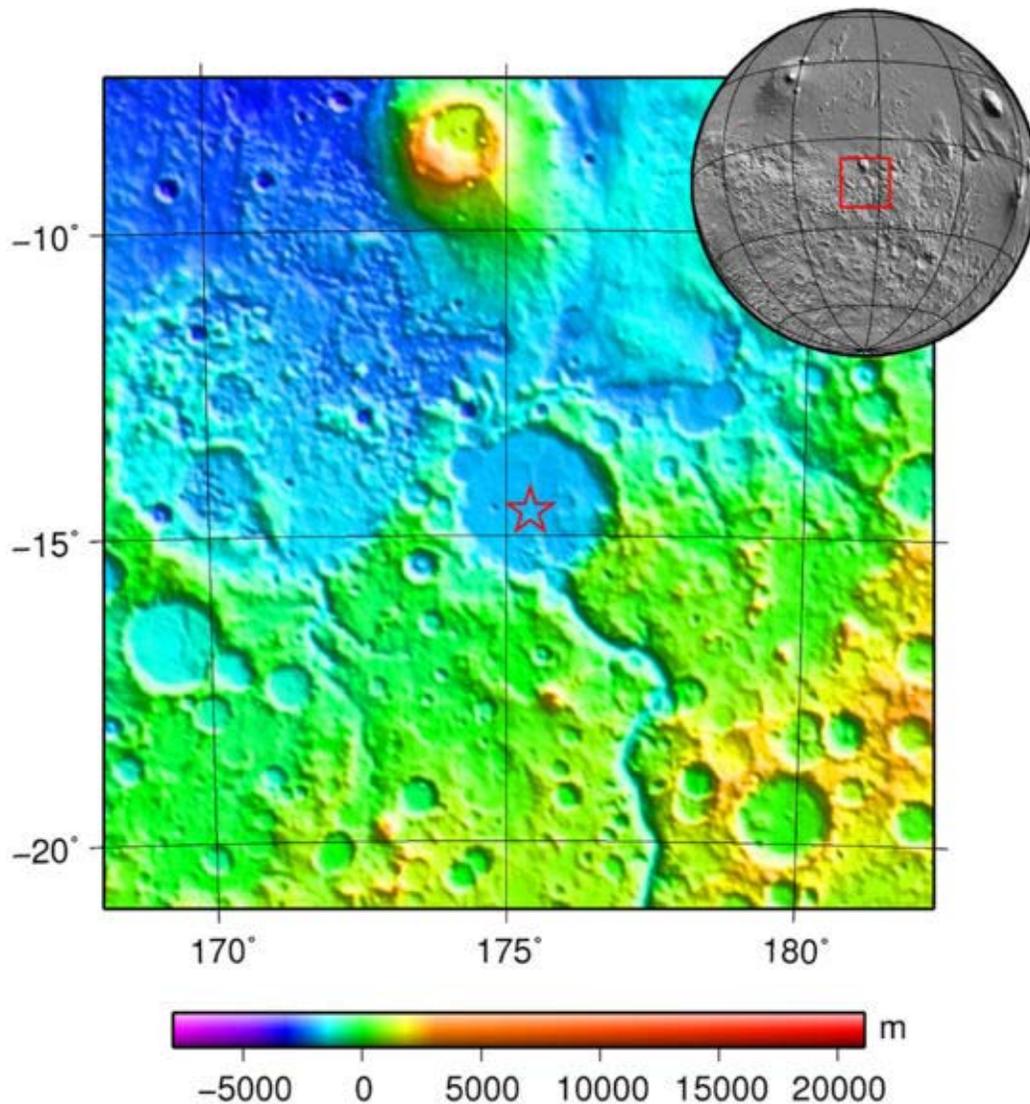


Spirit landing site, as imaged by MRO (2006-12-04)

Spirit Traverse Map (Sol 1506)



Current *Spirit* traverse map, to sol 1506 (April 02, 2008). The landing site is in the upper left



An overall view of MER-A *Spirit* landing site (denoted with a star)

Spirit (and its twin, *Opportunity*) are six-wheeled, solar-powered robots standing 1.5 m (4.9 ft) high, 2.3 m (7.5 ft) wide and 1.6 m (5.2 ft) long and weighing 180 kg (400 lb). Six wheels on a rocker-bogie system enable mobility over rough terrain. Each wheel has its own motor. The vehicle is steered at front and rear and is designed to operate safely at tilts of up to 30 degrees. Maximum speed is 50 mm/s (2 in/s); 1.8 km/h, although average speed is about 10 mm/s (0.4 in/s). Both *Spirit* and *Opportunity* have pieces of the fallen World Trade Center's metal on them which were "turned into shields to protect cables on the drilling mechanisms".

Solar arrays generate about 140 watts for up to four hours per Martian day (sol) while rechargeable lithium ion batteries store energy for use at night. *Spirit's* onboard computer uses a 20 MHz RAD6000 CPU with 128 MB of DRAM, 3 MB of EEPROM, and 256

MB of flash memory. The rover's operating temperature ranges from $-40\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$ to $104\text{ }^{\circ}\text{F}$) and Radioisotope heater units provide a base level of heating, assisted by electrical heaters when necessary. A gold film and a layer of silica aerogel provide insulation.

Communications depends on an omnidirectional low-gain antenna communicating at a low data rate and a steerable high-gain antenna, both in direct contact with Earth. A low gain antenna is also used to relay data to spacecraft orbiting Mars.

Fixed science instruments include

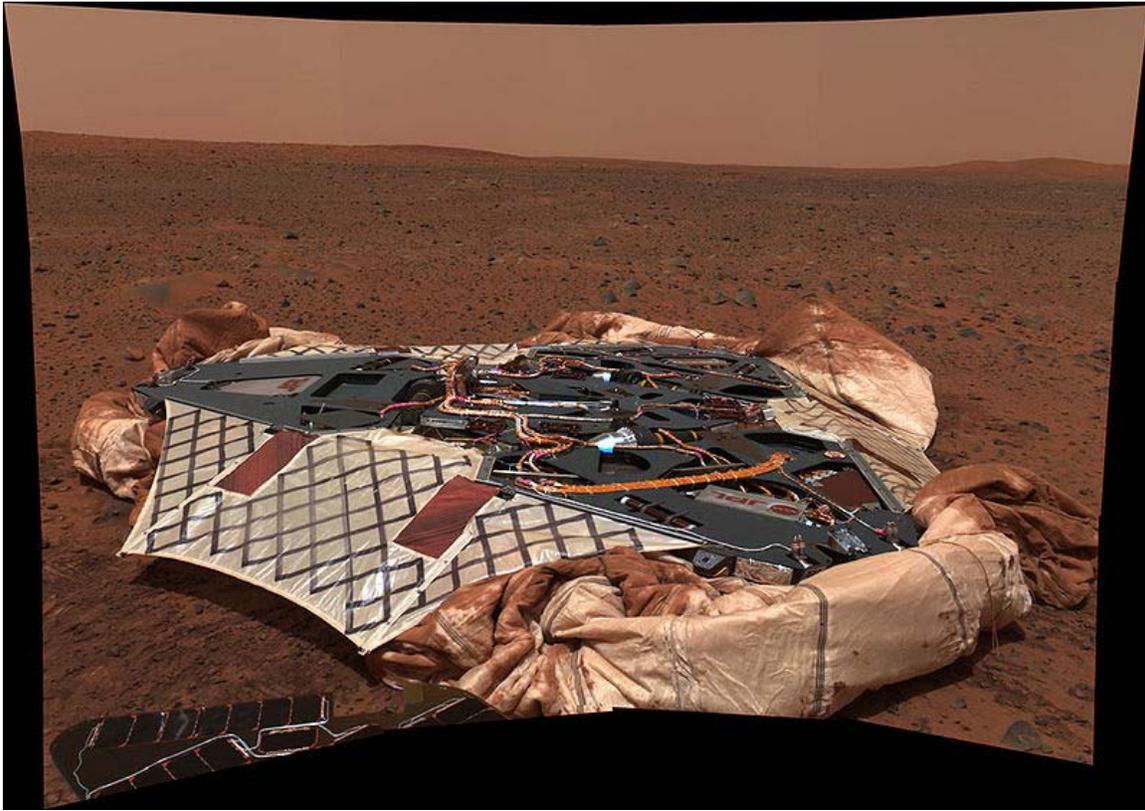
- Panoramic Camera (Pancam) - examines the texture, color, mineralogy, and structure of the local terrain.
- Navigation Camera (Navcam) - monochrome with a higher field of view but lower resolution, for navigation and driving.
- Miniature Thermal Emission Spectrometer (Mini-TES) - identifies promising rocks and soils for closer examination, and determines the processes that formed them.

The rover arm holds the following instruments

- Mössbauer spectrometer (MB) MIMOS II - used for close-up investigations of the mineralogy of iron-bearing rocks and soils.
- Alpha particle X-ray spectrometer (APXS) - close-up analysis of the abundances of elements that make up rocks and soils.
- Magnets - for collecting magnetic dust particles.
- Microscopic Imager (MI) - obtains close-up, high-resolution images of rocks and soils.
- Rock Abrasion Tool (RAT) - exposes fresh material for examination by instruments on-board.

The cameras produce 1024-pixel by 1024-pixel images, the data is compressed, stored, and transmitted later.

Mission overview



Spirit rover images its lander on the surface of Mars on January 18/19th 2004 (*Spirit* Sol 16)

The primary surface mission for *Spirit* was planned to last at least 90 sols. The mission has received several extensions and as of 8 April 2009 had passed 1,800 sols. On August 11, 2007, *Spirit* obtained the second longest operational duration on the surface of Mars for a lander or rover at 1282 Sols, one Sol longer than the Viking 2 lander. Viking 2 was powered by a nuclear cell whereas *Spirit* is powered by solar arrays. Currently the Mars probe with longest operational period is Viking 1 which lasted for 2245 Sols on the surface of Mars. Should *Spirit* still be operational on April 29, 2010, at 2246 Sols it would surpass Viking 1 as having longest operational duration on the surface of Mars for a lander or rover. However, due to a low power fault, it is unclear if the rover is still operational. An archive of weekly updates on the rover's status can be found at the *Spirit* Update Archive.

Spirit's total odometry as of February 1, 2010 (sol 2165) is 7,730.48 meters (4.80 mi).

Mission timeline

2004

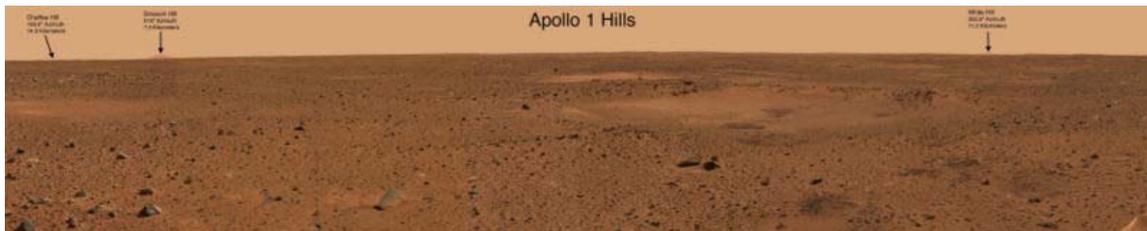
The *Spirit* Mars rover and lander arrived successfully on the surface of Mars on 04:35 Ground UTC on January 4, 2004. This was the start of its 90-sol mission, but solar cell cleaning events would mean it was the start of a much longer mission, lasting at least until 2010.

Landing site: Columbia Memorial Station

Spirit was targeted to a site that appears to have been affected by liquid water in the past, the crater Gusev, a possible former lake in a giant impact crater about 10 km from the center of the target ellipse at 14°34'18"S 175°28'43"E / 14.5718°S 175.4785°E.

After the airbag-protected landing craft settled onto the surface, the rover rolled out to take panoramic images. These give scientists the information they need to select promising geological targets and drive to those locations to perform on-site scientific investigations.

The panoramic image below shows a slightly rolling surface, littered with small rocks, with hills on the horizon up to 27 km away. The MER team named the landing site "Columbia Memorial Station," in honor of the seven astronauts killed in the Space Shuttle *Columbia* disaster.



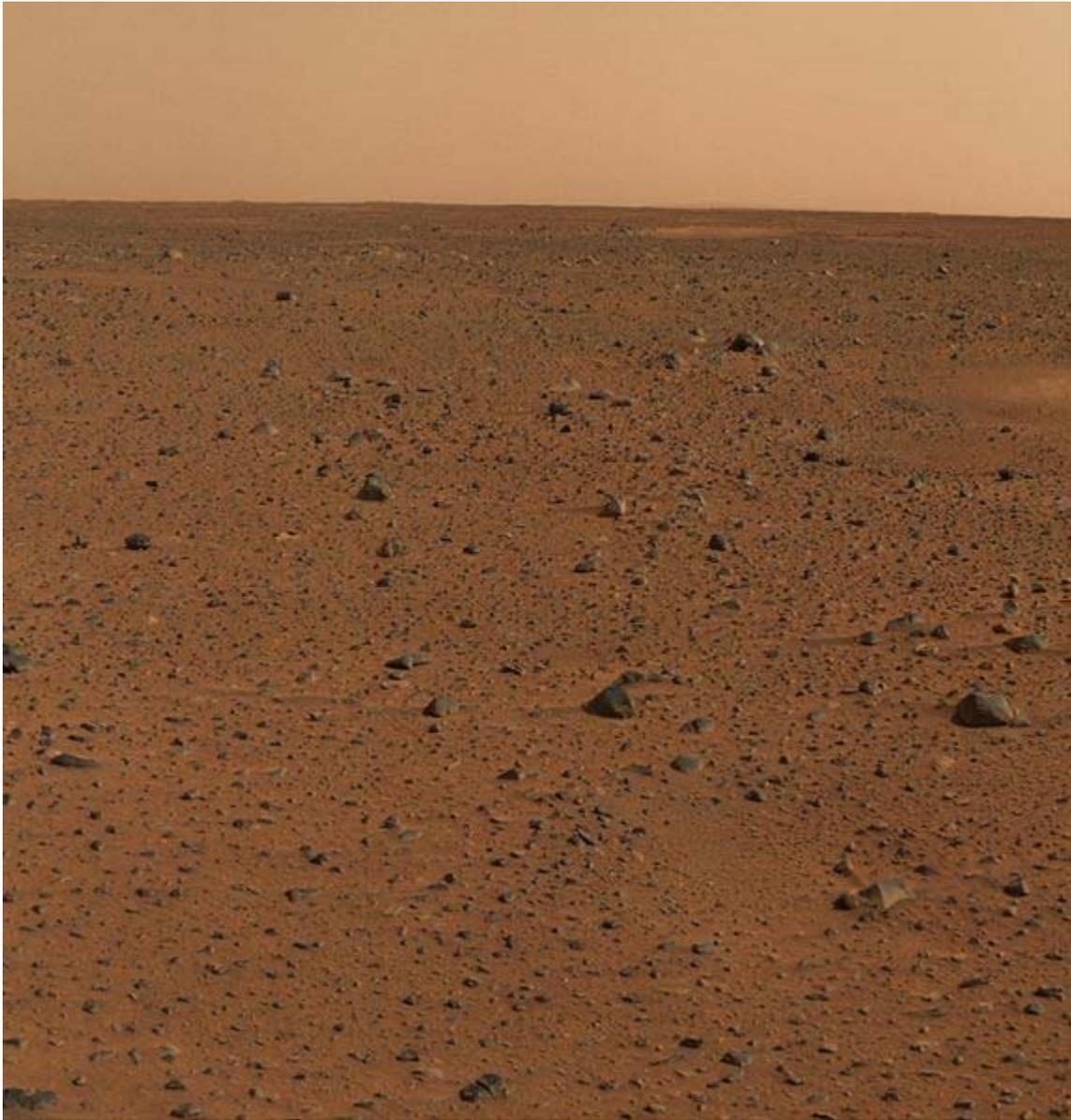
Apollo Hills panorama from the *Spirit* landing site

Sleepy Hollow

"Sleepy Hollow," a shallow depression in the Mars ground at the right side of the above picture, was targeted as an early destination when the rover drove off its lander platform. NASA scientists were very interested in this crater. It is 9 meters (30 feet) across and about 12 meters (40 feet) north of the lander.

"Just as the ancient mariners used sextants for 'shooting the Sun,' as they called it, we were successfully able to shoot the Sun with our panorama camera, then use that information to point the antenna," said JPL's Matt Wallace, mission manager.

First color image



The first color image compiled from images taken by Spirit; it was the highest resolution color image taken on another planet.

To the left is the first color image derived from images taken by the panoramic camera on the Mars Exploration Rover *Spirit*. It was the highest resolution image taken on the surface of another planet. "We're seeing a panoramic mosaic of four pancam images high by three wide," said camera designer Jim Bell of Cornell University. The picture shown originally had a full size of 4,000 by 3,000 pixels. However, a complete pancam panorama is even 8 times larger than that, and could be taken in stereo (i.e., two complete pictures, making the resolution twice as large again.) The colors are fairly accurate.

The MER pancams are black-and-white instruments. Thirteen rotating filter wheels produce multiple images of the same scene at different wavelengths. Once received on earth, these images can be combined to produce color images.

Sol 18 (January 21, 2004) flash memory management anomaly



Rover tracks on sol 85 from Mars Global Surveyor

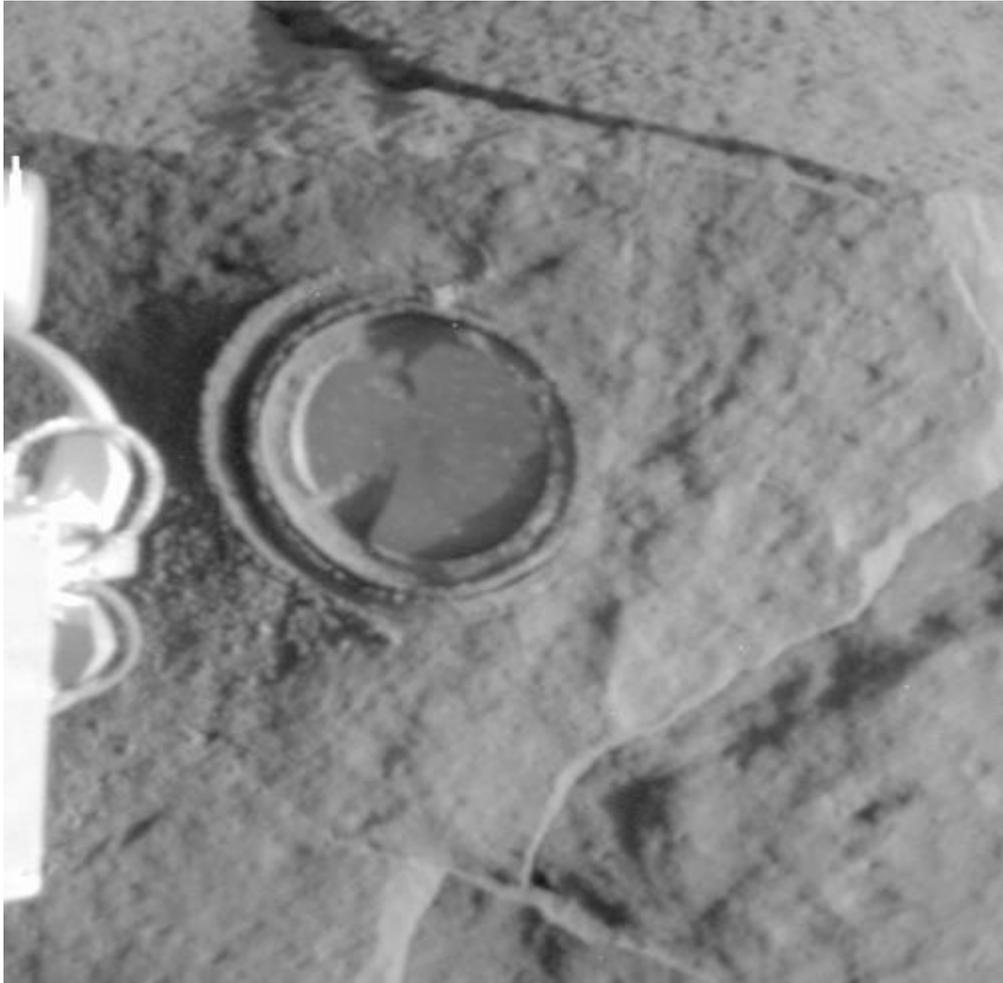
On January 21, 2004 (Sol 18), *Spirit* abruptly ceased communicating with mission control. The next day the rover radioed a 7.8 bit/s beep, confirming that it had received a transmission from Earth but indicating that the craft believed it was in a fault mode. Commands would only be responded to intermittently. This was described as a very serious anomaly, but potentially recoverable if it were a software or memory corruption issue rather than a serious hardware failure. *Spirit* was commanded to transmit engineering data, and on January 23 sent several short low-bitrate messages before finally transmitting 73 megabits via X band to *Mars Odyssey*. The readings from the engineering data suggested that the rover was not staying in sleep mode. As such, it was wasting its battery power and overheating — risk factors that could potentially destroy the rover if not fixed soon. On Sol 20, the command team sent it the command SHUTDWN_DMT_TIL ("Shutdown Dammit Until <time>") to try to cause it to suspend itself until a given time. It seemingly ignored the command.

The leading theory at the time was that the rover was stuck in a "reboot loop". The rover was programmed to reboot if there was a fault aboard. However, if there was a fault that occurred during reboot, it would continue to reboot forever. The fact that the problem persisted through reboot suggested that the error was not in RAM, but in either the flash memory, the EEPROM, or a hardware fault. The last case would likely doom the rover. Anticipating the potential for errors in the flash memory and EEPROM, the designers had made it so that the rover could be booted without ever touching the flash memory. The radio itself could decode a limited command set — enough to tell the rover to reboot without using flash. Without access to flash memory, *Spirit* booted fine, and the reboot cycle was broken.

On January 24 the rover repair team announced that the problem was with *Spirit's* flash memory and the software that wrote to it. The flash hardware was believed to be working correctly but the file management module in the software was "not robust enough" for the operations the *Spirit* was engaged in when the problem occurred, indicating that the problem was caused by a software bug as opposed to faulty hardware. NASA engineers finally came to the conclusion that there were too many files on the file system, which

was a relatively minor problem. Most of these files contained unneeded in-flight data. After realizing what the problem was, the engineers deleted some files, and eventually reformatted the entire flash memory system. On February 6 (Sol 33), the rover was restored to its original working condition, and science activities resumed.

First intentional grinding of a rock on Mars



Digital camera (the Pancam) image of a Mars rock (called Adirondack) taken after a RAT grind (the rock grinding tool)

The round, shallow depression in this image resulted from the first intentional grinding of a rock on Mars. The Rock Abrasion Tool (aka "RAT") on NASA's *Spirit* rover ground off the surface of a patch 45.5 millimeters (1.895 inches) in diameter on a rock called Adirondack during *Spirit's* 34th sol on Mars, February 6, 2004. The hole is 2.65 millimeters (0.1 inch) deep, exposing fresh interior material of the rock for close inspection with the rover's microscopic imager and two spectrometers on the robotic arm. This image was taken by *Spirit's* panoramic camera, providing a quick visual check of the success of the grinding.

"The RAT performed beyond our expectations," beamed Steve Gorevan, of Honeybee Robotics, New York, lead scientist for the rock abrasion tools on both rovers. "With the docile cutting parameters we set, I didn't think that it would cut this deep. In fact, when we saw virtually a complete circle, I was thrilled beyond anything I could have ever dreamed. Following up that glorious circular brushing — it's like back-to-back homers."

Mimi rock (Sol 40)



False color image of "Mimi"

This color image taken by the Mars Exploration Rover *Spirit's* panoramic camera on Sol 40 (February 13, 2004) is centered on an unusually flaky rock called Mimi. Mimi is only one of many features in the area known as "Stone Council", but looks very different from any rock that scientists have seen at the Gusev crater site so far. Mimi's flaky appearance leads scientists to a number of hypotheses. Mimi could have been subjected to pressure either through burial or impact, or may have once been a dune that was cemented into flaky layers, a process that sometimes involves the action of water.

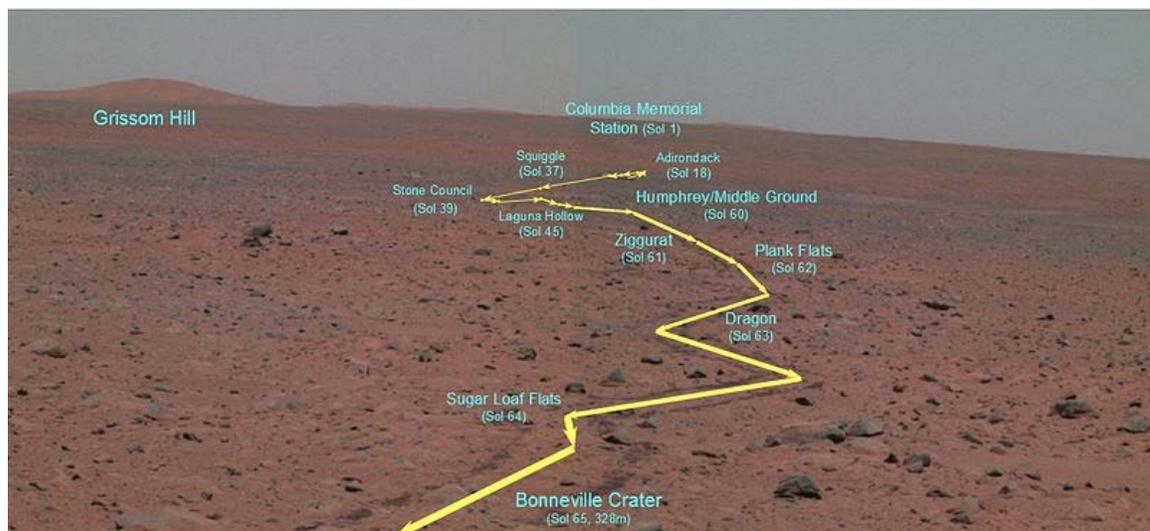
Humphrey and clues for water

On March 5, 2004, NASA announced that *Spirit* had found hints of water history on Mars in a rock dubbed "Humphrey". Dr. Raymond Arvidson, Ph.D., the McDonnell University Professor and chair of Earth and planetary sciences at Washington University in St. Louis, reported during a NASA press conference: "If we found this rock on Earth, we would say it is a volcanic rock that had a little fluid moving through it." In contrast to the rocks found by the twin rover *Opportunity*, this one was formed from magma and then acquired bright material in small crevices, which look like crystallized minerals. If this interpretation holds true, the minerals were most likely dissolved in water, which was either carried inside the rock or interacted with it at a later stage, after it formed.

Bonneville Crater

On March 11, 2004, the *Spirit* rover reached Bonneville crater after a 400-yard (370 m) journey. This crater is about 200 meters (220 yd) across with a floor about 10 metres (11 yd) below the surface. JPL decided that it would be a bad idea to send the rover down into the crater, as they saw no targets of interest inside. *Spirit* drove along the southern rim and continued to the southwest towards the Columbia Hills.

Spirit Rover Traverse – Bonneville Crater (Sol 65)



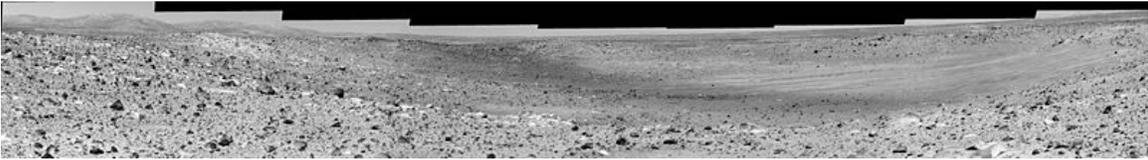
Mapping and GIS Laboratory, OSU

Looking back at the lander



Bonneville Crater

Missoula and Lahontan Craters, en route to Columbia Hills



Missoula Crater

Spirit reached Missoula crater on Sol 105. The crater is roughly 100 yards (91 m) across and 20 yards (18 m) deep. Missoula crater was not considered a high priority target due to the older rocks it contained. The rover skirted the northern rim, and continued to the southeast.



Lahontan crater on Sol 120

It then reached Lahontan crater on Sol 118, and drove along the rim until Sol 120. Lahontan is about 60 yards (55 m) across and about 10 yards (9.1 m) deep. A long, snaking sand dune stretches away from its southwestern side, and *Spirit* went around it, because loose sand dunes present an unknown risk to the ability of the rover wheels to get traction.

Columbia Hills

On Sol 159, *Spirit* reached the first of many targets at the base of the Columbia Hills called West Spur. Hank's Hollow was studied for 23 sols. Within Hank's Hollow was the strange looking rock dubbed "Pot of Gold".

From here, *Spirit* took a northerly path along the base of the hill towards the target Woolly Patch, which was studied from Sol 192 to Sol 199. By Sol 203, *Spirit* had driven southward up the hill and arrived at the rock dubbed "Clovis". Clovis was ground and analyzed from Sol 210 to Sol 225. Following Clovis came the targets of Ebenezer (Sols 226-235), Tetl (Sol 270), Uchben and Palinque (Sols 281-295), and Lutefisk (Sols 296-303). From Sols 239 to 262, *Spirit* powered down for solar conjunction, when communications with the Earth are blocked.

Slowly, *Spirit* has made its way around the summit of Husband Hill, and at Sol 344 was ready to climb over the newly designated "Cumberland Ridge" and into "Larry's Lookout" and "Tennessee Valley".

2005-2006

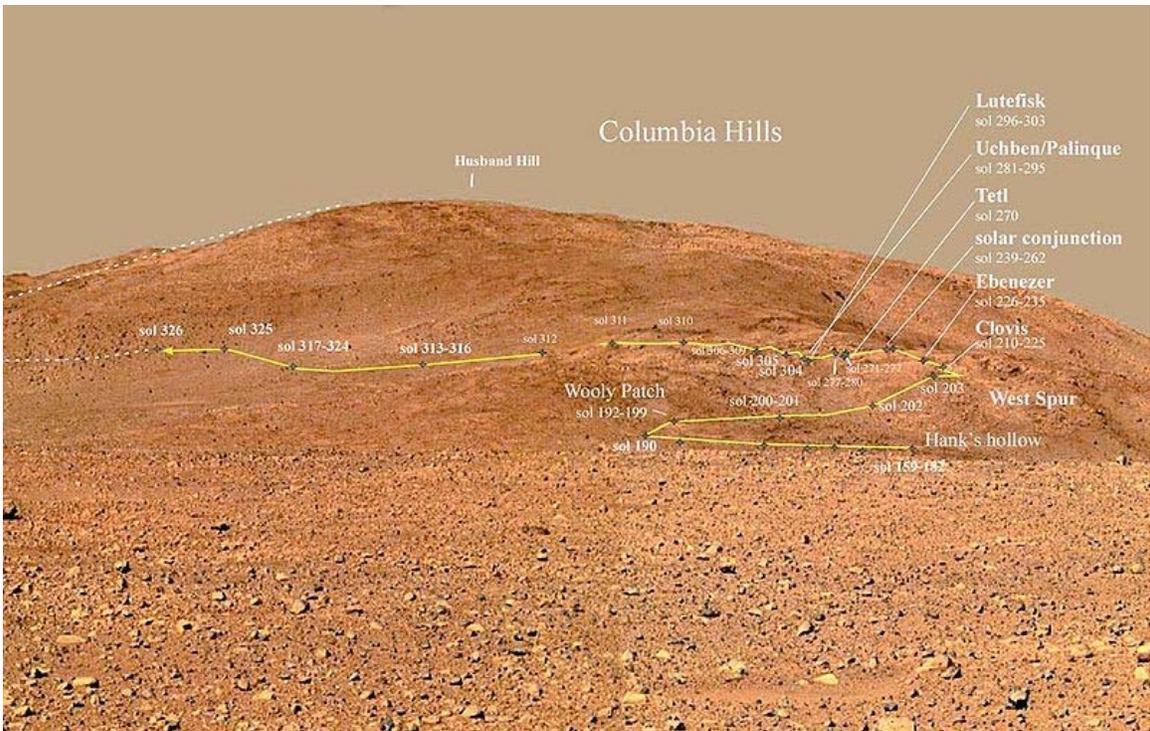
On Sol 371, *Spirit* arrived at a rock named "Peace" near the top of Cumberland Ridge. *Spirit* ground it with the RAT on Sol 373.

By Sol 390 (Mid-February 2005), *Spirit* was advancing towards "Larry's Lookout", by driving up the hill in reverse. The scientists at this time were trying to conserve as much energy as possible for the climb.

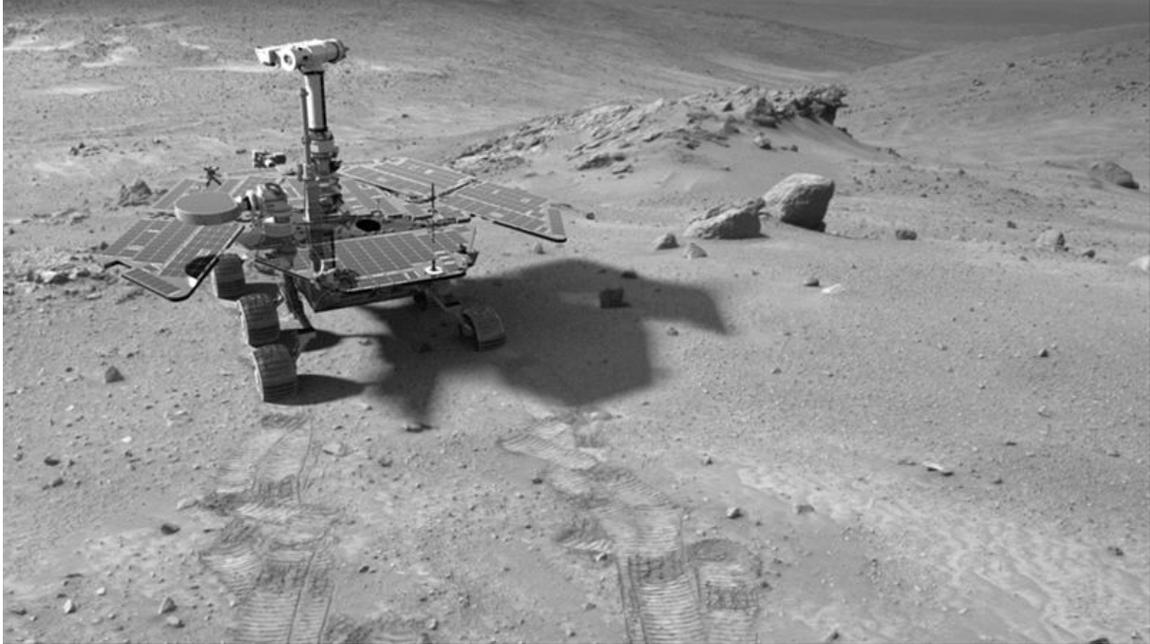
Spirit also investigated some targets along the way, including the soil target, "Paso Robles", which contained the highest amount of salt found on the red planet. The soil also contained a high amount of phosphorus in its composition, however not nearly as high as another rock sampled by *Spirit*, "Wishstone". Squyres said of the discovery, "We're still trying to work out what this means, but clearly, with this much salt around, water had a hand here".



Pot of Gold rock



Spirit's traverse up Husband Hill

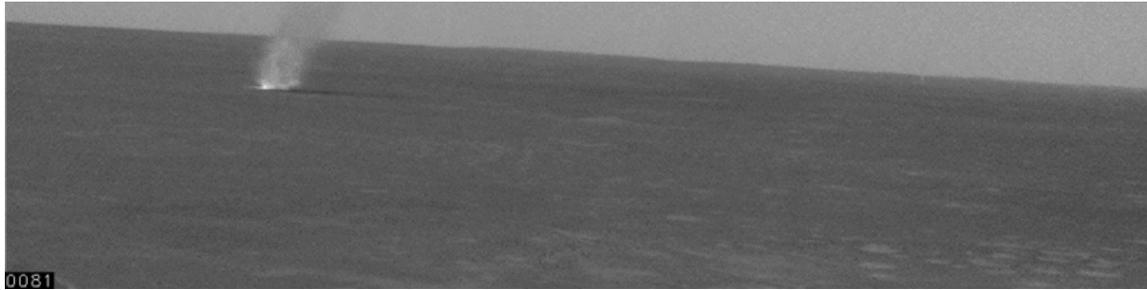


Spirit artificially added to image (taken by itself) of Larry's Lookout



Photograph of a Martian sunset taken by *Spirit* at Gusev crater, May 19, 2005

Dust devils



Dust devil on Mars, photographed by the Mars rover *Spirit*. The counter in the bottom-left corner indicates time in seconds after the first photo was taken in the sequence. At the final frames, one can see that the dust devil has left a trail on the Martian surface. Three other dust devils also appear in the background.

On March 9, 2005 (probably during the Martian night), the rover's solar panel efficiency jumped from around 60% of what it had originally been to 93%, followed on 10 March by the sighting of dust devils. NASA scientists speculate a dust devil must have swept the solar panels clean, possibly significantly extending the duration of the mission. This also marks the first time dust devils had been spotted by either *Spirit* or *Opportunity*, easily one of the top highlights of the mission to date. Dust devils had previously been photographed by only the *Pathfinder* probe.

Mission members monitoring the *Spirit* rover on Mars reported on March 12, 2005, that a lucky encounter with a dust devil had cleaned the solar panels of that robot. Power levels dramatically increased and daily science work was anticipated to be expanded.

Husband Hill summit

On Sol 582, August 21, 2005, *Spirit* reached the summit of Husband Hill and acquired a 360 degree panorama picture.



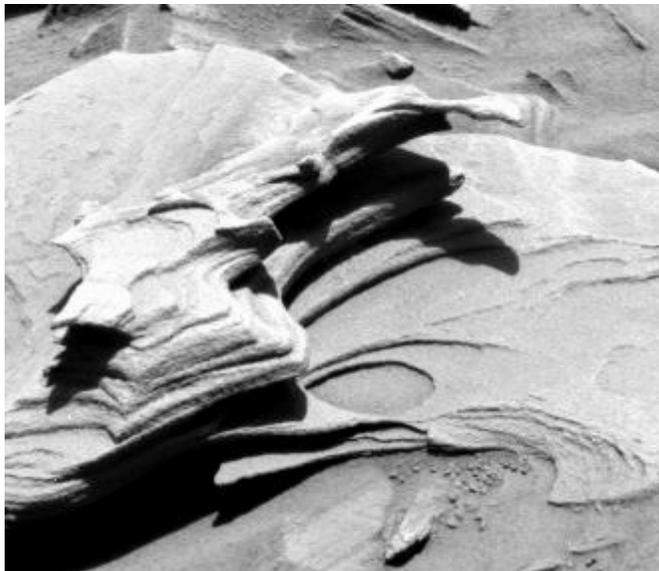
View from the Summit taken by *Spirit* on August 23, 2005 as the rover completed climb up "Husband Hill."



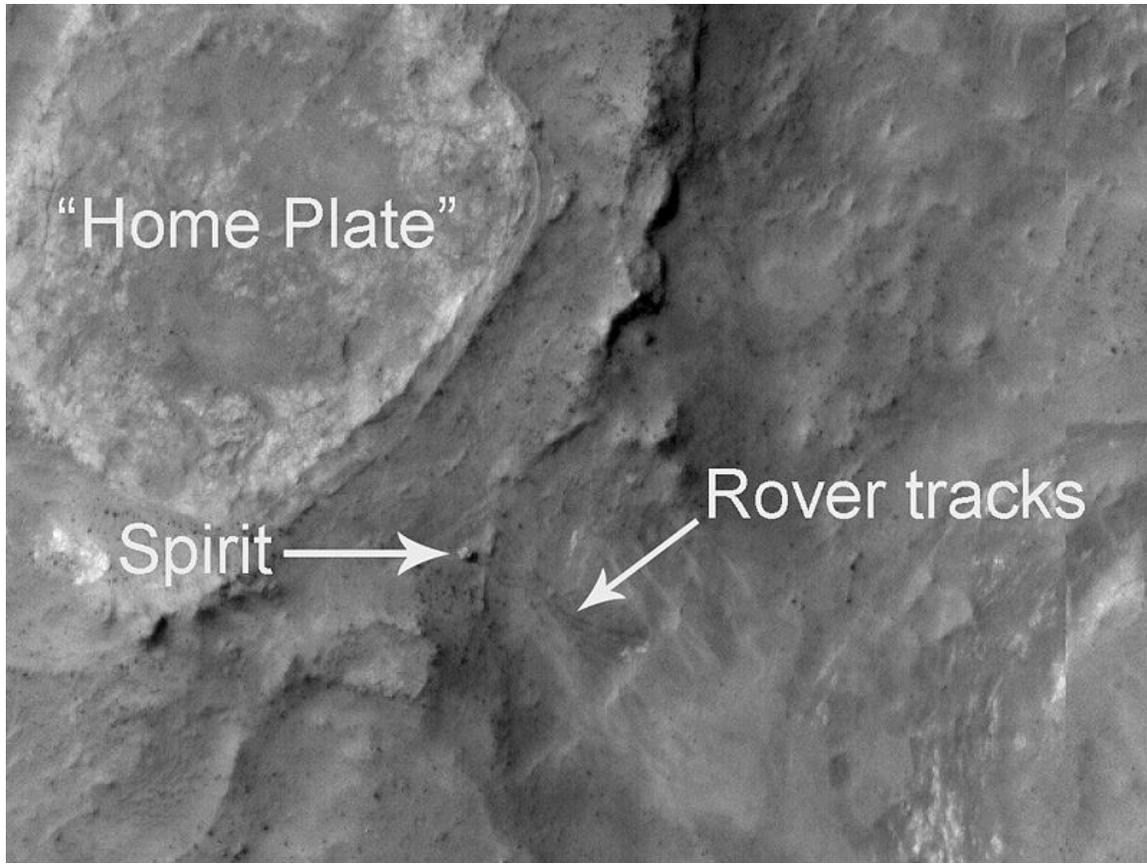
Vista while descending Husband Hill

Home Plate (Sol 744)

Spirit arrived at the north west corner of Home Plate, a raised and layered outcrop on sol 744 after an effort to maximize driving. Scientific observations have been conducted with *Spirit's* robotic arm.



Curious rock near edge of "Home Plate" with a jutting portion



Picture of Spirit, including tracks, taken from the Mars Reconnaissance Orbiter

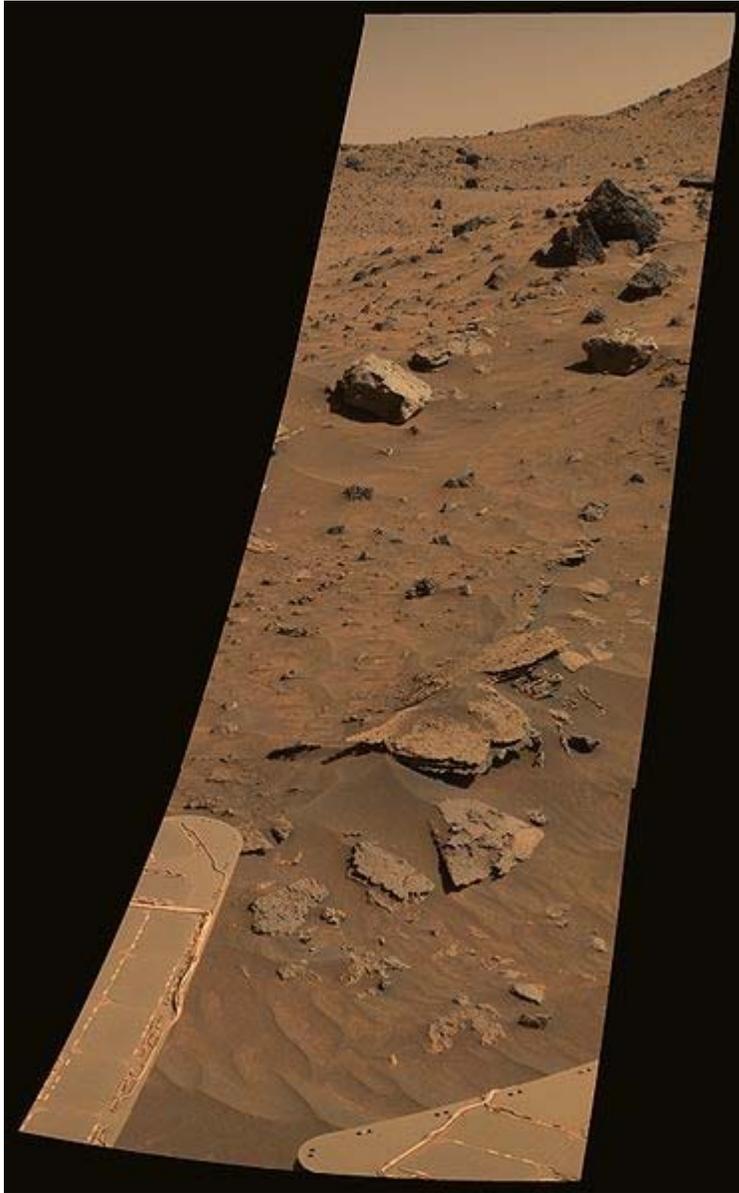
During 2007 *Spirit* spent several months near the base of the Home Plate plateau. On sol 1306 *Spirit* climbed onto the eastern edge of the plateau. In September and October it examined rocks and soils at several locations on the southern half of the plateau. On November 6, *Spirit* had reached the western edge of Home Plate, and started taking pictures for a panoramic overview of the western valley, with Grissom Hill and Husband Hill visible. The panorama image was published on NASA's website on January 3, 2008 to little attention, until January 23, when an independent website (Image w/ closeup) published a magnified detail of the left side of the original image in which is visible what looks much like a dark green humanoid sitting on a rock or walking down a hill with the right arm raised. This strange formation is also visible when viewing the image in full resolution on the NASA website. The presence of the feature in all separate images which were combined to make the color image as well as NavCam images from several days earlier, conclusively show that it is a permanent feature.

McCool Hill

Spirit's next stop was originally planned to be the north face of McCool Hill, where *Spirit* would receive adequate sunlight during the Martian winter. On March 16, 2006 JPL announced that *Spirit's* troublesome front wheel had stopped working altogether. Despite this, *Spirit* was still making progress toward McCool Hill because the control team

programmed the rover to drive toward McCool Hill backwards, dragging its broken wheel. In late March, *Spirit* encountered loose soil which was impeding its progress toward McCool Hill. A decision was made to terminate attempts to reach McCool Hill and instead park on a nearby ridge named Low Ridge Haven.

Low Ridge Haven



Possible meteorites found at Low Ridge

Reaching the ridge on April 9, 2006 and parking on the ridge with an 11° incline to the north, *Spirit* spent the next eight months on the ridge during which time undertaking observations of changes in the surrounding area. No drives were attempted because of the low power levels the rover was experiencing during the Martian winter. The rover made

its first drive, a short turn to position targets of interest within reach of the robotic arm, in early November 2006, following the shortest days of winter and solar conjunction when communications with Earth were severely limited.

While at Low Ridge, Spirit imaged two rocks of similar chemical nature to that of *Opportunity's* Heat Shield Rock, a meteorite on the surface of Mars. Named "Zhong Shan" for Sun Yat-sen and "Allan Hills" for the location in Antarctica where several Martian meteorites have been found, they stood out against the background rocks which were darker. Further spectrographic testing is being done to determine the exact composition of these rocks, which may turn out to also be meteorites.

2007-2008

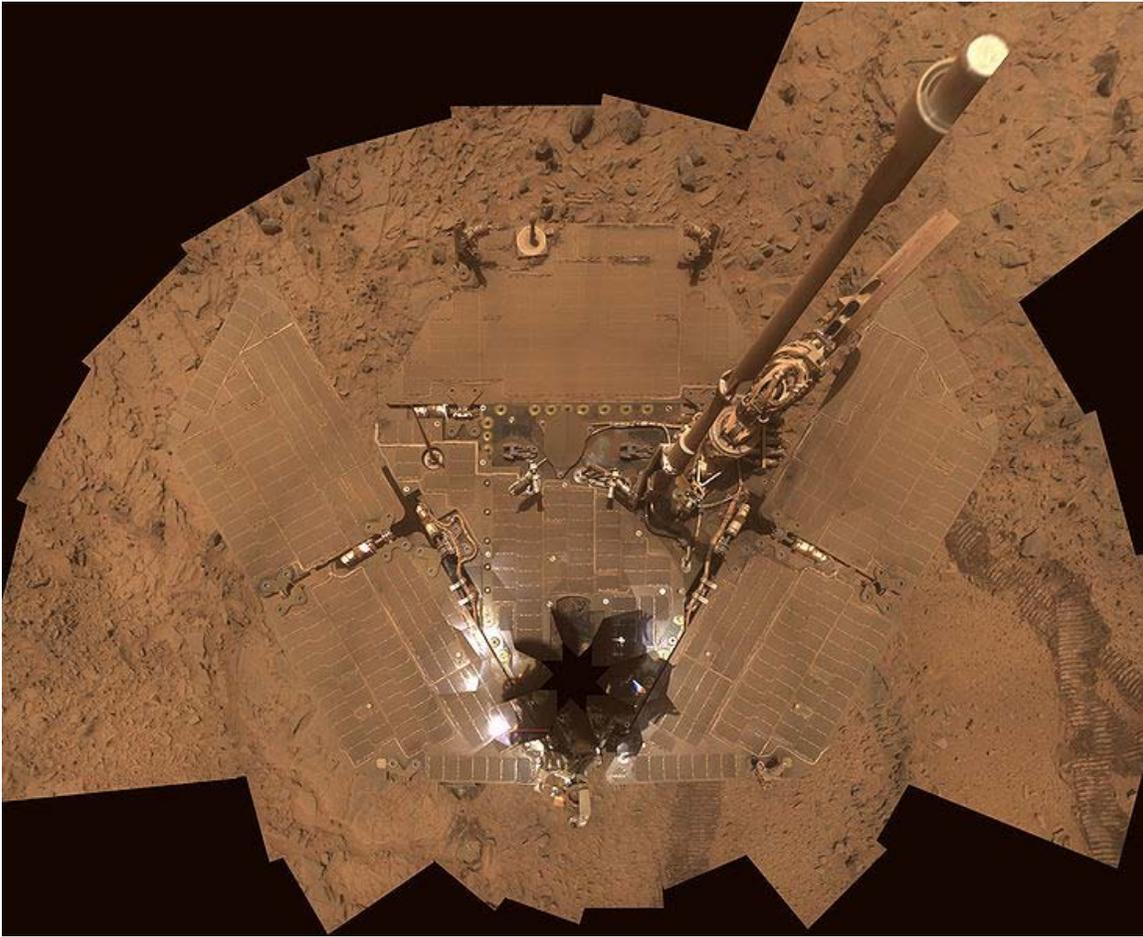
Software upgrade

On January 4, 2007, both rovers received new flight software to the onboard computers. The update was received just in time for the third anniversary of their landing. The new systems let the rovers decide whether or not to transmit an image, and whether or not to extend their arms to examine rocks, which would save much time for scientists as they would not have to sift through hundreds of images to find the one they want, or examine the surroundings to decide to extend the arms and examine the rocks.

Microbe clue

Spirit's dead wheel turned out to be a mixed blessing. As it was traveling in December 2007, pulling the dead wheel behind, the wheel scraped off the upper layer of the Martian soil, uncovering a patch of ground that scientists say shows evidence of a past environment that would have been perfect for microbial life. It is similar to areas on Earth where water or steam from hot springs came into contact with volcanic rocks. On Earth, these are locations that tend to teem with bacteria, said rover chief scientist Steve Squyres. "We're really excited about this," he told a meeting of the American Geophysical Union (AGU). The area is extremely rich in silica—the main ingredient of window glass. The researchers have now concluded that the bright material must have been produced in one of two ways. One: hot-spring deposits produced when water dissolved silica at one location and then carried it to another (i.e. a geyser). Two: acidic steam rising through cracks in rocks stripped them of their mineral components, leaving silica behind. "The important thing is that whether it is one hypothesis or the other, the implications for the former habitability of Mars are pretty much the same," Squyres explained to BBC News. Hot water provides an environment in which microbes can thrive and the precipitation of that silica entombs and preserves them. Squyres added, "You can go to hot springs and you can go to fumaroles and at either place on Earth it is teeming with life - microbial life."

Dust storms



Circular projection showing Spirit's solar panels covered in dust - October 2007

Towards the end of June 2007, a series of dust storms began clouding the Martian atmosphere with dust. The storms intensified and by July 20, both Spirit and Opportunity were facing the real possibility of system failure due to lack of power. NASA released a statement to the press which said (in part) "We're rooting for our rovers to survive these storms, but they were never designed for conditions this intense". The key problem caused by the dust storms was a dramatic reduction in solar power caused by there being so much dust in the atmosphere that it was blocking 99 percent of direct sunlight to the rover Opportunity, and slightly more to the rover Spirit.

Normally the solar arrays on the rovers are able to generate up to 700 watt-hours (2,500 kJ) of power per Martian day. After the storms, the amount of power generated was greatly reduced to 128 watt-hours (460 kJ). If the rovers generate less than 150 watt-hours (540 kJ) per day they must start draining their batteries to run survival heaters. If the batteries run dry, key electrical elements are likely to fail due to the intense cold. Both landers were put into the lowest-power setting in order to wait out the storms. In early August the storms began to clear slightly, allowing the rovers to successfully charge their batteries. They were kept in hibernation in order to wait out the remainder of the storm.

On November 10, 2008, a large dust storm further reduced the output of the solar panels to 89 watt-hours (320 kJ) per day—a critically low level. NASA officials were hopeful that Spirit would survive the storm, and that the power level would rise once the storm had passed and the skies started clearing. They attempted to conserve power by shutting down systems for extended periods of time, including the heaters. On November 13, 2008 the rover awoke and communicated with mission control as scheduled.

From November 14, 2008 to November 20, 2008 Spirit averaged 169 watt-hours (610 kJ) per day. The heaters for the thermal emission spectrometer, which uses about 27 watt-hours (97 kJ) per day, have been disabled since November 11, 2008. Tests on the thermal emission spectrometer indicate that it is undamaged, and the heaters for it will be enabled when there is sufficient power. The solar conjunction, where the Sun is between Earth and Mars, started on November 29, 2008 and communication with the rovers was not possible until December 13, 2008.

2009

On February 6, 2009, a beneficial wind blew off some of the dust accumulated on the panels. This has led to an increase in power output to 240 watt hours per day. NASA officials have said that this increase in energy will be used predominantly for driving.

On April 18, 2009 and April 28, 2009 power output of the solar arrays were increased by cleaning events. The power output of *Spirit's* solar arrays has gone from 223 watt hours per day on March 31, 2009 to 372 watt hours per day on April 29, 2009.

Dusty soil with poor cohesion



Bright soil in the left half of the image is loose, fluffy material churned by the rover's left-front wheel.

On May 1, 2009 troubles in driving began. The rover's wheels appeared to be stuck in soft soil with the rover itself resting on a spot of iron(III) sulfate hidden under a veneer of normal-looking soil. For the rover's mobility, iron sulfate is an insidious material with very little cohesion, so that it was very tough for the rover wheels to get a grip on it. JPL team members simulated the situation by means of a rover mock-up and computer models to attempt to get the rover back on track, but it was immobile for several months. Indeed, it is particularly difficult to reproduce experimentally on Earth the same soil mechanical conditions as those prevailing on Mars under low gravity and under very weak atmospheric pressure. Tests with a lighter version of a mock-up of Spirit were conducted at JPL in a special sandbox to attempt to simulate the cohesion behavior of poorly consolidated soils under low gravity. Preliminary extrication drives began on November 17, 2009.

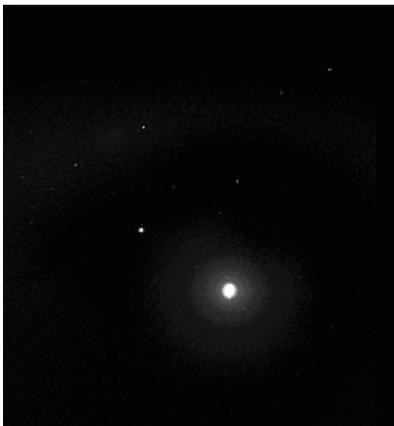
On December 17, 2009, the right-front wheel suddenly began to operate normally for the first three out of four rotations attempts. It was unknown what effect it would have on freeing the rover if the wheel became fully operational again. The right rear wheel had also stalled on November 28 and has not been working since, leaving the rover with only four fully operational wheels. If the team were unable to gain movement and adjust the tilt of the solar panels, or gain a beneficial wind to clean the panels, the rover would only be able to sustain operations until May 2010.

2010

On January 26, 2010, after several months attempting to free the rover, NASA decided to redefine the mobile robot mission by calling it a stationary research platform. Efforts were directed in preparing a more suitable orientation of the platform in relation to the Sun in an attempt to allow a more efficient recharge of the platform's batteries. This was needed to keep some systems operational during the Martian winter. On March 30, 2010, Spirit skipped a planned communication session and as anticipated from recent power-supply projections, has probably entered a low-power hibernation mode, which could last for months.

As of December 2010, the last communication with the rover was on sol 2210 (March 22, 2010) and there is a strong possibility the rover's batteries lost so much power at some point that the mission clock stopped. In previous winters the rover was able to park on a Sun-facing slope and keep its internal temperatures above -40 Celsius, but since the rover is stuck on flat ground it is estimated that internal temperatures dropped to -55 Celsius. If *Spirit* has survived these conditions and there has been a cleaning event, the possibility remains that with the southern summer solstice not arriving until March 2011, solar energy may continue to increase to a level that "wakes up" the rover.

Astronomy



Night sky of Mars showing Deimos (left) and Phobos (right) in front of Sagittarius, as seen by Mars Exploration Rover *Spirit* on August 26, 2005.



Earth from Mars

Spirit pointed its cameras towards the sky and observed a transit of the Sun by Mars' moon Deimos. It also took the first photo of Earth from the surface of another planet in early March 2004.

In late 2005, *Spirit* took advantage of a favorable energy situation to make multiple nighttime observations of both of Mars' moons Phobos and Deimos. These observations included a "lunar" (or rather phobal) eclipse as *Spirit* watched Phobos disappear into Mars's shadow. Some of *Spirit's* star gazing was designed to look for a predicted meteor shower caused by Halley's Comet, and although at least four imaged streaks were suspect meteors, they could not be unambiguously differentiated from those caused by cosmic rays.

A transit of Mercury from Mars took place on January 12, 2005 from about 14:45 UTC to 23:05 UTC. Theoretically, this could have been observed by both *Spirit* and *Opportunity*; however, camera resolution did not permit seeing Mercury's 6.1" angular diameter. They were able to observe transits of Deimos across the Sun, but at 2' angular diameter, Deimos is about 20 times larger than Mercury's 6.1" angular diameter. Ephemeris data

generated by JPL Horizons indicates that *Opportunity* would have been able to observe the transit from the start until local sunset at about 19:23 UTC Earth time, while *Spirit* would have been able to observe it from local sunrise at about 19:38 UTC until the end of the transit.

Equipment wear and failures

Although both rovers have passed their original mission time of 90 sols many times over, the extended time on the surface and therefore additional stress on components has resulted in some issues developing.

On sol 779 (March 13, 2006), the right front wheel ceased working after having covered 4.2 mi (7 km) on Mars. Engineers began driving the rover backwards, dragging the dead wheel. Although this has resulted in changes to driving techniques, the dragging effect has become a useful tool. The wheel dragging has partially cleared soil away on the surface as the rover travels and allows for imaging areas that would normally be inaccessible. But in mid-December 2009, to the surprise of the engineers, the right front wheel showed slight movement in a wheel-test on Sol 2113 and clearly rotated with normal resistance on three of four wheel-tests on Sol 2117, but stalled on the fourth.

On sols 2100-2101, the right rear wheel also stalled and has not been working since.

The grinding surface of the Rock Abrasion Tool has worn down, and the device can only be used to brush targets.

All of the other science instruments and engineering cameras continue to function. The Mössbauer spectrometer takes much longer to produce results than it did earlier in the mission because of the decay of its radioactive source.

Honors

To the rover

To commemorate *Spirit's* great contribution to the exploration of Mars, an asteroid, 37452 Spirit, has been named after it. The name was proposed by Ingrid van Houten-Groeneveld who along with Cornelis Johannes van Houten and Tom Gehrels discovered the asteroid on September 24, 1960.

Ruben H. Fleet Museum and the Liberty Science Center also has an IMAX show called Roving Mars that documents the journey of both Spirit and Opportunity, using both CG and actual imagery.

From the rover

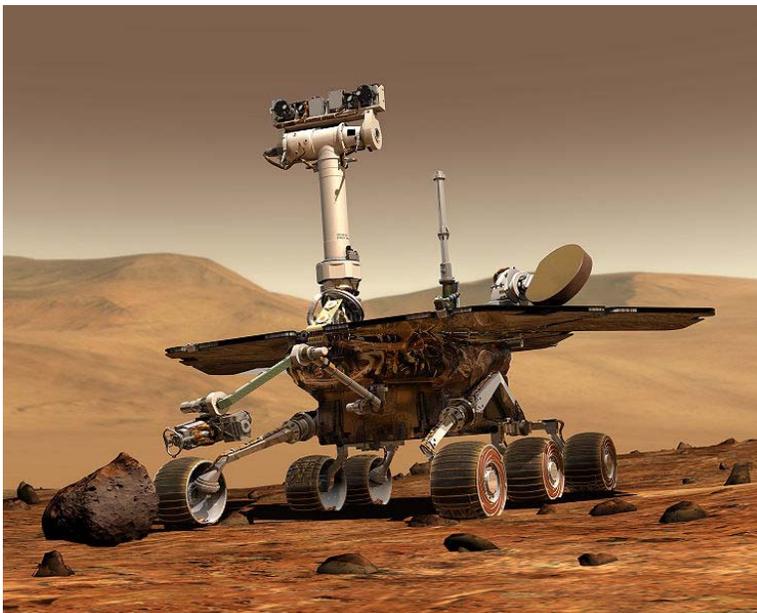
On January 27, 2004 NASA memorialized the crew of Apollo 1 by naming three hills to the north of "Columbia Memorial Station" as the Apollo 1 Hills. On February 2, 2004 the

astronauts on Columbia's final mission were further memorialized when NASA named a set of hills to the east of the landing site the Columbia Hills Complex, denoting seven peaks in that area as "Anderson", "Brown", "Chawla", "Clark", "Husband", "McCool", and "Ramon"; NASA has submitted these geographical feature names to the IAU for approval.

Chapter- 7

Opportunity Rover

Opportunity Rover (MER-B)



Artist's Concept of Rover on Mars

Operator	NASA
Mission type	Rover
Orbital insertion date	Landed on January 25, 2004
Launch date	July 7, 2003
Launch vehicle	Delta II 7925H 9.5 rocket
Mission duration	Planned: 90 sols (92.5 days) Current: 2546 days since landing
COSPAR ID	2003-032A
Homepage	JPL's Mars Exploration Rover home

page

Mass	185 kg (408 lb)
Power	Solar panels
Batteries	Rechargeable lithium ion batteries



The launch patch for *Opportunity*, featuring Duck Dodgers (Daffy Duck)

Opportunity, mission designation **MER-B (Mars Exploration Rover - B)**, is the second of the two rovers of NASA's ongoing Mars Exploration Rover Mission. As of 10 December 2010, it had traveled more than 26 kilometers on Mars since landing successfully at Meridiani Planum on January 25, 2004 05:05 Ground UTC (*circa* 13:15 local time), three weeks after its twin *Spirit* (MER-A) touched down on the other side of the planet.

Opportunity has continued to function effectively over twenty times longer than its planned 90-sol mission, aided by solar cell cleaning events, and it continues to perform extensive geological analysis of Martian rocks and planetary surface features.

Mission highlights include completion of the 90-sol mission, discovery of the first meteorite on another planet, Heat Shield Rock (*Meridiani Planum*), and over two years studying Victoria crater. The rover narrowly survived dust-storms in 2007, and is now making its way to Endeavour crater.

On May 19, 2010, *Opportunity* reached 2246 sols of operation, making it the longest Mars surface mission in history, breaking the record of 2245 sols set by Viking 1.

The Jet Propulsion Laboratory (JPL), a division of the California Institute of Technology in Pasadena, manages the Mars Exploration Rover project for NASA's Office of Space Science, Washington.

Objectives



Delta II Heavy (7925H-9.5) lifting off from pad 17-B carrying MER-B in 2003 with *Opportunity* rover.

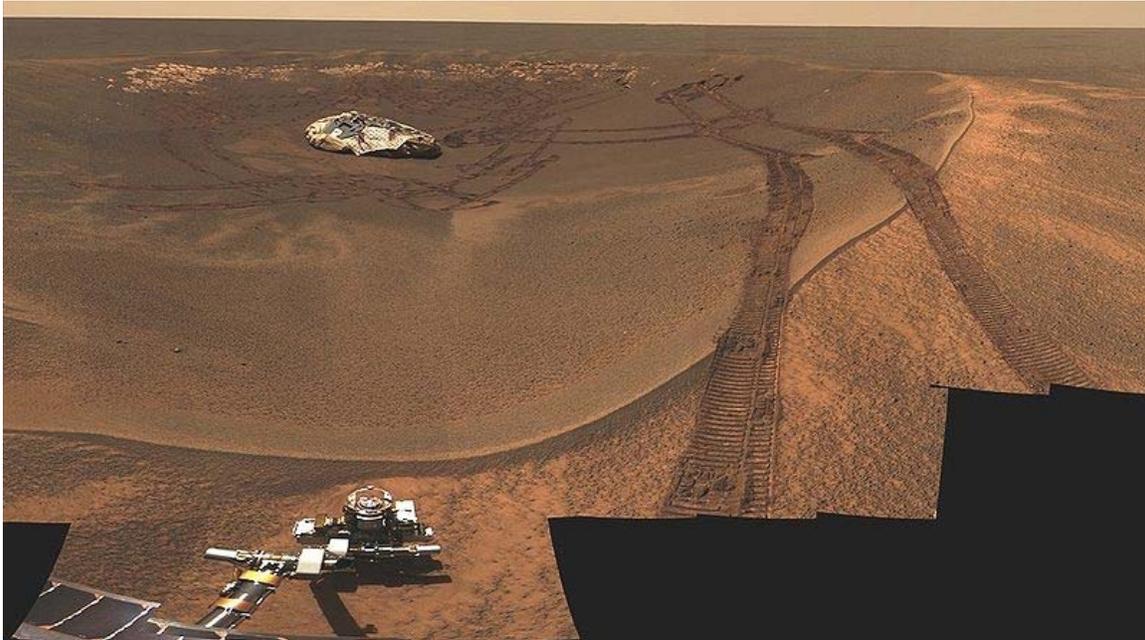
The scientific objectives of the Mars Exploration Rover mission are to:

- Search for and characterize a variety of rocks and soils that hold clues to past water activity. In particular, samples sought will include those that have minerals deposited by water-related processes such as precipitation, evaporation, sedimentary cementation or hydrothermal activity.
- Determine the distribution and composition of minerals, rocks, and soils surrounding the landing sites.
- Determine what geologic processes have shaped the local terrain and influenced the chemistry. Such processes could include water or wind erosion, sedimentation, hydrothermal mechanisms, volcanism, and cratering.
- Perform calibration and validation of surface observations made by Mars Reconnaissance Orbiter instruments. This will help determine the accuracy and effectiveness of various instruments that survey Martian geology from orbit.
- Search for iron-containing minerals, identify and quantify relative amounts of specific mineral types that contain water or were formed in water, such as iron-bearing carbonates.
- Characterize the mineralogy and textures of rocks and soils and determine the processes that created them.
- Search for geological clues to the environmental conditions that existed when liquid water was present.
- Assess whether those environments were conducive to life.

During the next two decades, NASA will continue to conduct missions to address whether life ever arose on Mars. The search begins with determining whether the Martian environment was ever suitable for life. Life, as we understand it, requires water, so the

history of water on Mars is critical to finding out if the Martian environment was ever conducive to life. Although the Mars Exploration Rovers do not have the ability to detect life directly, they are offering very important information on the habitability of the environment in the planet's history.

Design and construction



Eagle Crater, with Opportunity lander, as seen from MER-B *Opportunity* just after exiting the crater.

Opportunity (along with its twin, *Spirit*) is a six-wheeled, solar-powered robot standing 1.5 m (4.9 ft) high, 2.3 m (7.5 ft) wide and 1.6 m (5.2 ft) long and weighing 180 kg (400 lb). Six wheels on a rocker-bogie system enable mobility over rough terrain. Each wheel has its own motor, the vehicle is steered at front and rear and is designed to operate safely at tilts of up to 30 degrees. Maximum speed is 50 mm/s (2 in/s) although average speed is about a fifth of this. Both *Spirit* and *Opportunity* have pieces of the fallen World Trade Center's metal on them which were "turned into shields to protect cables on the drilling mechanisms".

Solar arrays generate about 140 watts for up to four hours per Martian day (sol) while rechargeable lithium ion batteries store energy for use at night. *Opportunity's* onboard computer uses a 20 MHz RAD6000 CPU with 128 MB of DRAM, 3 MB of EEPROM, and 256 MB of flash memory. The rover's operating temperature ranges from $-40\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$ to $104\text{ }^{\circ}\text{F}$) and radioisotope heaters provide a base level of heating, assisted by electrical heaters when necessary. A gold film and a layer of silica aerogel provide insulation.

Communications depends on an omnidirectional low-gain antenna communicating at a low data rate and a steerable high-gain antenna, both in direct contact with Earth. A low gain antenna is also used to relay data to spacecraft orbiting Mars.

Fixed science instruments include

- Panoramic Camera (Pancam) - examines the texture, color, mineralogy, and structure of the local terrain.
- Navigation Camera (Navcam) - monochrome with a higher field of view but lower resolution, for navigation and driving.
- Miniature Thermal Emission Spectrometer (Mini-TES) - identifies promising rocks and soils for closer examination, and determines the processes that formed them.

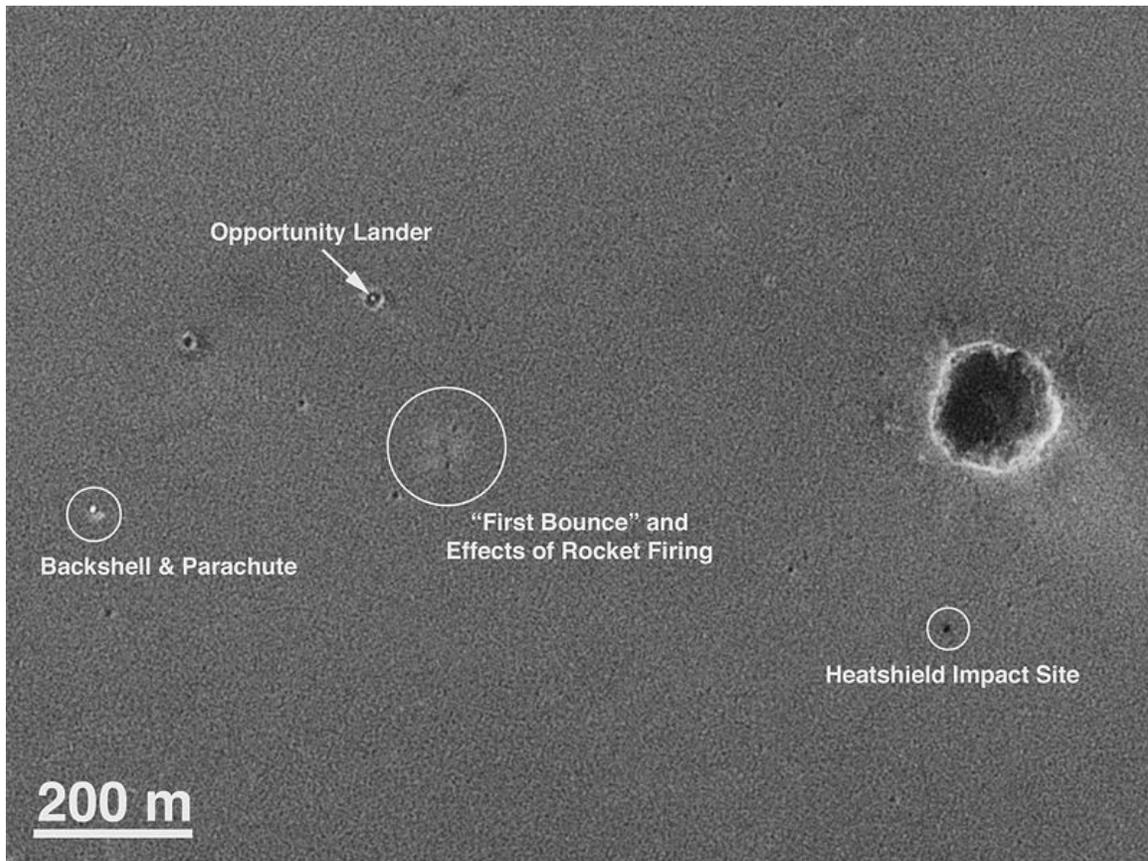
The rover arm holds the following instruments

- Mössbauer spectrometer (MB) MIMOS II - used for close-up investigations of the mineralogy of iron-bearing rocks and soils.
- Alpha particle X-ray spectrometer (APXS) - close-up analysis of the abundances of elements that make up rocks and soils.
- Magnets - for collecting magnetic dust particles
- Microscopic Imager (MI) - obtains close-up, high-resolution images of rocks and soils.
- Rock Abrasion Tool (RAT) - exposes fresh material for examination by instruments on-board.

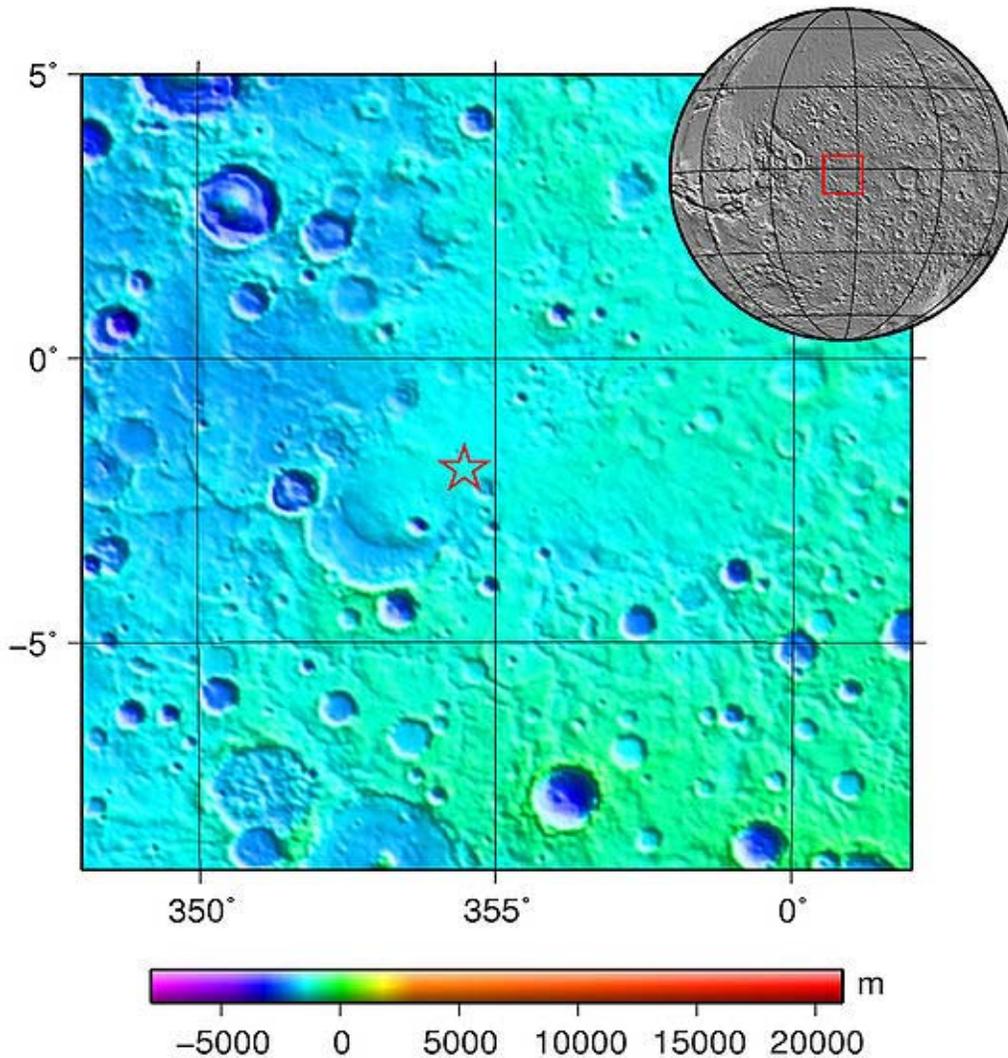
The cameras produce 1024-pixel by 1024-pixel images, the data is compressed with ICER, stored, and transmitted later.

The rover's name was chosen through a NASA-sponsored student essay competition.

Mission overview



Mars Global Surveyor orbiter's photograph of landing site showing "hole in one"



Opportunity's landing site (denoted with a star).

The primary surface mission for *Opportunity* was planned to last 90 sols. The mission has received several extensions and as of 17 November 2009 had passed 2,100 sols. An archive of weekly updates on the rover's status can be found at the *Opportunity* Update Archive.

From its initial landing, by chance, into an impact crater amidst an otherwise generally flat plain, *Opportunity* has successfully investigated soil and rock samples and taken panoramic photos of its landing site. Its sampling allowed NASA scientists to make hypotheses concerning the presence of hematite and past presence of water on the surface of Mars. Following this, it was directed to travel across the surface of Mars to investigate another crater site, Endurance crater, which it investigated from June — December 2004. Subsequently, *Opportunity* examined the impact site of its own heat shield and discovered an intact meteorite, now known as Heat Shield Rock, on the surface of Mars.

From late April 2005 to early June of that year, *Opportunity* was perilously lodged in a sand dune, with several wheels buried in the sand. Over a six week period Earth-based physical simulations were performed to decide how best to extract the rover from its position without risking a permanent immobilization of the valuable vehicle. Successful maneuvering a few centimeters at a time eventually freed the rover, which resumed its travels.

Opportunity was directed to proceed in a southerly direction to Erebus crater, a large, shallow, partially buried crater and a stopover on the way south towards Victoria crater, between October 2005 and March 2006. It experienced some mechanical problems with its robotic arm.

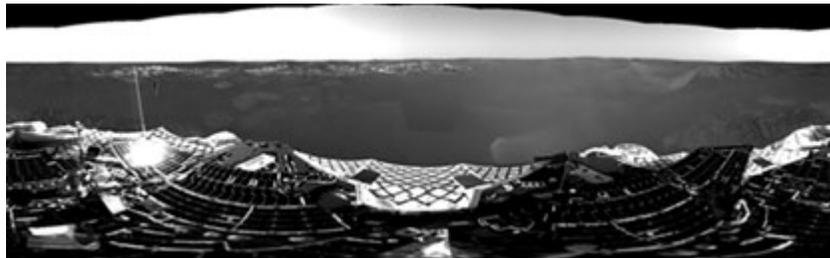
In late September 2006, *Opportunity* reached Victoria crater and explored along the rim in a clockwise direction. In June 2007 it returned to *Duck Bay*, its original arrival point; in September 2007 it entered the crater to begin a detailed study. In August 2008, *Opportunity* left Victoria crater and is currently going towards Endeavour crater.

Opportunity's total odometry as of December 8, 2010 (sol 2444) is 26,120.98 meters (16.23 mi).

Mission timeline

2004

Landing site: "Eagle" crater



Opportunity's first 360-degree grayscale panorama, taken by the navcam on Sol 1 of the mission, showing interior of Eagle crater at Meridiani Planum, shortly after touchdown in 2004.

Opportunity landed in Meridiani Planum at $1^{\circ}57'S$ $354^{\circ}28'E$ / $1.95^{\circ}S$ $354.47^{\circ}E$, about 25 km downrange (east) of its intended target. Although Meridiani is a flat plain, without the rock fields seen at previous Mars landing sites, *Opportunity* rolled into an impact crater 22 meters in diameter, with the rim of the crater approximately 10 meters (32 ft) from the rover. NASA Scientists were so excited about landing in a crater that they called the landing a "hole in one", however they were not aiming for the crater (or even knew it existed). Later, the crater was named *Eagle crater* and the landing site designated "Challenger Memorial Station". This was the darkest landing site ever visited by a

spacecraft on Mars. It would be two weeks before *Opportunity* was able to get a better look at its surroundings.

Scientists were intrigued by the abundance of rock outcrops dispersed throughout the crater, as well as the crater's soil, which appeared to be a mixture of coarse gray grains and fine reddish grains. This sweeping look at the unusual rock outcropping near *Opportunity* was captured by the rover's panoramic camera. Scientists believe the seemingly layered rocks are either volcanic ash deposits or sediments laid down by wind or water. It was given the name *Opportunity Ledge*.

Geologists said that the layers—some no thicker than a finger—indicate the rocks likely originated either from sediments carried by water or wind, or from falling volcanic ash. "We should be able to distinguish between those two hypotheses", said Dr. Andrew Knoll of Harvard University, Cambridge, a member of the science team for *Opportunity* and its twin, *Spirit*. If the rocks are sedimentary, water is a more likely source than wind, he said.

These layered rocks measure only 10 centimeters (4 inches) tall and are thought to be either volcanic ash deposits or sediments carried by water or wind. The layers are very thin measuring just a few millimeters thick in some cases.



First color panorama taken by *Opportunity*, showing the Martian landscape at Meridiani Planum, shortly after it touched down in 2004

"Opportunity Ledge" outcroppings

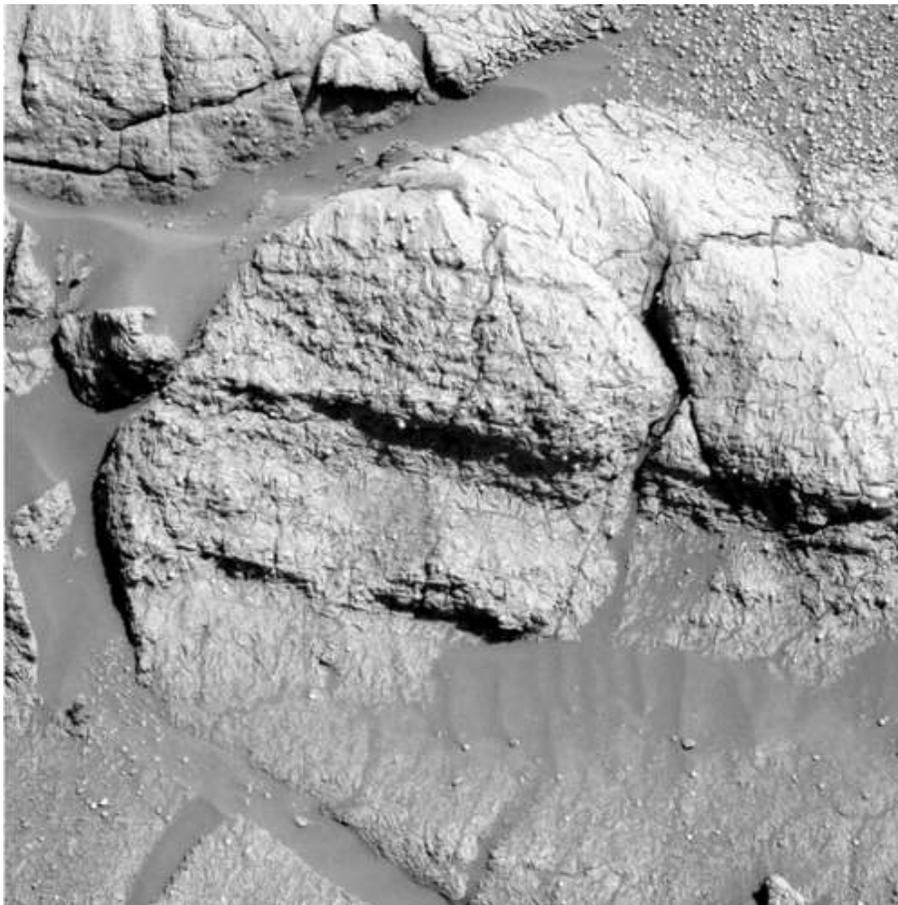


This panorama of Eagle crater shows outcroppings, which are thought to have water origins.

On Sol 15, *Opportunity* took a close up of the rock "Stone Mountain" in the outcrop area of the crater, raising speculation that the rock consisted of very fine grain or dust, in contrast to Earth sandstone, which is compacted sand with rather large grains. The weathering agent eroding away layers of this rock seemed to be visible as dark spots.

A picture received on February 10 (taken on Sol 16) showed that the thin layers in the bedrock converge and diverge at low angles, suggesting that some "moving current" such as volcanic flow, wind, or water formed these rocks. The discovery of these layers was significant for scientists who had planned this mission to test the "water hypothesis" rigorously.

***El Capitan* outcropping**



Section of *El Capitan*

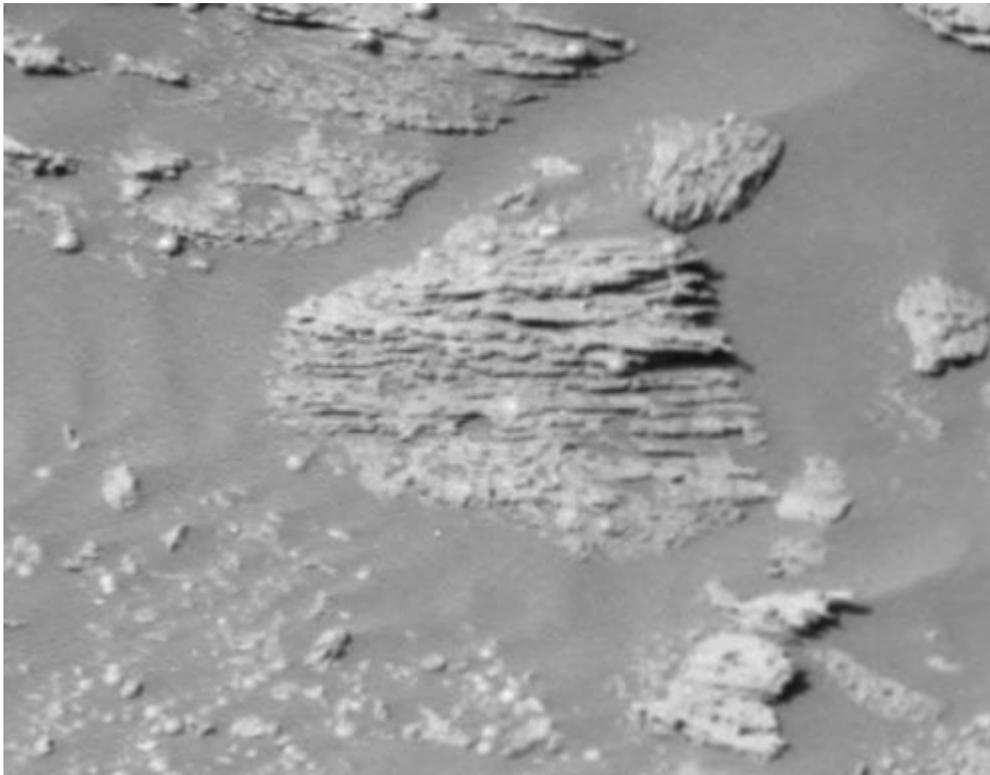
On February 19 the survey of "Opportunity Ledge" was declared successful. A specific target in the outcrop (dubbed "*El Capitan*"), whose upper and lower portions appeared to differ in layering and weathering characteristics, was selected for further investigation. *El Capitan*, about 10 centimeters (4 inches) high, was named after a mountain in Texas. *Opportunity* reached "*El Capitan*" on Sol 27, and took a first picture of the rocks with its panoramic camera.

On Sol 30, *Opportunity* used its Rock Abrasion Tool (RAT) for the first time to investigate the rocks around *El Capitan*. The image on the right-hand side shows a close up view taken after the drilling and cleaning process was complete. Due to chance, two spherules were also cut partially, and seem to show scratches and other marks made by the diamond-crusted grind tool. The black areas are artifacts of the imaging process, when parts of the picture are missing.

During a press conference on March 2 mission scientists discussed their conclusions about the bedrock, and the evidence for the presence of liquid water during their formation. They presented the following reasoning to explain the small, elongated voids in the rock visible on the surface and after grinding into it.

These voids are consistent with features known to geologists as "vugs". These are formed when crystals form inside a rock matrix and are later removed through erosive processes, leaving behind voids. Some of the features in this picture are "disk-like", which is consistent with certain types of crystals, notably sulfate minerals.

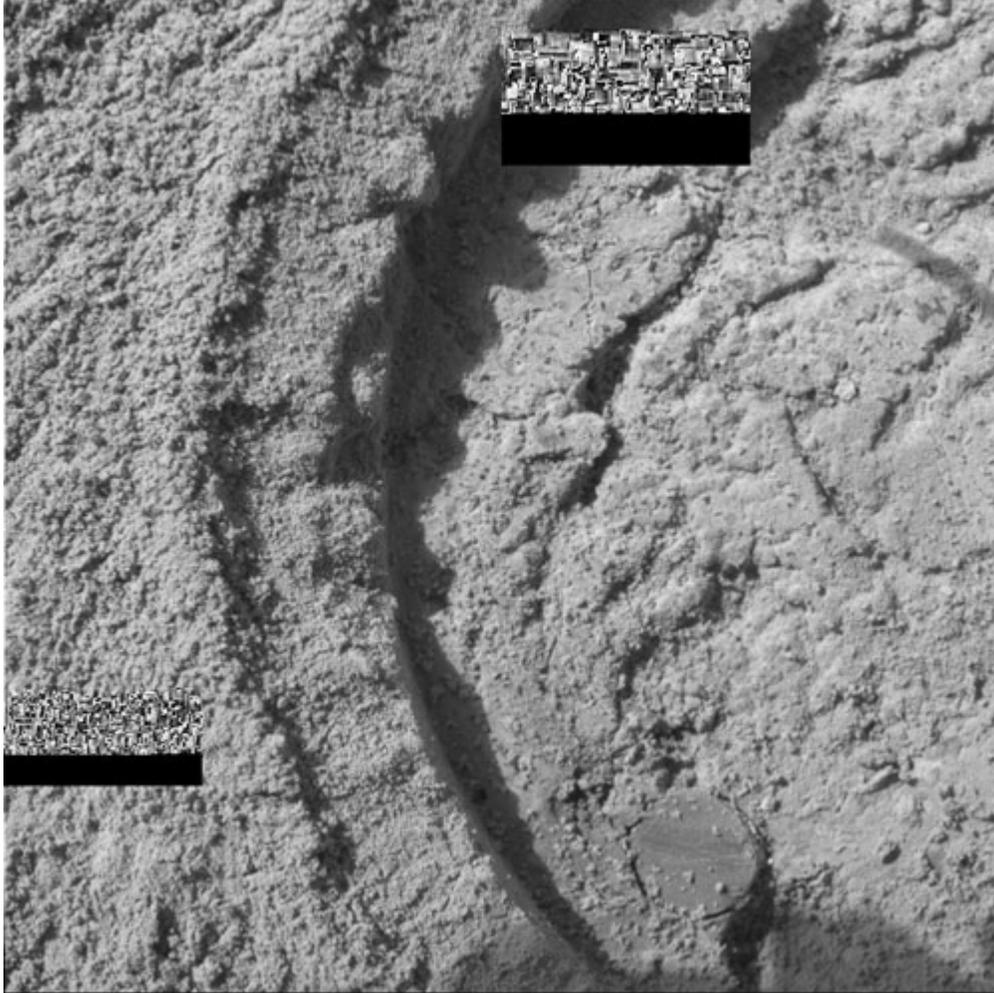
Additionally, mission members presented first data from the Mössbauer spectrometer taken at the bedrock site. The iron spectrum obtained from the rock *El Capitan* shows strong evidence for the mineral jarosite. This mineral contains hydroxide ions, which indicates the presence of water when the minerals were formed. Mini-TES data from the same rock showed that it consists of a considerable amount of sulfates.



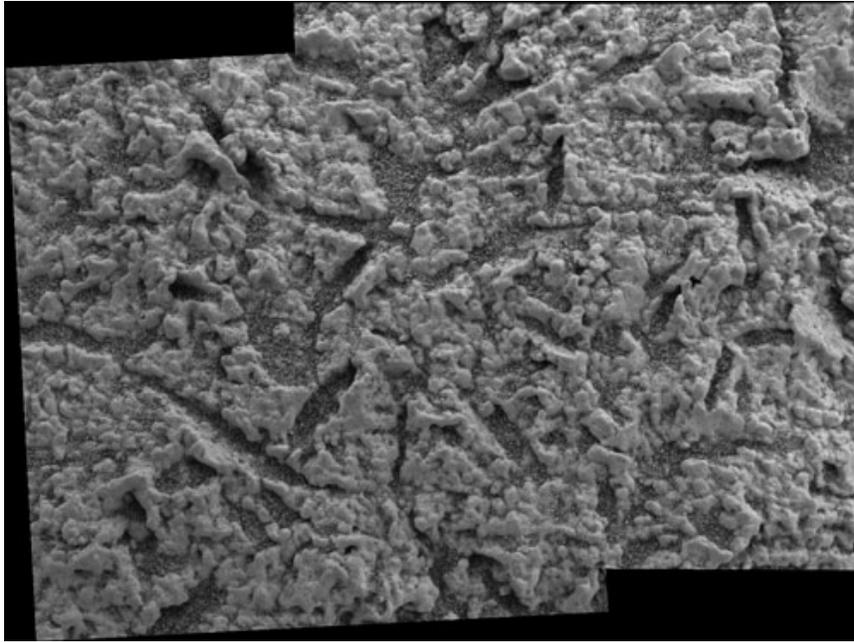
Thin Rock layers, not all parallel to each other



Close up of a rock outcrop

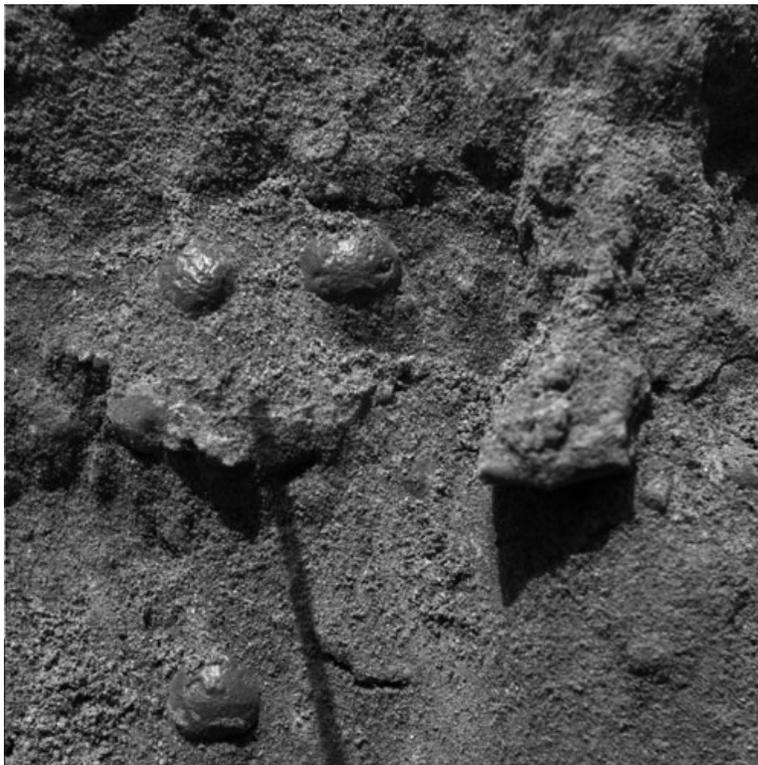


Section of hole created by RAT

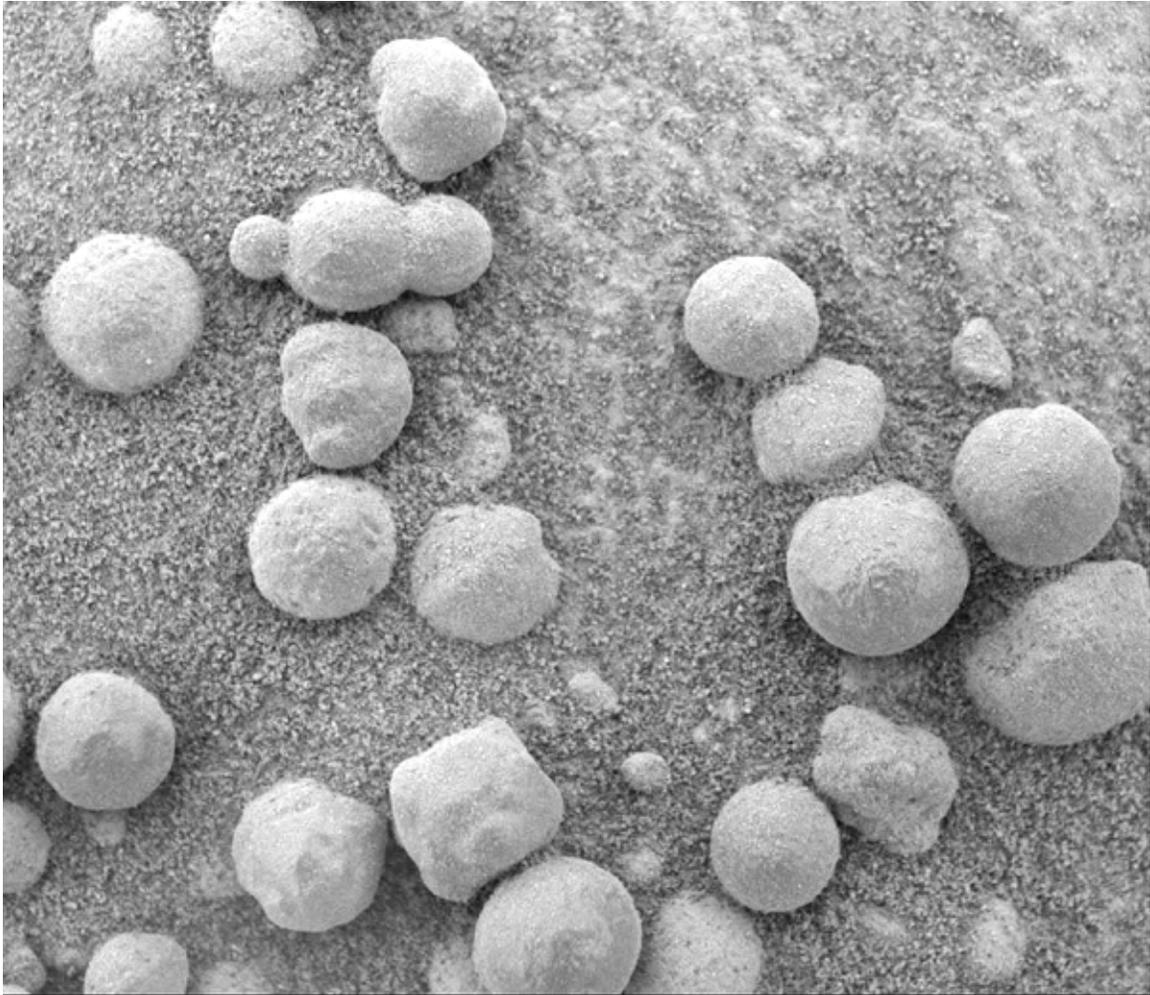


Voids or "vugs" inside the rock

***Opportunity* digs a trench**



This image, taken by the microscopic imager, reveals shiny, spherical objects embedded within the trench wall



"Blueberries" (hematite spheres) on a rocky outcrop at Eagle Crater. Note the merged triplet in the upper left.

The rover alternately pushed soil forward and backward out of the trench with its right front wheel while other wheels held the rover in place. The rover turned slightly between bouts of digging to widen the hole. "We took a patient, gentle approach to digging", Biesiadecki said. The process lasted 22 minutes.

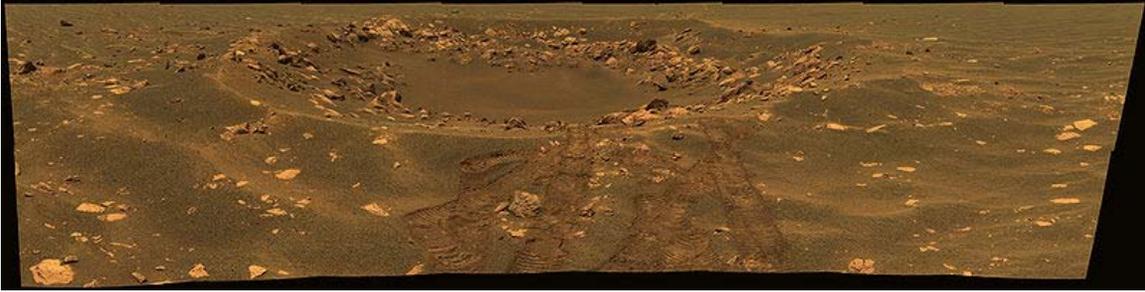
The resulting trench—the first dug by either Mars Exploration Rover—is about 50 centimeters (20 inches) long and 10 centimeters (4 inches) deep. "It came out deeper than I expected", said Dr. Rob Sullivan of Cornell University, Ithaca, N.Y., a science-team member who worked closely with engineers to plan the digging.

Two features that caught scientists' attention were the clotty texture of soil in the upper wall of the trench and the brightness of soil on the trench floor, Sullivan said.

By inspecting the sides and floor of a hole it dug, *Opportunity* found some things it did not see beforehand, including round pebbles that are shiny and soil so fine-grained that the rover's microscope cannot make out individual particles.

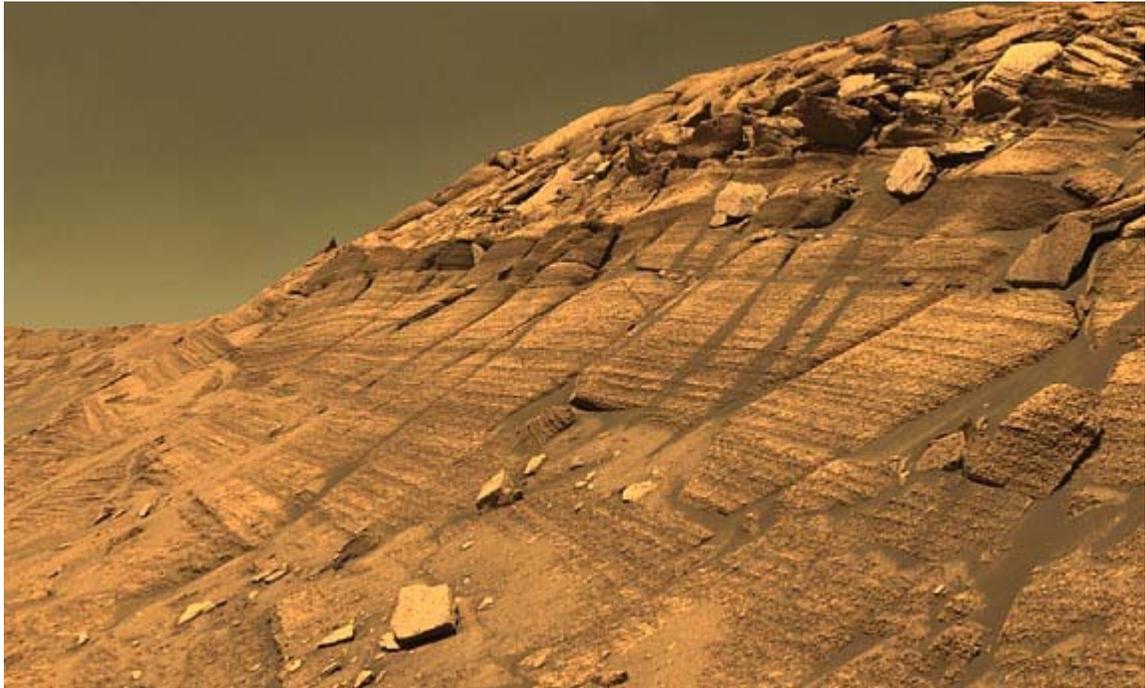
"What's underneath is different than what's at the immediate surface", said Dr. Albert Yen, rover science team member at NASA's Jet Propulsion Laboratory, Pasadena, Calif.

Initial scientific results from the Opportunity rover were published in the journal *Science*



Fram crater on Sol 84, April 24, 2004

Endurance crater



The view of Burns Cliff inside of Endurance Crater

On April 30, 2004 *Opportunity* reached Endurance crater, which was known to have many layers of rocks. In May the rover circumnavigated the crater, and made

observations with Mini-TES and the panoramic camera. The rock "Lion Stone" was investigated and found to be similar in composition to the layers found in Eagle crater.

On June 4, 2004 mission members announced their intention to drive *Opportunity* into Endurance, even if it should turn out to be impossible to get back out, targeting the various rock layers that were identified in the pictures from the crater rim. "This is a crucial and careful decision for the Mars Exploration Rovers' extended mission", said Dr. Edward Weiler, NASA's associate administrator for space science. Dr Squyres, principal investigator from Cornell University said: "Answering the question of what came before the evaporites is the most significant scientific issue we can address with *Opportunity* at this time."

A first drive into the crater was executed June 8 and *Opportunity* backed out again the same day. It was found that the angle of the surface was well inside the safety margin (about 18 degrees), and the full excursion towards the rock layer of interest was started. During Sols 134 (June 12), 135, and 137 the rover drove deeper and deeper into the crater. Although some wheel slip was observed, driving was discovered to be possible even at slope angles up to 30 degrees.

Wispy clouds, similar to Earth's cirrus clouds, were spotted.

Opportunity spent roughly 180 sols inside the crater, before backing out of it again in late December 2004. Scientific results of the sedimentary geology of the crater were published in the journal *Earth and Planetary Science Letters*



Endurance Crater panorama (approximate true color)

2005

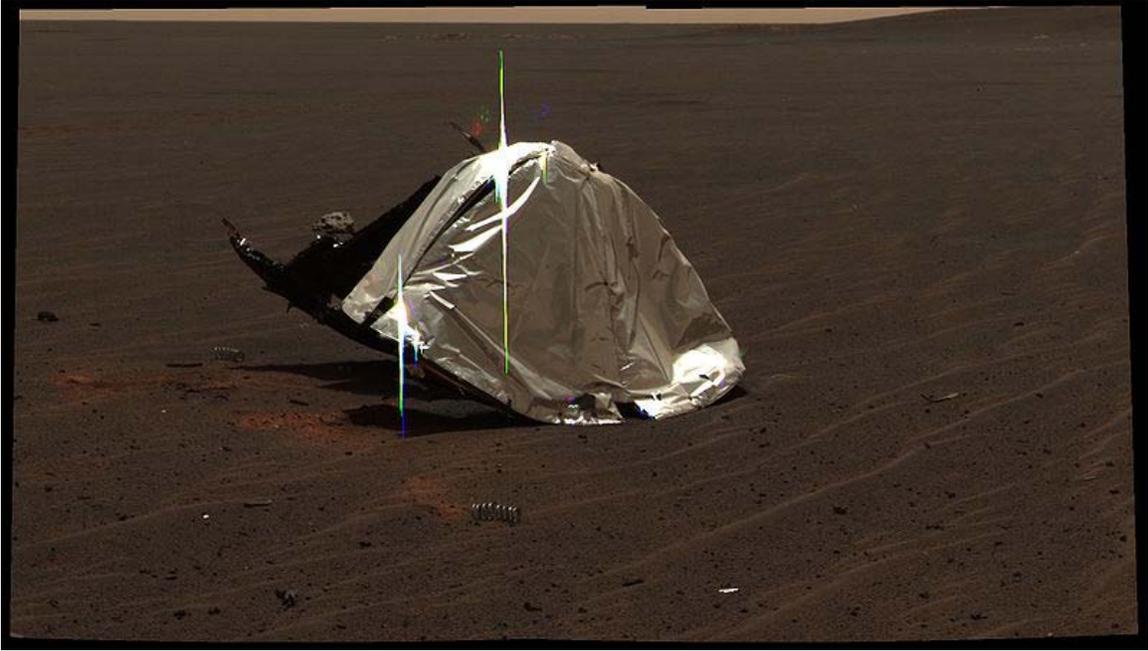
Heat Shield Rock

After exiting Endurance crater, in January 2005 *Opportunity* went to examine its own discarded heat shield. While in the vicinity of the heat shield, it happened to come upon an object which was immediately suspected and soon confirmed to be a meteorite. The meteorite was promptly named Heat Shield Rock, and is the first meteorite identified on another planet (although the Bench Crater and Hadley Rille were found earlier on the Moon).

After about 25 sols of observations *Opportunity* headed south for a crater named Argo, nearly 300 m from the heat shield.



Heat Shield Rock was the first meteorite ever identified on another planet



Heat shield, with Heat Shield Rock just above and to the left in the background

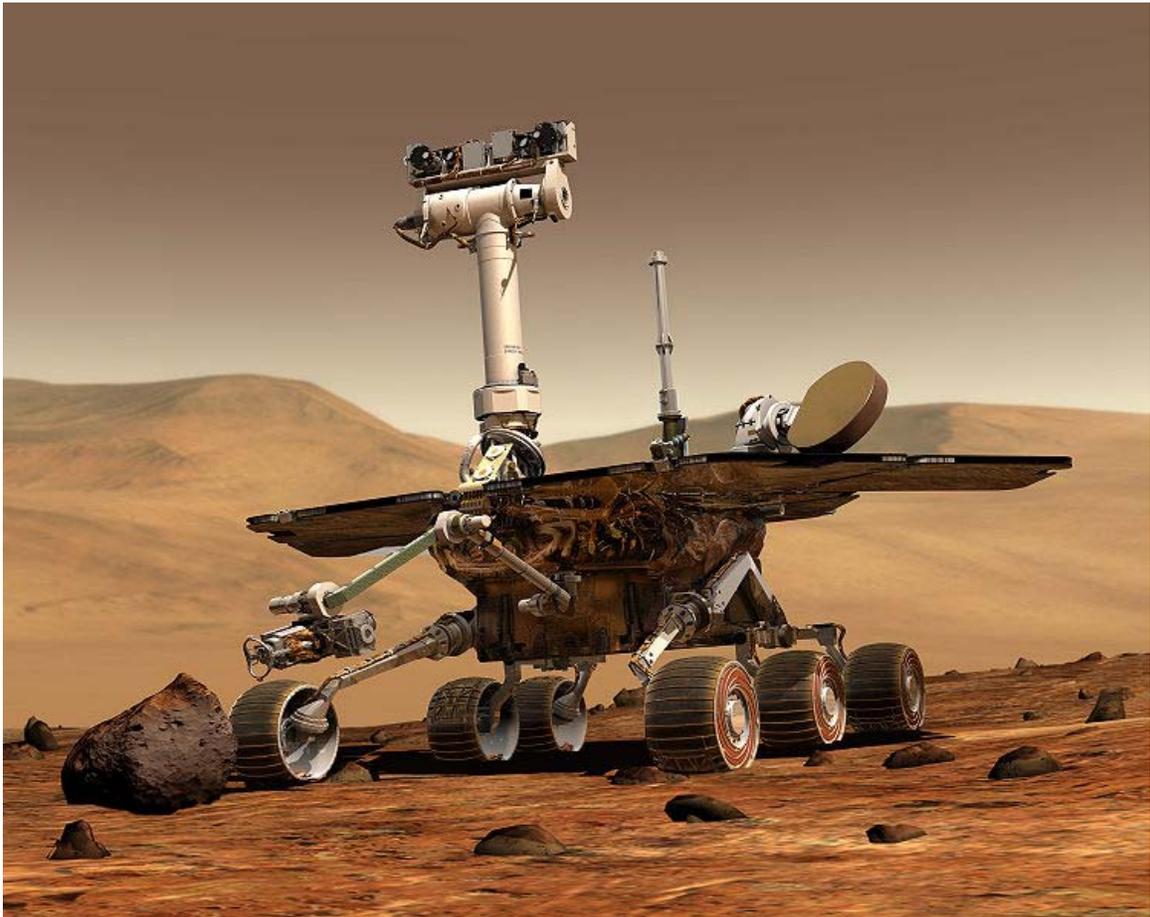
Southern transit

The rover was commanded to dig another trench on the vast plains of Meridiani Planum, on Sol 366, and observations continued until Sol 373 (February 10, 2005). The rover then passed the craters "Alvin" and "Jason", and by Sol 387, approached a "crater triplet" on its way to Vostok Crater. Along the way, *Opportunity* set a distance record for one-day travel by either rover: 177.5 meters (582 ft), on February 19, 2005. On Sol 389 (February 26, 2005), the rover approached one of the three craters, dubbed Naturaliste. A rock target named "Normandy" was chosen for investigation on Sol 392, and *Opportunity* remained there until Sol 395.

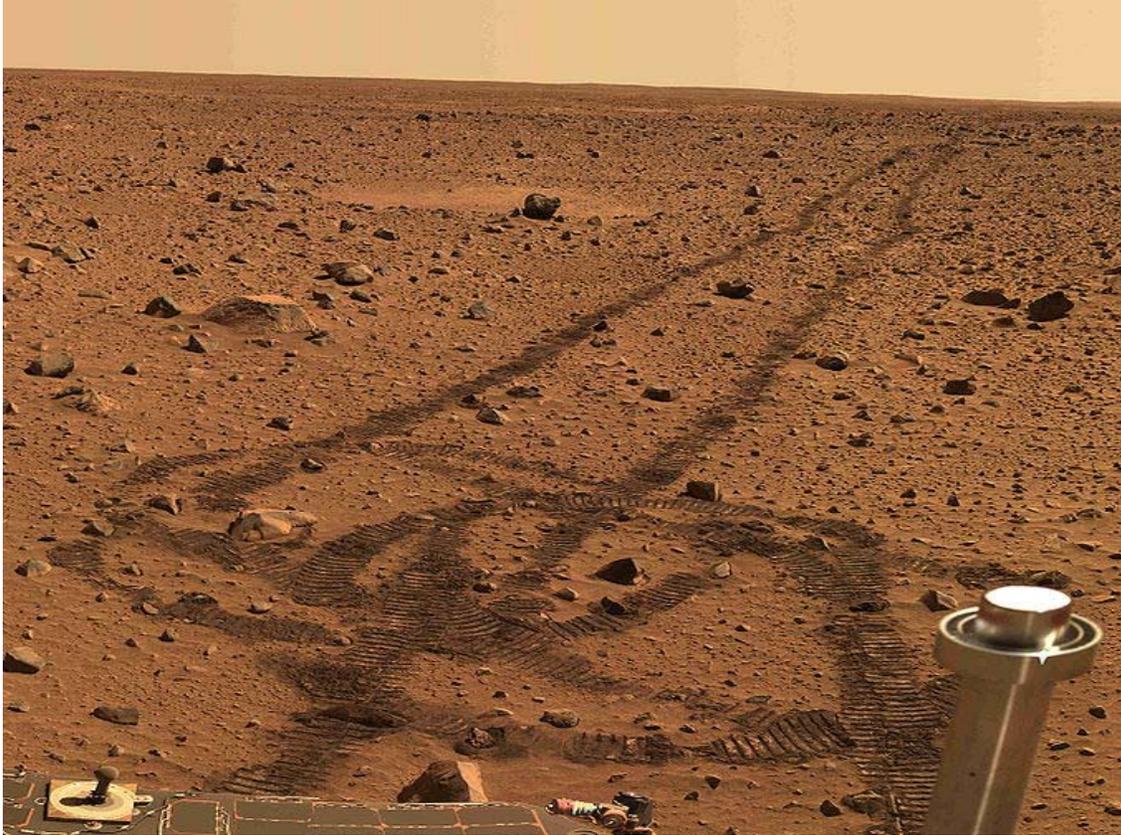
Opportunity reached Vostok Crater on Sol 399, finding it mostly filled with sand and lined by outcrops. It was then ordered south into what has been called "etched terrain", to search for more bedrock.

Chapter- 8

Mars Exploration Rover



Artist's conception of rover on Mars



Part of a panorama taken by the Spirit rover in 2004

NASA's **Mars Exploration Rover Mission (MER)** is an ongoing robotic space mission involving two rovers, *Spirit and Opportunity*, exploring the planet Mars. It began in 2003 with the sending of the two rovers — MER-A *Spirit* and MER-B *Opportunity* — to explore the Martian surface and geology.

The mission's scientific objective was to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars. The mission is part of NASA's Mars Exploration Program, which includes three previous successful landers: the two Viking program landers in 1976 and Mars Pathfinder probe in 1997.

The total cost of building, launching, landing and operating the rovers on the surface for the initial 90-Martian-day (sol) primary mission was US\$820 million. Since the rovers have continued to function beyond their initial 90 sol primary mission, they have each received five mission extensions. The fifth mission extension was granted in October 2007, and runs to the end of 2009. The total cost of the first four mission extensions was \$104 million, and the fifth mission extension is expected to cost at least \$20 million.

In July 2007, during the fourth mission extension, Martian dust storms blocked sunlight to the rovers and threatened the ability of the craft to gather energy through their solar panels, causing engineers to fear that one or both of them might be permanently disabled. However, the dust storms lifted, allowing them to resume operations.

On May 1, 2009, during its fifth mission extension, *Spirit* became stuck in soft soil on Mars. After nearly nine months of attempts to get the rover back on track, including using test rovers on Earth, NASA announced on January 26, 2010 that *Spirit* was being retasked as a stationary science platform. This mode will enable *Spirit* to assist scientists in ways that a mobile platform could not, such as detecting "wobbles" in the planet's rotation that would indicate a liquid core.

In recognition of the vast amount of scientific information amassed by both rovers, two asteroids have been named in their honor: 37452 Spirit and 39382 Opportunity. The mission is managed for NASA by the Jet Propulsion Laboratory, which designed, built, and is operating the rovers.

Objectives

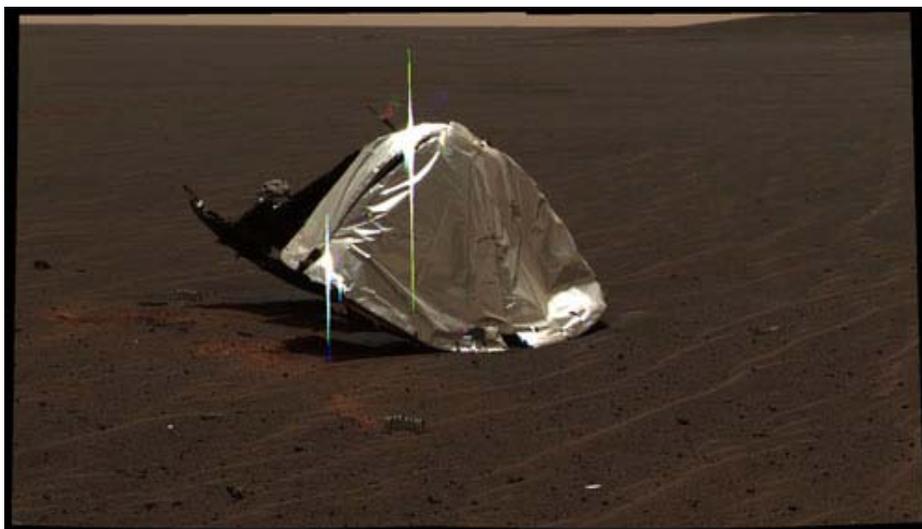
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NASA's Mars Exploration Rover *Spirit* casts a shadow over the trench that the rover is examining with tools on its robotic arm. *Spirit* took this image with its front hazard-avoidance camera on February 21, 2004, during the rover's 48th martian day, or sol 48.



Opportunity's discarded heat shield

History

On January 21, 2004, the Deep Space Network lost contact with *Spirit*, for reasons originally thought to be related to a thunderstorm over Australia. The rover transmitted a message with no data, but later that day missed another communications session with the Mars Global Surveyor. The next day, JPL received a beep from the rover, indicating that it was in fault mode. On January 23, the flight team succeeded in making the rover send. The fault was believed to have been caused by an error in the rover's flash memory subsystem. The rover did not perform any scientific activities for ten days, while engineers updated its software and ran tests. The problem was corrected by reformatting *Spirit's* flash memory and using a software patch to avoid memory overload; *Opportunity* was also upgraded with the patch as a precaution. *Spirit* returned to full scientific operations by February 5.

On March 23, 2004, a news conference was held announcing "major discoveries" of evidence of past liquid water on the Martian surface. A delegation of scientists showed pictures and data revealing a stratified pattern and cross bedding in the rocks of the outcrop inside a crater in Meridiani Planum, landing site of MER-B, *Opportunity*. This suggested that water once flowed in the region. The irregular distribution of chlorine and bromine also suggests that the place was once the shoreline of a salty sea, now evaporated.

On April 8, 2004, NASA announced that it was extending the mission life of the rovers from three to eight months. It immediately provided additional funding of US \$15 million through September, and \$2.8 million per month for continuing operations. Later that month, *Opportunity* arrived at Endurance crater, taking about five days to drive the 200 meters. NASA announced on September 22 that it was extending the mission life of the rovers for another six months. *Opportunity* was to leave Endurance crater, visit its discarded heat shield, and proceed to Victoria crater. *Spirit* was to attempt to climb to the top of the Columbia Hills.

With the two rovers still functioning well, NASA later announced another 18 month extension of the mission to September 2006. *Opportunity* was to visit the "Etched Terrain" and *Spirit* was to climb a rocky slope toward the top of Husband Hill. On August 21, 2005, *Spirit* reached the summit of Husband Hill after 581 sols and a journey of 4.81 kilometers (2.99 mi).



Spirit's "postcard" view from the summit of Husband Hill: a windswept plateau strewn with rocks, small exposures of outcrop, and sand dunes. The view is to the north, looking down upon the "Tennessee Valley". This approximate true-color composite spans about 90 degrees and consists of eighteen frames captured by the rover's panoramic camera.

Spirit celebrated its one Martian year anniversary (669 sols or 687 Earth days) on November 20, 2005. *Opportunity* celebrated its anniversary on December 12, 2005. At the beginning of the mission, it was expected that the rovers would not survive much longer than 90 Martian days. The Columbia Hills were "just a dream", according to rover driver Chris Leger. *Spirit* explored the semicircular rock formation known as Home Plate. It is a layered rock outcrop that puzzles and excites scientists. It is thought that its rocks are explosive volcanic deposits, though other possibilities exist, including impact deposits or sediment borne by wind or water.

Spirit's front right wheel ceased working on March 13, 2006, while the rover was moving itself to McCool Hill. Its drivers attempted to drag the dead wheel behind *Spirit*, but this only worked until reaching an impassable sandy area on the lower slopes. Drivers directed *Spirit* to a smaller sloped feature, dubbed "Low Ridge Haven", where it spent the long Martian winter, waiting for spring and increased solar power levels suitable for driving. That September, *Opportunity* reached the rim of Victoria crater, and Spaceflight Now reported that NASA had extended mission for the two rovers through September 2007. On February 6, 2007, *Opportunity* became the first spacecraft to traverse ten kilometers (10,000 meters) on the surface of Mars.

Opportunity was poised to enter Victoria Crater from its perch on the rim of Duck Bay on June 28, 2007, but due to extensive dust storms, it was indefinitely delayed until the dust had cleared and power returned to safe levels. Two months later, *Spirit* and *Opportunity* resumed driving after hunkering down during raging dust storms that limited solar power to a level that nearly caused the permanent failure of both rovers.

On October 1, 2007, both *Spirit* and *Opportunity* entered their fifth mission extension that could possibly extend operations into 2009, allowing the rovers to have spent five years exploring the Martian surface, pending their continued survival.

On August 26, 2008, *Opportunity* began its three-day climb out of Victoria crater amidst concerns that power spikes, similar to those seen on *Spirit* before the failure of its right-front wheel, might prevent it from ever being able to leave the crater if a wheel failed. Project scientist Bruce Banerdt also said, "We've done everything we entered Victoria Crater to do and more." *Opportunity* will return to the plains in order to characterize Meridiani Planum's vast diversity of rocks—some of which may have been blasted out of craters such as Victoria. The rover had been exploring Victoria Crater since September 11, 2007. As of January 2009, the two rovers had collectively sent back 250,000 images and traveled over 21 kilometers (13 mi).

After driving about 3.2 kilometers (2 mi) since it left Victoria crater, *Opportunity* first saw the rim of Endeavour crater on March 7, 2009. It passed the 10-mile mark (16 kilometers) along the way on sol 1897. Meanwhile, at Gusev crater, *Spirit* was dug in deep into the Martian sand, much as *Opportunity* was at Purgatory Dune in 2005.

On January 3 and January 24, 2010, *Spirit* and *Opportunity* marked six years on Mars, respectively. On January 26, NASA announced that *Spirit* will be used as a stationary research platform after several months of unsuccessful attempts to free the rover from soft sand.

NASA announced on March 24, 2010, that *Opportunity*, which has an estimated remaining drive distance of 12 km to Endeavour Crater, has traveled over 20 km since the start of its mission. Each rover was designed with a mission driving distance goal of just 600 meters. One week later, they announced that *Spirit* may have gone into hibernation for the Martian winter and might not wake up again for months.

On September 8, 2010, it was announced that *Opportunity* had reached the halfway point of the 19-kilometer journey between Victoria crater and Endeavour crater.

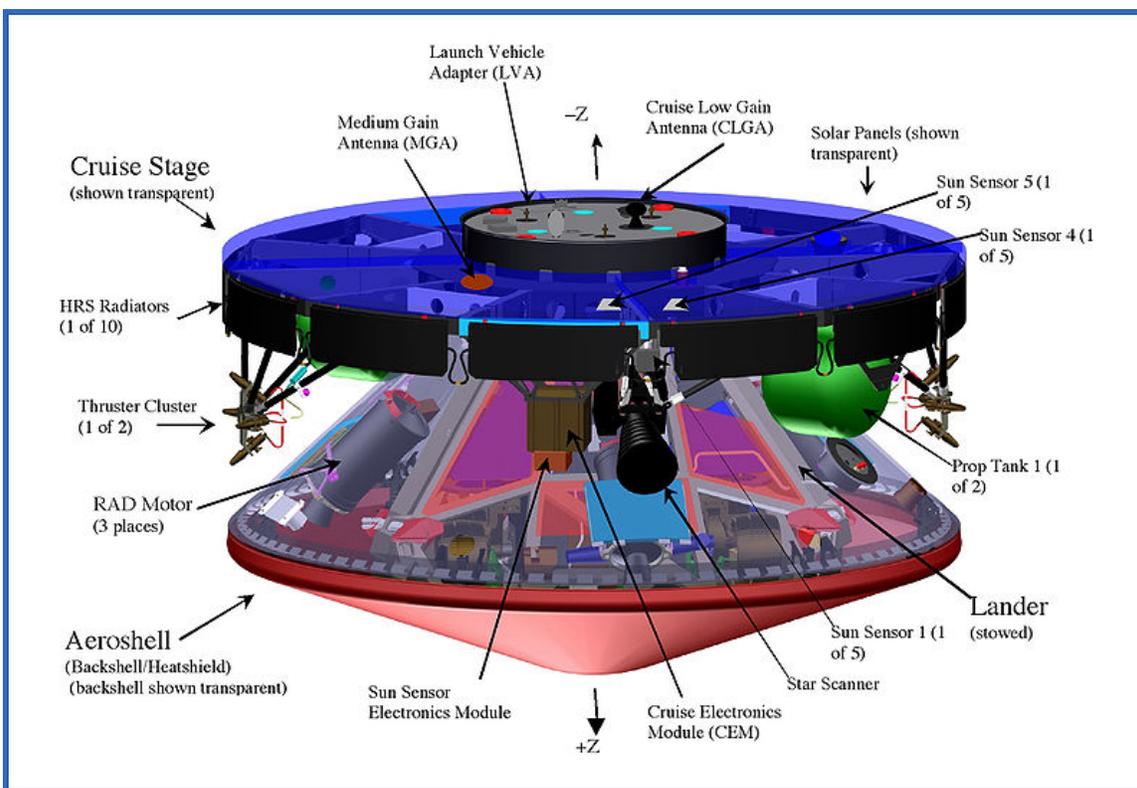
Spacecraft design



Delta II Heavy lifting off with MER-A on June 10, 2003



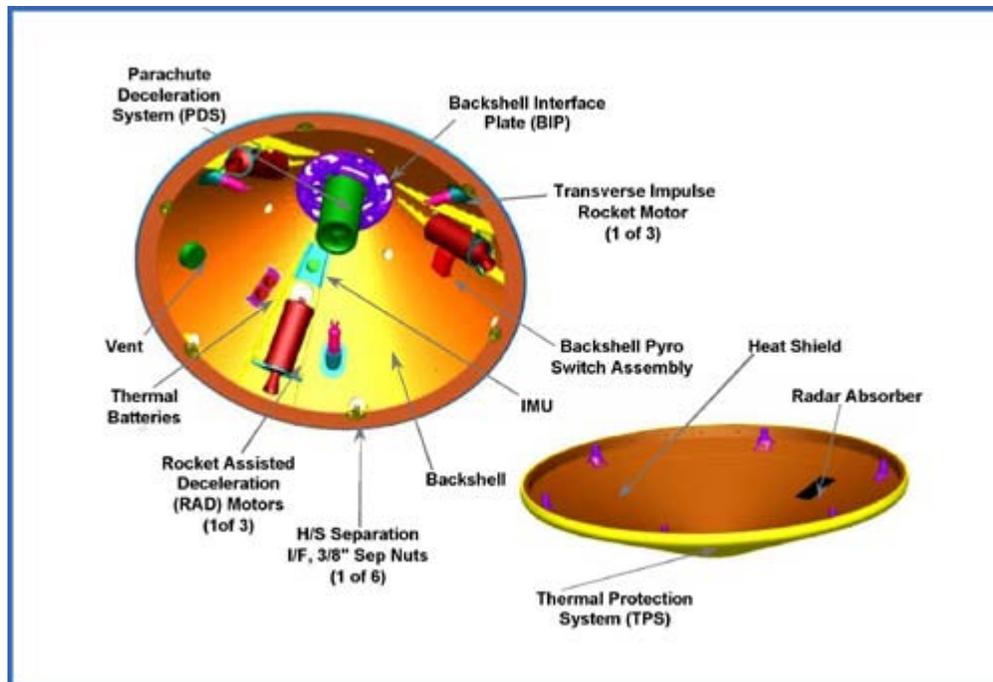
Delta II Heavy (7925H-9.5) lifting off from pad 17-B carrying MER-B



MER cruise stage diagram (Courtesy NASA/JPL-Caltech)



Cruise stage of *Opportunity* rover



Overview of the Mars Exploration Rover aeroshell



MER launch configuration, break apart illustration

The Mars Exploration Rover was designed to be stowed in the nose of a Delta II rocket. Each spacecraft consists of several components:

- Rover: 185 kg (408 lb)
- Lander: 348 kg (767 lb)
- Backshell / Parachute: 209 kg (461 lb)
- Heat Shield: 78 kg (172 lb)
- Cruise Stage: 193 kg (425 lb)
- Propellant: 50 kg (110 lb)
- Instruments: 5 kg (11 lb)

Total mass is 1,063 kg (2,343 lb).

Cruise stage

The cruise stage is the component of the spacecraft that is used for travel from Earth to Mars. It is very similar to the Mars Pathfinder in design and is approximately 2.65 meters (8.7 ft) in diameter and 1.6 m (5.2 ft) tall, including the entry vehicle (see below).

The primary structure is aluminium with an outer ring of ribs covered by the solar panels, which are about 2.65 m (8.7 ft) in diameter. Divided into five sections, the solar arrays can provide up to 600 watts of power near Earth and 300 W at Mars.

Heaters and multi-layer insulation keep the electronics "warm". A freon system removes heat from the flight computer and communications hardware inside the rover so they do not overheat. Cruise avionics systems allow the flight computer to interface with other electronics, such as the sun sensors, star scanner and heaters.

Navigation

The star scanner (with a backup system) and sun sensor allowed the spacecraft to know its orientation in space by analyzing the position of the Sun and other stars in relation to itself. Sometimes the craft could be slightly off course; this was expected, given the 500 million kilometer (320 million mile) journey. Thus navigators planned up to six trajectory correction maneuvers, along with health checks.

To ensure the spacecraft arrived at Mars in the right place for its landing, two light-weight, aluminium-lined tanks carried about 31 kg (about 68 lb) of hydrazine propellant. Along with cruise guidance and control systems, the propellant allowed navigators to keep the spacecraft on course. Burns and pulse firings of the propellant allowed three types of maneuvers:

- An axial burn uses pairs of thrusters to change spacecraft velocity;
- A lateral burn uses two "thruster clusters" (four thrusters per cluster) to move the spacecraft "sideways" through seconds-long pulses;
- Pulse mode firing uses coupled thruster pairs for spacecraft precession maneuvers (turns).

Communication

The spacecraft used a high-frequency X band radio wavelength to communicate, which allowed for less power and smaller antennas than many older craft, which used S band.

Navigators sent commands through two antennas on the cruise stage: a **cruise low-gain antenna** mounted inside the inner ring, and a **cruise medium-gain antenna** in the outer ring. The low-gain antenna was used close to Earth. It is omni-directional, so the transmission power that reached Earth fell faster with increasing distance. As the craft moved closer to Mars, the Sun and Earth moved closer in the sky as viewed from the craft, so less energy reached Earth. The spacecraft then switched to the medium-gain antenna, which directed the same amount of transmission power into a tighter beam toward Earth.

During flight, the spacecraft was spin-stabilized with a spin rate of two revolutions per minute (rpm). Periodic updates kept antennas pointed toward Earth and solar panels toward the Sun.

Aeroshell

The aeroshell maintained a protective covering for the lander during the seven month voyage to Mars. Together with the lander and the rover, it constituted the "entry vehicle". Its main purpose was to protect the lander and the rover inside it from the intense heat of entry into the thin Martian atmosphere. It was based on the Mars Pathfinder and Mars Viking designs.

Parts

The aeroshell was made of two main parts: a heat shield and a backshell. The heat shield was flat and brownish, and protected the lander and rover during entry into the Martian atmosphere and acted as the first aerobrake for the spacecraft. The backshell was large, cone-shaped and painted white. It carried the parachute and several components used in later stages of entry, descent, and landing, including:

- A parachute (stowed at the top of the backshell);
- The backshell electronics and batteries that fire off pyrotechnic devices like separation nuts, rockets and the parachute mortar;
- A Litton LN-200 Inertial Measurement Unit (IMU), which monitors and reports the orientation of the backshell as it swings under the parachute;
- Three large solid rocket motors called RAD rockets (Rocket Assisted Descent), each providing about a ton of force (10 kilonewtons) for about 4 seconds;
- Three small solid rockets called TIRS (mounted so that they aim horizontally out the sides of the backshell) that provide a small horizontal kick to the backshell to help orient the backshell more vertically during the main RAD rocket burn.

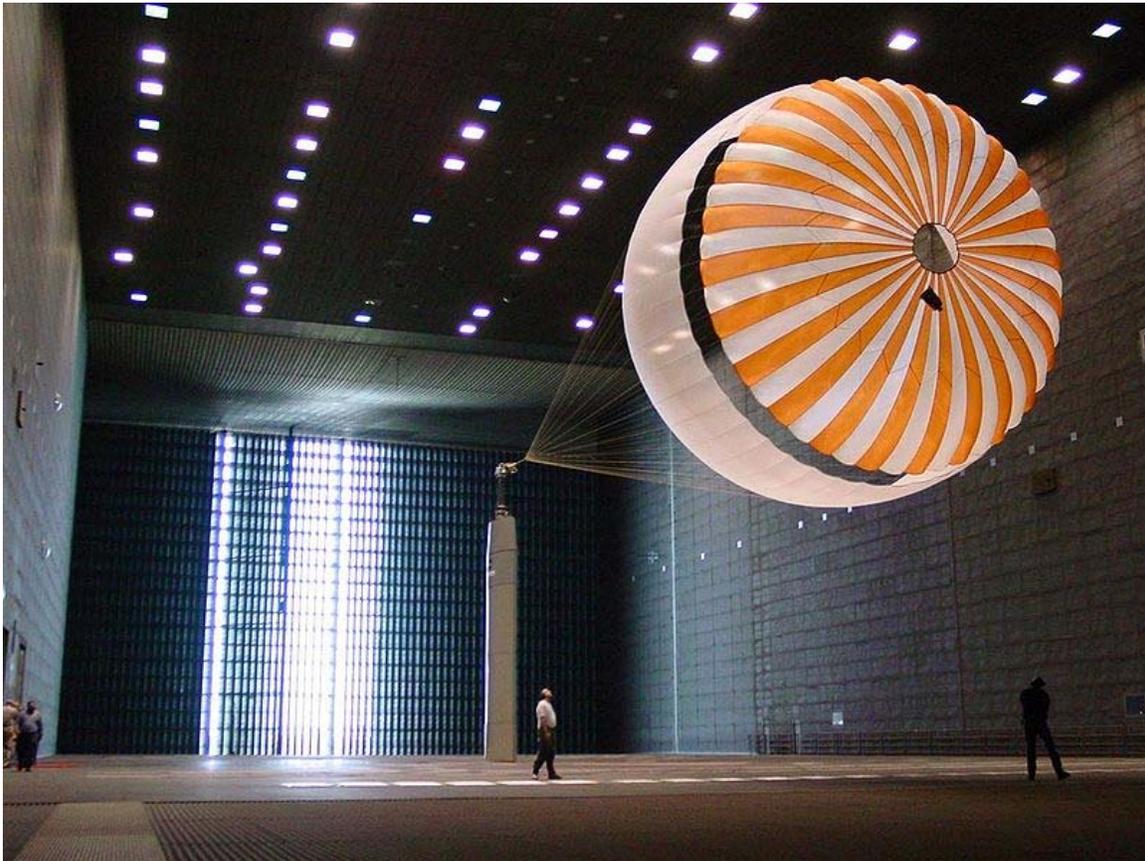
Composition

Built by the Lockheed Martin Astronautics Co. in Denver, Colorado, the aeroshell is made of an aluminium honeycomb structure sandwiched between graphite-epoxy face sheets. The outside of the aeroshell is covered with a layer of phenolic honeycomb. This honeycomb is filled with an ablative material (also called an "ablator"), that dissipates heat generated by atmospheric friction.

The ablator itself is a unique blend of cork wood, binder and many tiny silica glass spheres. It was invented for the heat shields flown on the Viking Mars lander missions. A similar technology was used in the first US manned space missions Mercury, Gemini and Apollo. It was specially formulated to react chemically with the Martian atmosphere during entry and carry heat away, leaving a hot wake of gas behind the vehicle. The vehicle slowed from 19000 km/h (about 12000 mph) to about 1600 km/h (1000 mph) in about a minute, producing about 60 m/s^2 (6 g) of acceleration on the lander and rover.

The backshell and heat shield are made of the same materials, but the heat shield has a thicker, 1/2 inch (12.7 mm), layer of the ablator. Instead of being painted, the backshell was covered with a very thin aluminized PET film blanket to protect it from the cold of deep space. The blanket vaporized during entry into the Martian atmosphere.

Parachute



Mars Exploration Rover's parachute test

The parachute helped slow the spacecraft during entry, descent, and landing. It is located in the backshell.

Design

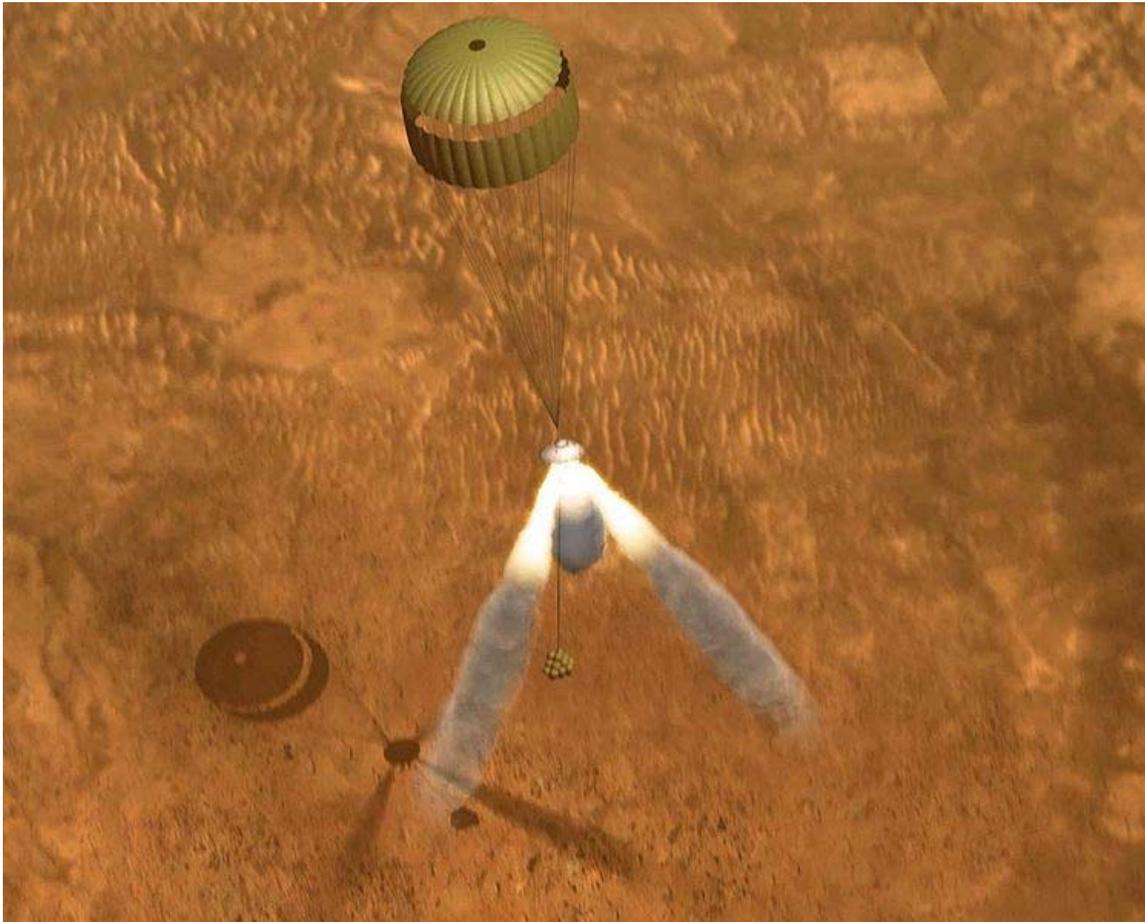
The 2003 parachute design was part of a long-term Mars parachute technology development effort and is based on the designs and experience of the Viking and Pathfinder missions. The parachute for this mission is 40% larger than Pathfinder's because the largest load for the Mars Exploration Rover is 80 to 85 kilonewtons (kN) or 18,000 to 19,000 lbf (85 kN) when the parachute fully inflates. By comparison, Pathfinder's inflation loads were approximately 35 kN (about 8,000 lbf). The parachute was designed and constructed in South Windsor, Connecticut by Pioneer Aerospace, the company that also designed the parachute for the *Stardust* mission.

Composition

The parachute is made of two durable, lightweight fabrics: polyester and nylon. A triple bridle made of Kevlar connects the parachute to the backshell.

The amount of space available on the spacecraft for the parachute is so small that the parachute had to be pressure-packed. Before launch, a team tightly folded the 48 suspension lines, three bridle lines, and the parachute. The parachute team loaded the parachute in a special structure that then applied a heavy weight to the parachute package several times. Before placing the parachute into the backshell, the parachute was heat set to sterilize it.

Connected systems



Descent is halted by retrorockets and lander is dropped 10m (30 ft) to the surface in this computer generated impression.

Zylon Bridles: After the parachute was deployed at an altitude of about 10 km (6 miles) above the surface, the heatshield was released using 6 separation nuts and push-off springs. The lander then separated from the backshell and "rappelled" down a metal tape on a centrifugal braking system built into one of the lander petals. The slow descent down the metal tape placed the lander in position at the end of another bridle (tether), made of a nearly 20 m (65 ft) long braided Zylon.

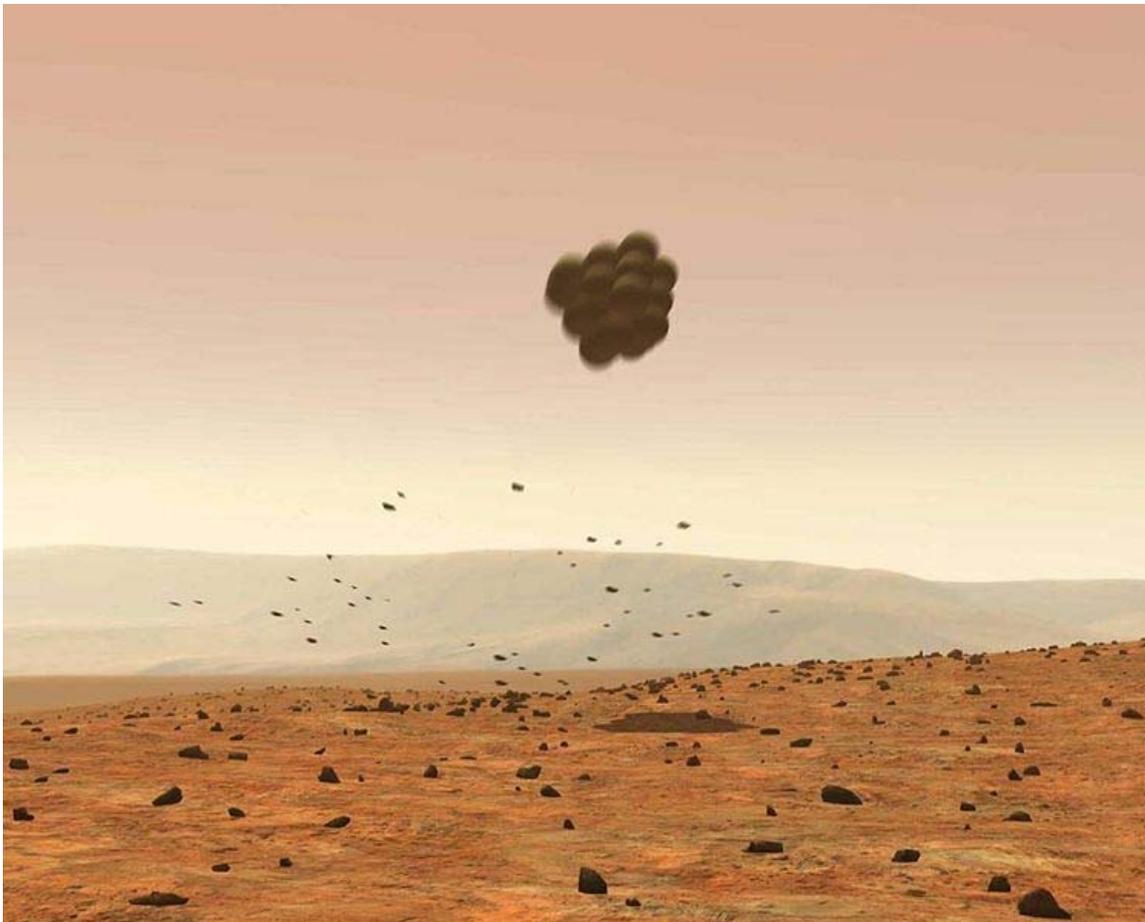
Zylon is an advanced fiber material, similar to Kevlar, that is sewn in a webbing pattern (like shoelace material) to make it stronger. The Zylon bridle provides space for airbag

deployment, distance from the solid rocket motor exhaust stream, and increased stability. The bridle incorporates an electrical harness that allows the firing of the solid rockets from the backshell as well as provides data from the backshell inertial measurement unit (which measures rate and tilt of the spacecraft) to the flight computer in the rover.

Rocket assisted descent (RAD) motors: Because the atmospheric density of Mars is less than 1% of Earth's, the parachute alone could not slow down the Mars Exploration Rover enough to ensure a safe, low landing speed. The spacecraft descent was assisted by rockets that brought the spacecraft to a dead stop 10–15 m (30–50 ft) above the Martian surface.

Radar altimeter unit: A radar altimeter unit was used to determine the distance to the Martian surface. The radar's antenna is mounted at one of the lower corners of the lander tetrahedron. When the radar measurement showed the lander was the correct distance above the surface, the Zylon bridle was cut, releasing the lander from the parachute and backshell so that it was free and clear for landing. The radar data also enabled the timing sequence on airbag inflation and backshell RAD rocket firing.

Airbags



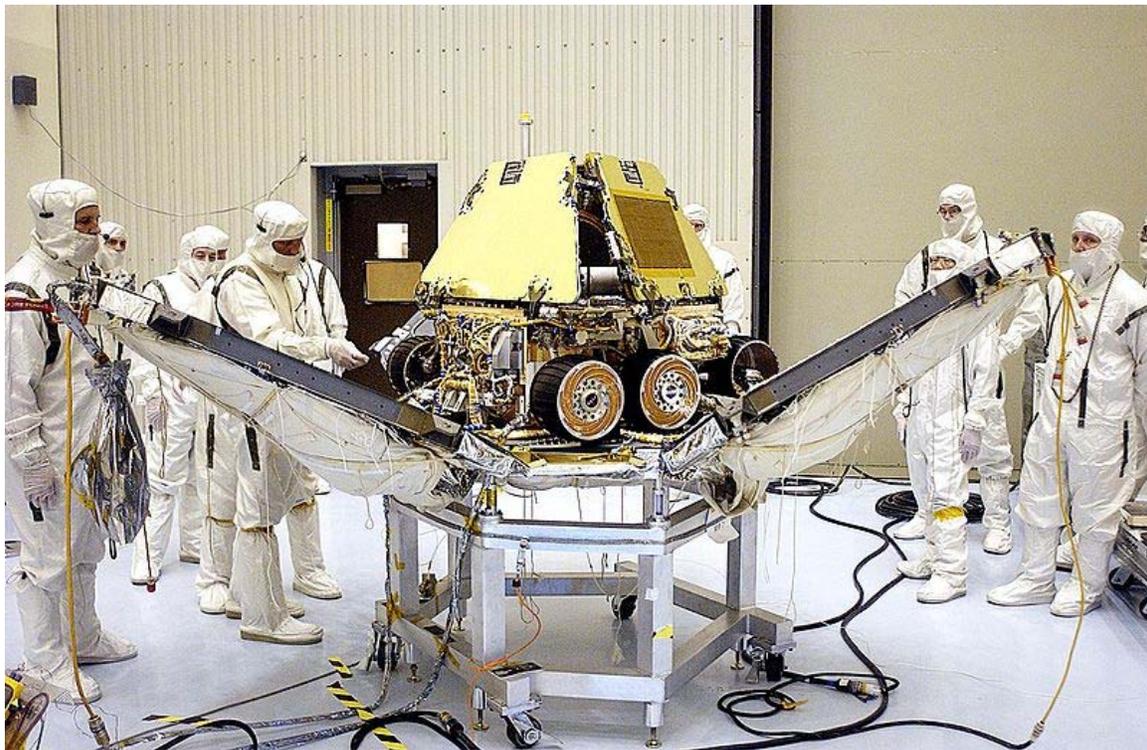
Artist's concept of inflated airbags

Airbags used in the Mars Exploration Rover mission are the same type that Mars Pathfinder used in 1997. They had to be strong enough to cushion the spacecraft if it landed on rocks or rough terrain and allow it to bounce across Mars' surface at freeway speeds after landing. The airbags had to be inflated seconds before touchdown and deflated once safely on the ground.

The airbags were made of Vectran, like those on Pathfinder. Vectran has almost twice the strength of other synthetic materials, such as Kevlar, and performs better in cold temperatures. Six 100 denier (10 mg/m) layers of Vectran protected one or two inner bladders of Vectran in 200 denier (20 mg/m). Using 100 denier (10 mg/m) leaves more fabric in the outer layers where it is needed, because there are more threads in the weave.

Each rover used four airbags with six lobes each, all of which were connected. Connection was important, since it helped abate some of the landing forces by keeping the bag system flexible and responsive to ground pressure. The airbags were not attached directly to the rover, but were held to it by ropes crisscrossing the bag structure. The ropes gave the bags shape, making inflation easier. While in flight, the bags were stowed along with three gas generators that are used for inflation.

Lander



MER lander petals opening (Courtesy NASA/JPL-Caltech)

The spacecraft lander is a protective "shell" that houses the rover, and together with the airbags, protects it from the forces of impact.

The lander is a tetrahedron shape, whose sides open like petals. It is strong and light, and made of beams and sheets. The beams consist of layers of graphite fiber woven into a fabric that is lighter than aluminium and more rigid than steel. Titanium fittings are glued and fitted onto the beams to allow it to be bolted together. The rover was held inside the lander by bolts and special nuts that were released after landing with small explosives.

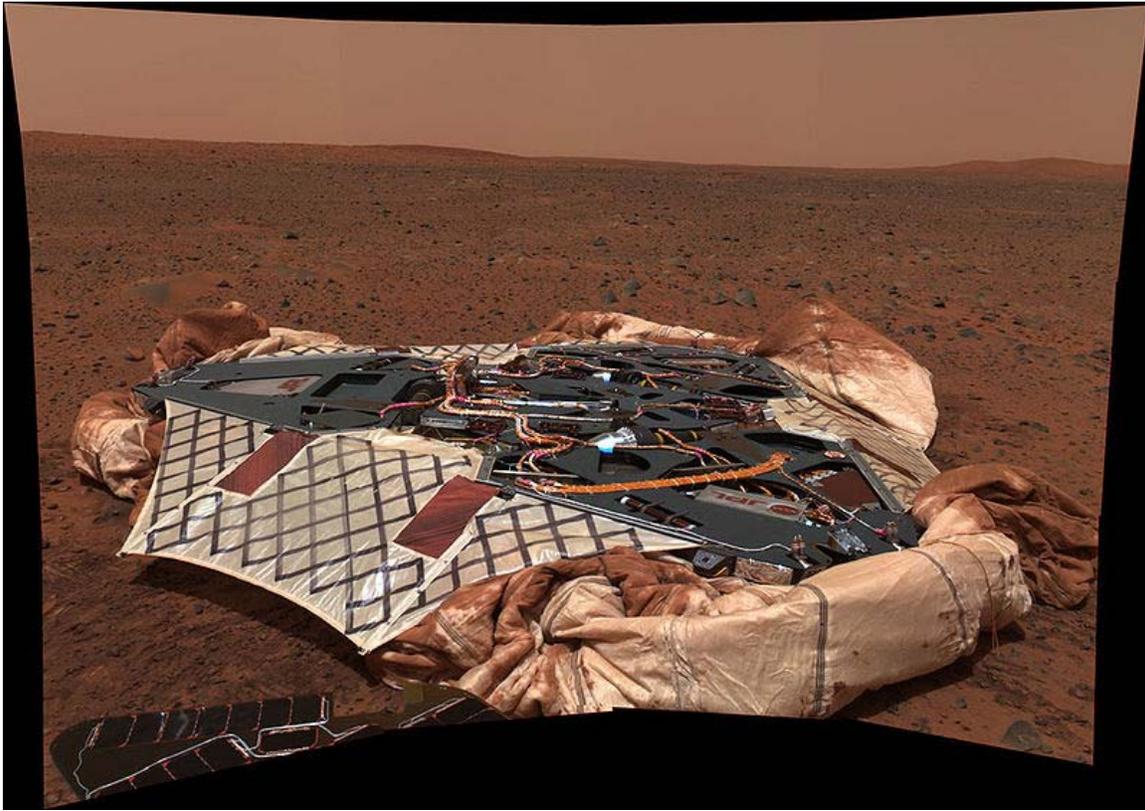
Uprighting

After the lander stopped bouncing and rolling on the ground, it came to rest on the base of the tetrahedron or one of its sides. The sides then opened to make the base horizontal and the rover upright. The sides are connected to the base by hinges, each of which has a motor strong enough to lift the lander. The rover plus lander has a mass of about 533 kilograms (1,175 pounds). The rover alone weighs about 185 kg (408 lb). The gravity on Mars is about 38% of Earth's, so the motor does not need to be as powerful as it would on Earth.

The rover contains accelerometers to detect which way is down (toward the surface of Mars) by measuring the pull of gravity. The rover computer then commanded the correct lander petal to open to place the rover upright. Once the base petal was down and the rover was upright, the other two petals were opened.

The petals initially opened to an equally flat position, so all sides of the lander were straight and level. The petal motors are strong enough so that if two of the petals come to rest on rocks, the base with the rover would be held in place like a bridge above the ground. The base will hold at a level even with the height of the petals resting on rocks, making a straight flat surface throughout the length of the open, flattened lander. The flight team on Earth could then send commands to the rover to adjust the petals and create a safe path for the rover to drive off the lander and onto the Martian surface without dropping off a steep rock.

Moving the payload onto Mars



Spirit's lander on Mars

The moving of the rover off the lander is called the egress phase of the mission. The rover must avoid having its wheels caught in the airbag material or falling off a sharp incline. To help this, a retraction system on the petals slowly drags the airbags toward the lander before the petals open. Small ramps on the petals fan out to fill spaces between the petals. They cover uneven terrain, rock obstacles, and airbag material, and form a circular area from which the rover can drive off in more directions. They also lower the step that the rover must climb down. They are nicknamed "batwings", and are made of Vectran cloth.

About three hours were allotted to retract the airbags and deploy the lander petals.

Rover design



Mars Exploration Rover vs. Sojourner rover (Courtesy NASA/JPL-Caltech)

The rovers are six-wheeled, solar-powered robots that stand 1.5 m (4.9 ft) high, 2.3 m (7.5 ft) wide and 1.6 m (5.2 ft) long. They weigh 180 kg (400 lb), 35 kg (80 lb) of which is the wheel and suspension system.

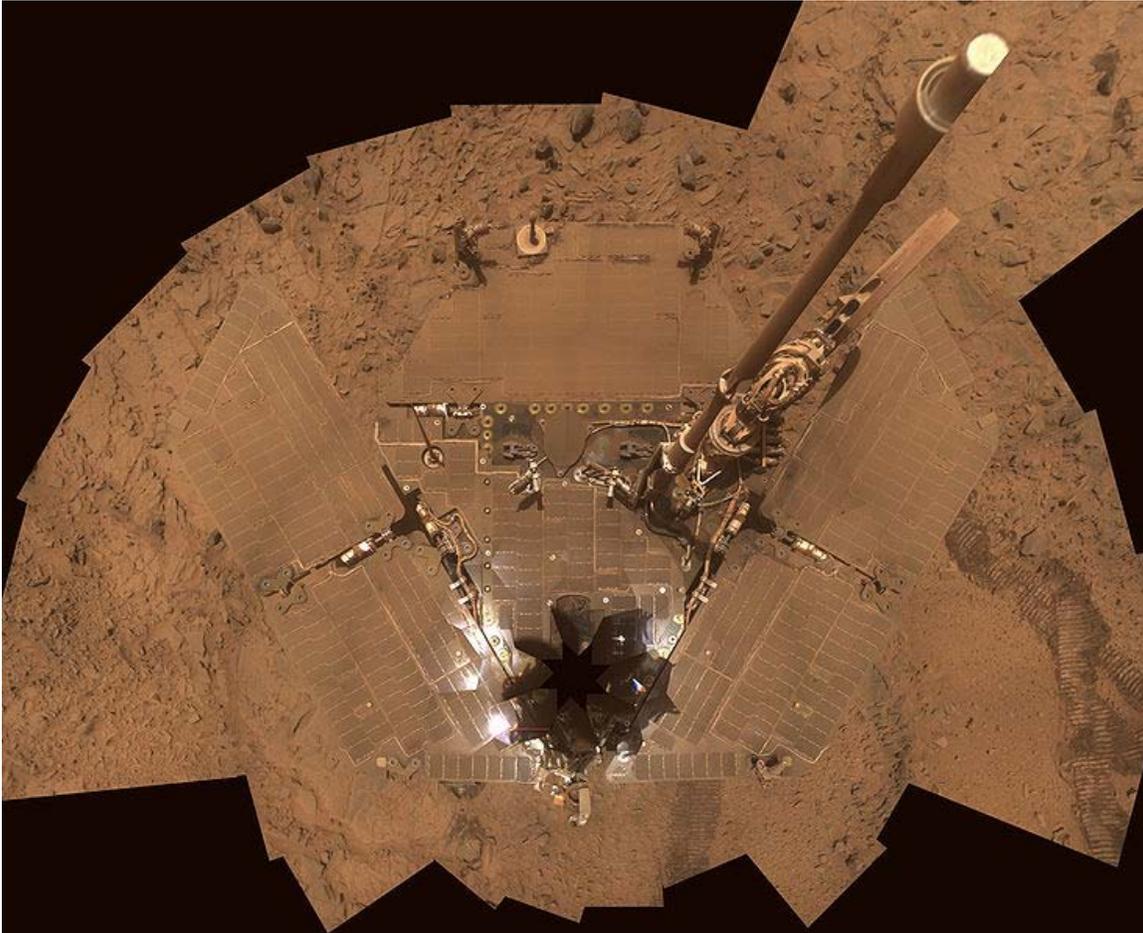
Drive system

Each rover has six wheels mounted on a rocker-bogie suspension system that ensures wheels remain on the ground while driving over rough terrain. The design reduces the range of motion of the rover body by half, and allows the rover to go over obstacles or through holes that are more than a wheel diameter (250 mm or 10 inches) in size. Each wheel also has cleats, providing grip for climbing in soft sand and scrambling over rocks.

Each wheel has its own motor. The two front and two rear wheels each have individual steering motors. This allows the vehicle to turn in place, a full revolution, and to swerve and curve, making arching turns. The rover is designed to withstand a tilt of 45 degrees in any direction without overturning. However, the rover is programmed through its "fault protection limits" in its hazard avoidance software to avoid exceeding tilts of 30 degrees.

Each rover can spin one of its front wheels in place to grind deep into the terrain. It is to remain motionless while the digging wheel is spinning. The rovers have a top speed on flat hard ground of 50 mm/s (2 in/s). The average speed is 10 mm/s, because its hazard avoidance software causes it to stop every 10 seconds for 20 seconds to observe and understand the terrain into which it has driven.

Power and electronic systems



Circular projection showing MER-A *Spirit's* solar panels covered in dust in October 2007 on Mars. Unexpected Cleaning events have periodically increased power.

When fully illuminated, the rover triplejunction solar arrays generate about 140 watts for up to four hours per Martian day (sol). The rover needs about 100 watts to drive. Its power system includes two rechargeable lithium ion batteries weighing 7.15 kg (16 pounds) each, that provide energy when the sun is not shining, especially at night. Over time, the batteries will degrade and will not be able to recharge to full capacity.

For comparison, the future Mars Science Laboratory's power system is composed of a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) produced by Boeing. The MMRTG is designed to provide 125W of electrical power at the start of the mission, falling to 100W after 14 years of service. It will be used to power the MSL's many

systems and instruments. Solar panels were also considered for the MSL, but RTGs provide constant power, regardless of the time of day, and thus the versatility to work in dark environments and high latitudes where solar energy is not readily available. The MSL will generate 2.5 kilowatt hours per day, compared to the Mars Exploration Rovers, which can generate about 0.6 kilowatt hours per day.

It was thought that by the end of the 90-sol mission, the capability of the solar arrays to generate power would likely be reduced to about 50 watts. This was due to anticipated dust coverage on the solar arrays, and the change in season. Over three Earth years later, however, the rovers' power supplies hovered between 300 watt-hours and 900 watt-hours per day, depending on dust coverage. Cleaning events (dust removal by wind) have occurred more often than NASA expected, keeping the arrays relatively free of dust and extending the life of the mission. During a 2007 global dust storm on Mars, both rovers experienced some of the lowest power of the mission; *Opportunity* dipped to 128 watt-hours. In November 2008, Spirit had overtaken this low-energy record with a production of 89 watt-hours, due to dust storms in the region of Gusev crater.

The rovers run a VxWorks embedded operating system on a radiation-hardened 20 MHz RAD6000 CPU with 128 MB of DRAM with error detection and correction and 3 MB of EEPROM. Each rover also has 256 MB of flash memory. To survive during the various mission phases, the rover's vital instruments must stay within a temperature of -40°C to $+40^{\circ}\text{C}$ (-40°F to 104°F). At night, the rovers are heated by eight radioisotope heater units (RHU), which each continuously generate 1 W of thermal energy from the decay of radioisotopes, along with electrical heaters that operate only when necessary. A sputtered gold film and a layer of silica aerogel are used for insulation.

Communication

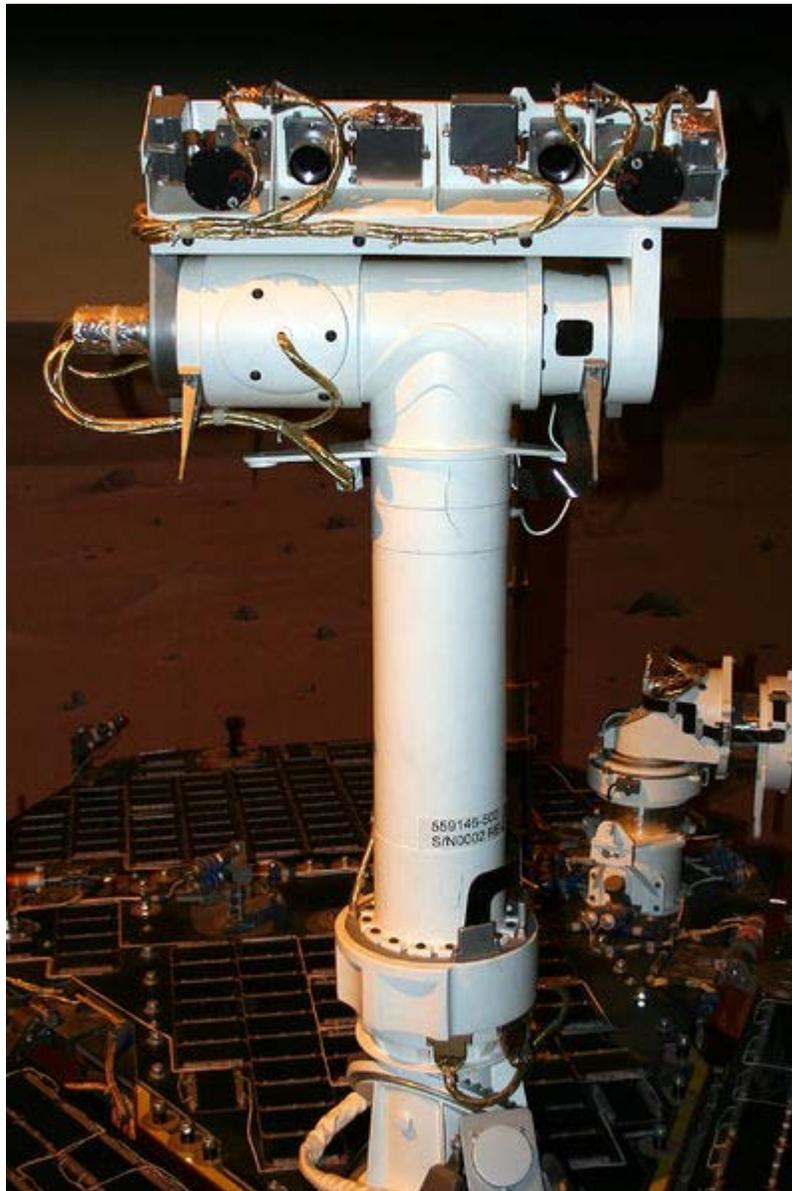
The rover has a low-gain and a high-gain antenna. The low-gain antenna is omnidirectional, and transmits data at a low rate to Deep Space Network (DSN) antennas on Earth. The high-gain antenna is directional and steerable, and can transmit data to Earth at a higher rate. The rovers also use the low-gain antennas to communicate with spacecraft orbiting Mars, the Mars Odyssey and (before its failure) the Mars Global Surveyor. The orbiters relay data from and to Earth; most data to Earth is relayed through Odyssey. The orbiters are closer to the rovers than the antennas on Earth, and have a view of Earth for much longer than the rovers. The orbiters communicate with the rovers using UHF antennas, which have shorter range than the low and high-gain antennas. One UHF antenna is on the rover, and one is on a petal of the lander to aid in gaining information during the critical landing event.

The rovers have a total of 9 cameras, which produce 1024-pixel by 1024-pixel images at 12 bits per pixel, but most navigation camera images and image thumbnails are truncated to 8 bits per pixel to conserve memory and transmission time. All images are then compressed using ICER before being stored and sent to Earth. Navigation, thumbnail, and many other image types are compressed to approximately 0.8 to 1.1 bits/pixel. Lower

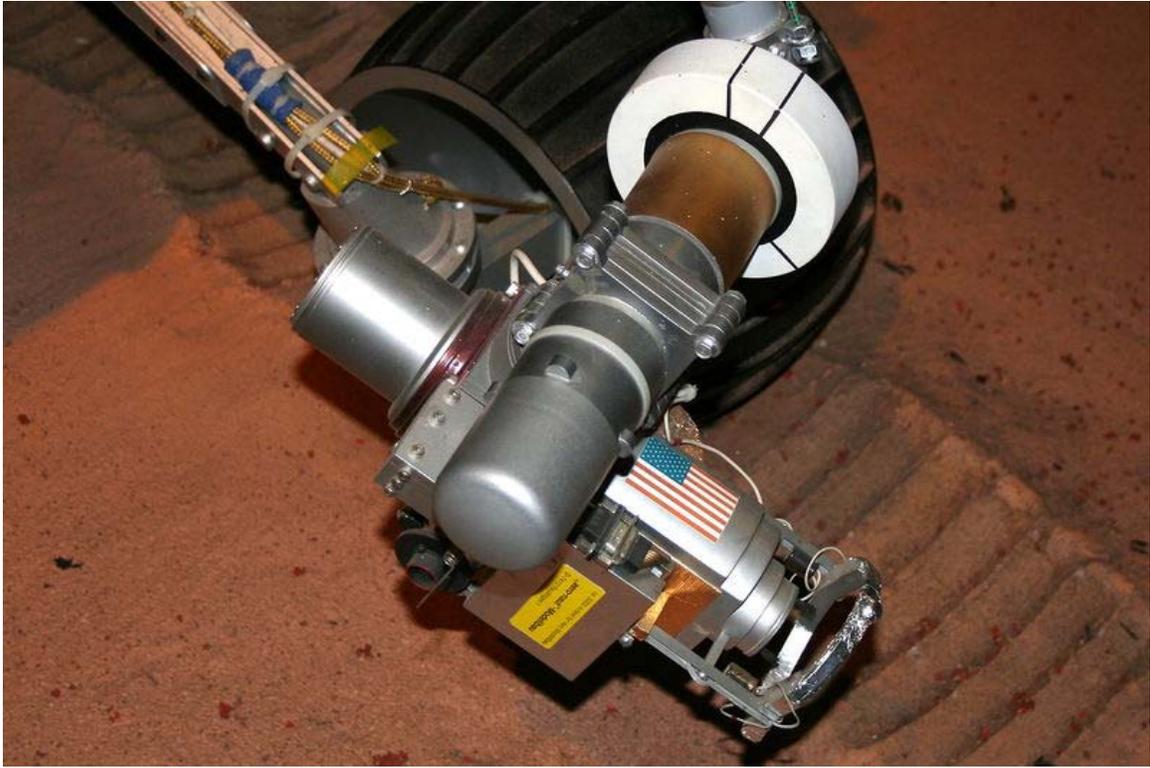
bit rates (less than 0.5 bit/pixel) are used for certain wavelengths of multi-color panoramic images.

ICER is based on wavelets, and was designed specifically for deep-space applications. It produces progressive compression, both lossless and lossy, and incorporates an error-containment scheme to limit the effects of data loss on the deep-space channel. It outperforms the lossy JPEG image compressor and the lossless Rice compressor used by the Mars Pathfinder mission.

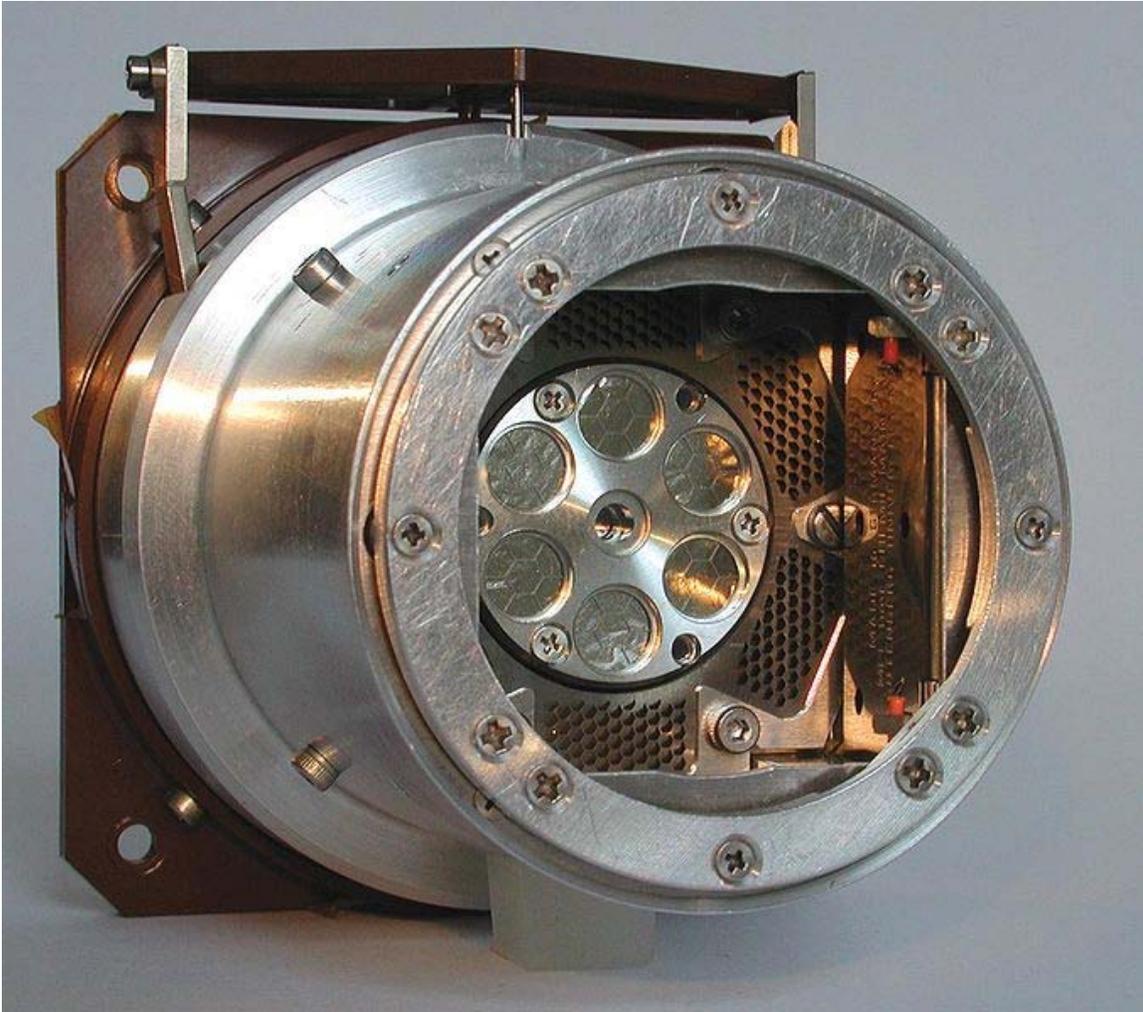
Scientific instrumentation



Panoramic Camera (Pancam)



Rock Abrasion Tool (RAT)



Alpha particle X-Ray Spectrometer (APXS) (Courtesy NASA/JPL-Caltech)

The rover has various instruments. Three are mounted on one assembly:

- Panoramic Camera (Pancam), for determining the texture, color, mineralogy, and structure of the local terrain.
- Navigation Camera (Navcam), that has higher field of view but lower resolution and is monochromatic, for navigation and driving.
- A mirror for the Miniature Thermal Emission Spectrometer (Mini-TES), which identifies promising rocks and soils for closer examination, and determines the processes that formed them. It was built by Arizona State University.

The cameras are mounted 1.5 meters high on the Pancam Mast Assembly. One motor turns the assembly horizontally a whole revolution. Another points the cameras vertically, at most straight up or down. A third motor points the Mini-TES, up to 30° above the horizon and 50° below. The assembly was built by Ball Aerospace & Technologies Corp., Boulder, Colorado, as was the High-Gain Antenna Gimbal (HGAG).

Four monochromatic hazard cameras (Hazcams) are mounted on the rover's body, two in front and two behind.

The instrument deployment device (IDD), also called the rover arm, holds the following:

- Mössbauer spectrometer (MB) MIMOS II, developed by Dr. Göstar Klingelhöfer at the Johannes Gutenberg University in Mainz, Germany, is used for close-up investigations of the mineralogy of iron-bearing rocks and soils.
- Alpha Particle X-Ray Spectrometer (APXS), developed by the Max Planck Institute for Chemistry in Mainz, Germany, is used for close-up analysis of the abundances of elements that make up rocks and soils.
- Magnets, for collecting magnetic dust particles, developed by Jens Martin Knudsen's group at the Niels Bohr Institute, Copenhagen. The particles are analyzed by the Mössbauer Spectrometer and X-ray Spectrometer to help determine the ratio of magnetic particles to non-magnetic particles and the composition of magnetic minerals in airborne dust and rocks that have been ground by the Rock Abrasion Tool. There are also magnets on the front of the rover, which are studied extensively by the Mössbauer spectrometer.
- Microscopic Imager (MI) for obtaining close-up, high-resolution images of rocks and soils. Development was led by Ken Herkenhoff's team at the USGS Astrogeology Research Program.
- Rock Abrasion Tool (RAT), developed by Honeybee Robotics, for removing dusty and weathered rock surfaces and exposing fresh material for examination by instruments on-board.

The robotic arm is able to place instruments directly up against rock and soil targets of interest.