Phoenix on Mars

The latest successful landing craft has made new discoveries about water on the red planet

Walter Goetz

Since we received our first close-up photographs of Mars, when Mariner 4 flew by it in 1965, our nearest neighbor has appeared to be much like our own planet in many ways, but also distinctly different. Mars is about half the size and has about 40 percent of the gravity of Earth, it's at least 55 million kilometers away (depending on the two planets' positions in their orbits), and it currently takes at least nine months to get there. But like Earth, Mars has polar ice caps, clouds in its atmosphere and seasonal weather patterns. It has familiar geological features, such as volcanoes and canyons. However, although there are signs of floods in the ancient past, Mars is now apparently a barren world.

What is the history of liquid water on Mars? Has water ever been stable on its surface (or in its near subsurface) for a geologically significant period of time? Was Mars warm and wet in ancient times? If so, what triggered the apparent change in climate? And could primitive terrestrial life-forms evolve in the present or past Martian environment? These are the main questions that have driven the exploration of Mars since the mid-1960s. In addition, if humans ever tried to travel to, or even set up an outpost on, another planet, Mars would likely be the first choice, so there's even more reason to learn as much as possible about our neighboring planet.

Missions to Mars have been a mix of failure and success. The first working spacecraft to land on the planet's surface were Viking 1 and 2 in the mid-1970s, and they returned the first color images of the planet. They also sent back data long past their planned mission lifetime, until 1982 and 1980, respectively. Their experiments on Martian soil, looking for signs of microscopic life, were inconclusive. More than a decade later, a mission to send an orbiter to Mars ended in failure, but another, Mars Global Surveyor, arrived in 1997 and returned data until October 2006. Also in 1997, the Mars Pathfinder lander, with its Sojourner rover, landed safely and was remarkably successful.

In 1999 the Mars Climate Orbiter and the Mars Polar Lander both failed and were lost upon arrival at Mars. The Mars Surveyor 2001 mission, including an orbiter, a lander and a rover, was canceled in 2000, but its orbiter was repurposed and successfully launched as the 2001 Mars Odyssey orbiter. This orbiter has also relayed information back from the twin rovers, Spirit and Opportunity, which landed in 2004. The European Space Agency (ESA) saw the safe arrival of its orbiter, Mars Express, in 2003, although the lander was lost on deployment. The Mars Reconnaissance Orbiter safely joined Mars's orbit in 2006, providing the highest camera resolution yet.

However, after the Mars Polar Lander crashed and the Mars Surveyor 2001 mission was canceled in 2000, there seemed to be no hope for a new mission to the Martian arctic regions. The situation changed early in 2002 when the Mars Odyssey orbiter discovered large amounts of near-surface hydrogen in exactly these regions. The hydrogen reservoir was interpreted as water ice—less than a meter below the surface. It was argued that such arctic water ice might contain the long-searched for (and long-missed) organic compounds that could signify the presence of life, either past or present.

These discoveries led a group, headed by Peter H. Smith of the University of Arizona, to develop a mission that would build on previous designs and use the already completed, but unused, Mars Surveyor lander. Thus was born the Phoenix Mars Lander, named because like the mythical bird, it had been resurrected from the ashes of its predecessors. The rocket that carried Phoenix was launched on August 4, 2007, and the spacecraft landed safely on May 25, 2008.

Anatomy of a Lander

Phoenix's suite of scientific instruments includes several imaging systems that have different levels of resolution. From lowest to highest resolution, these instruments are its stereo surface imager (SSI), which can show about 1 millimeter per pixel; a robotic arm camera (RAC), with a resolution of more than 24 micrometers per pixel; an optical microscope that can reach about 4 micrometers per pixel; and an atomic force microscope (AFM) that can show about 0.1 micrometers per scan. Our group at the Max Planck Institute for Solar System Research, in collaboration with the University of Arizona, contributed the RAC and the focal-plane assembly of the optical microscope.

The lander also has a wet chemistry laboratory unit (WCL), where it can mix Martian soil in liquid water. The unit consists of four such cells, each designed for a single use. The resulting aqueous solution is analyzed by ion-selective electrodes, which provide information on the compounds in the soil (such as salts) that are soluble in liquid water.

Another important instrument is a thermal analyzer, designed to heat soil

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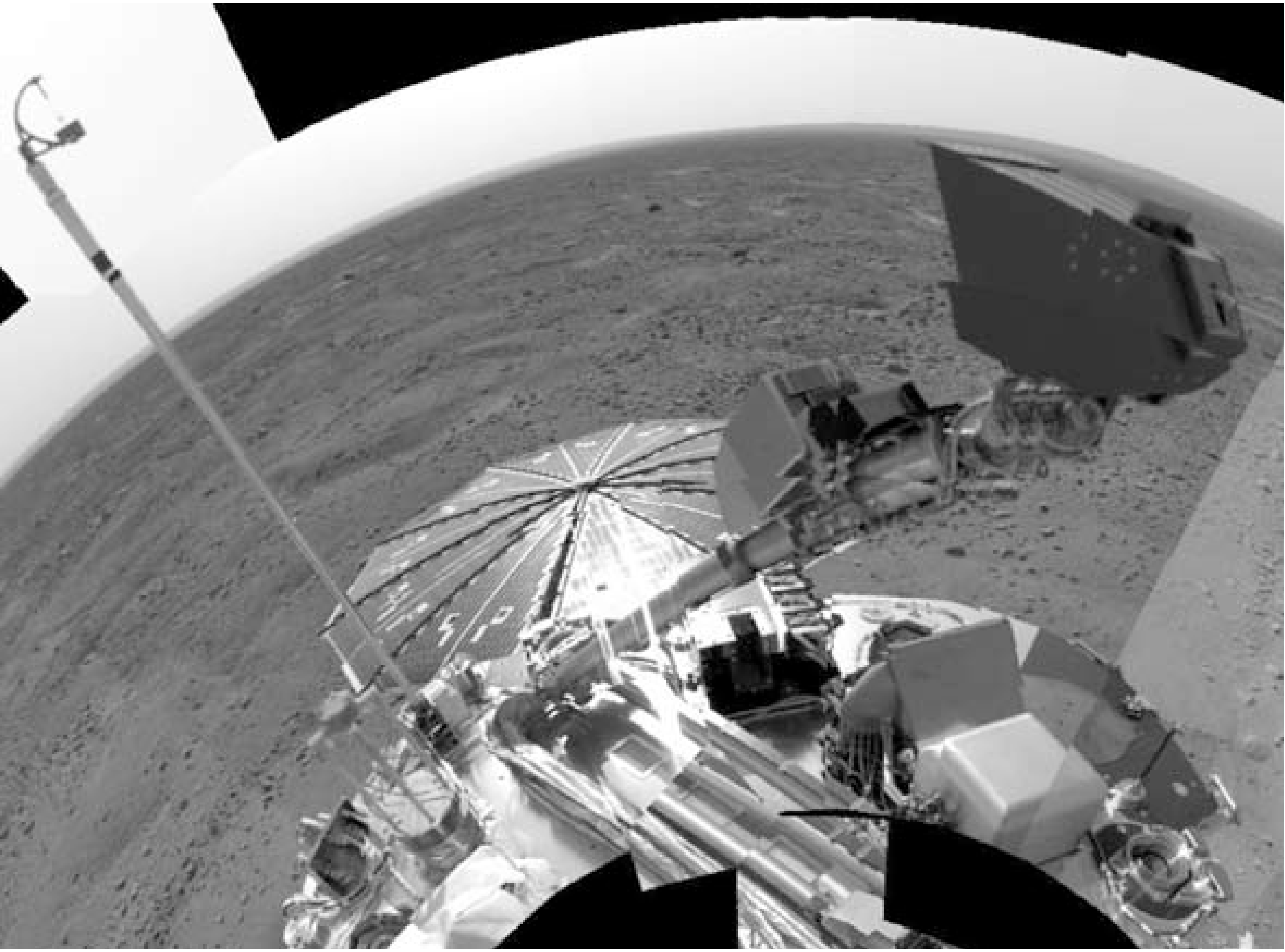


Figure 1. More than a simple tourist snapshot of itself in an exotic locale, this self-portrait of the Phoenix lander shows a remarkable feat: the safe arrival, descent and landing of the spacecraft onto the surface of Mars, a result that is still not a given for interplanetary missions. Not only that, the lander also carried out a series of studies on water ice, soil chemistry and weather patterns over the course of several months in 2008. Phoenix is a Cinderella story, as the lander was originally constructed for the cancelled 2001 Mars Surveyor mission. Its resurrection and deployment to Mars' polar regions has provided great insights into the water cycle on our neighboring planet. This panorama of the lander, showing its robot arm partially deployed, was taken during the first few days after landing. (Image courtesy of NASA/JPL/University of Arizona and M. T. Lemmon, Texas A&M University.)

samples up to 1,000 degrees Celsius; the evaporating gases are then studied by mass spectroscopy. This instrument group (referred to as the Thermal and Evolved Gas Analyzer, or TEGA) should be able to characterize the inventory of potential organic compounds in the Martian soil by detecting either the parent organic molecules or their thermally generated fragments, as the temperatures where specific gases are released constrain the identity of the parent compound. As the amount of heat is increased at known levels, any additional increase in temperature also reveals phase transitions in the compounds, which can possibly be identified by their enthalpic characteristics.

The spacecraft also has a robotic arm that is in itself a scientific instrument, as it allows the lander to characterize the physical properties of the soil. The scoop at the end of the 2.3-meter-long arm allows controllers to select and transfer specific soil samples to various instruments. An ice drill is mounted to the backside of the scoop. The robotic arm camera is positioned on the arm so that it can see into the scoop and image the collected soil sample at high resolution. A sensor mounted next to the scoop can measure the soil's electric and thermal conductivity between four needles. An additional sensor can measure the atmospheric water vapor pressure and the relative humidity of the atmosphere.

A meteorological mast, provided by the Canadian Space Agency, collects data about the Martian weather that help describe how water cycles between the solid and gas phases at the landing site. Its central instrument is a LIDAR (Light Detection And Ranging) that probes the vertical structure of the atmosphere by measuring the travel time of its emitted light as it is backscattered by suspended particles (such as dust and ice) in the air. Pressure and temperature sensors are

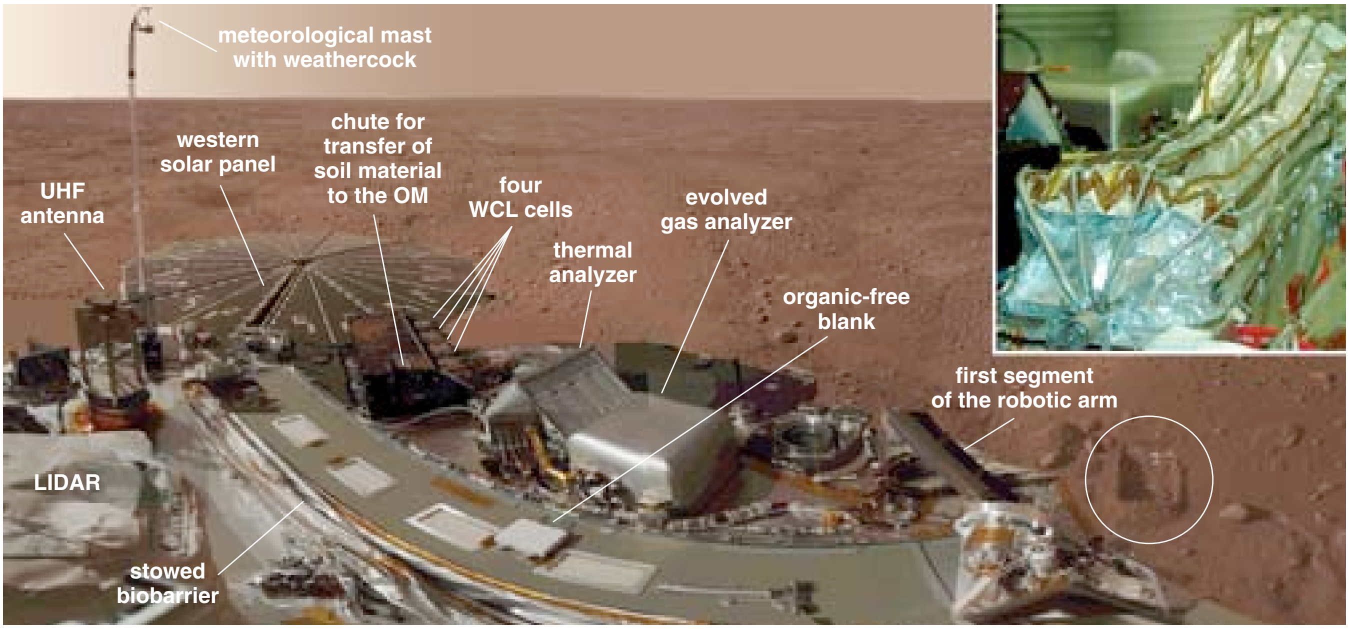


Figure 2. An image of the lander by its stereo surface imager shows a number of Phoenix's scientific instruments. At left, a LIDAR (Laser Detection And Ranging) is used in conjunction with the metorological mast and weathercock for weather studies. A UHF (ultra-high frequency) antenna relays data to an orbiting satellite. The lander has two large circular solar panels, the western-facing one of which is shown. A chute is used to transfer soil samples to the optical microscope (OM). A wet chemistry laboratory (WCL) has four cells in which it can mix soil samples with liquid for analysis. A thermal analyzer and evolved gas analyzer heat samples and look at the gases emitted, respectively. A Teflon block, called an organic-free blank, is used to serve as a baseline reference for organic molecules. One segment of the robotic arm can be seen at the right of the image, next to a trench about 20 centimeters wide *(white circle)* that was later analyzed for water ice. The inset at upper right shows a foldable cover, called a biobarrier, that protected the robotic arm and scoop from biological contamination during flight. This cover folded towards the front of the lander and was stowed after landing. (Image courtesy of NASA/JPL/University of Arizona and M. T. Lemmon, Texas A&M University; inset image courtesy of IEEE and R. G. Bonitz, NASA/JPL.)

mounted to the mast at three different heights above the deck (25, 50 and 100 centimeters), and the mast is topped by a Danish-produced weathercock (telltale, or wind indicator). The SSI provides complementary data on the atmospheric dust opacity and water vapor abundance by imaging the solar disk through specific visible and near-infrared filters.

Where It All Happens

Spectroscopic data and high-resolution images from various orbiters (including Mars Global Surveyor, Odyssey, Mars Express and Mars Reconnaissance Orbiter) were available prior to landing and were used extensively to select the best landing site for Phoenix, both in terms of safety and for the best chance of doing useful research.

The distance from the landing site to the northern border of the volcanic Tharsis region is about 500 kilometers and to the nearest volcano (Alba Patera) is about 1,800 kilometers. The north-polar ice cap and the circumpolar dunes are located about 2,000 kilometers north of the lander. On a large scale, we expected volcanic ashes from the Tharsis province as well as sand grains from the north-polar dunes at the site. The landing site is also situated about 20 kilometers west from the Heimdall crater, which has a diameter of 11 kilometers and a depth of about 1 kilometer. Thus ejected soil from these depths may also be found at the landing site.

A few days after landing, the terrain below the spacecraft was examined by the RAC in order to confirm the stability of the spacecraft's position. The first image showed a bright, even surface (called "Holy Cow"; the nomenclature followed fairy-tale themes) that was uncovered by the action of the descent thrusters. Apparently, the subsurface ice discovered by Odyssey in 2002 was right there—only a few centimeters below the surface. The images suggest that this is ice-rich regolith rather than pure water ice. Over the course of about 50 Martian days (or sols), another icy soil patch, dubbed "Snow Queen" and located just next to Holy Cow, developed numerous cracks after it lost its thermally insulating blanket of soil.

During the Phoenix mission, 12 trenches were excavated, the deepest being 18.3 centimeters. The appearance of the subsurface soil was different from trench to trench. In some trenches (such as one dubbed "Dodo Goldilock") almost pure ice was found, as determined by the spectra acquired by the SSI. Other trenches yielded ice-rich regolith, whereas in some no ice was found at all. In the Dodo Goldilock trench, bright centimeter-sized clumps disappeared over the course of four sols. This observation suggests that the bright material in the shallow subsurface is indeed water ice. So far, it is not clear why the ice/regolith mixing ratio varies so much within a few meters.

The surface of the Martian polar environment takes on a hummocky appearance that might account for some of the soil inconsistencies. The basic model for the formation of these "polygons" was developed by Ronald Sletten and his colleagues at the University of Washington. Seasonal contraction and expansion of soil generates wedge-shaped fractures. During winter, fine-grained debris moves into these wedges and prevents them from completely closing again during the next summer. The seasonal stress generated by these processes is relaxed by the formation of mounds (or polygons) at a certain spatial frequency. The net result is a slow cyclic transport of soil material. This erosional process is known as cryoturbation and occurs frequently in terrestrial environments around the edges of glacial regions.

The Heimdall crater formed about 500 million years ago. It seems likely that

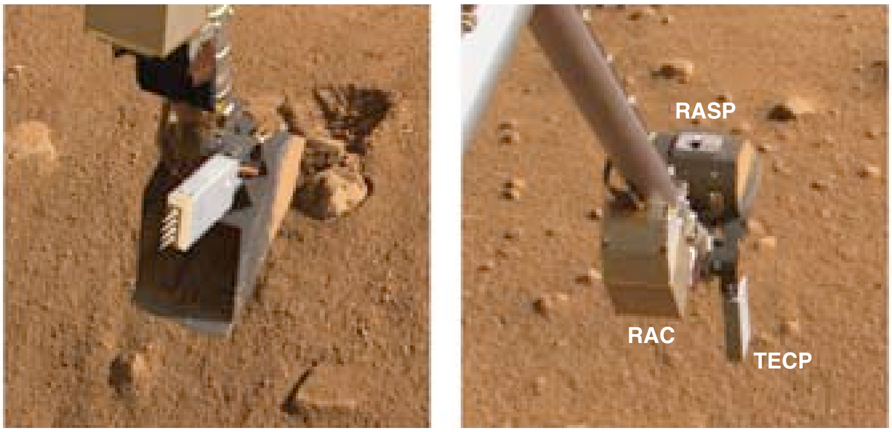


Figure 3. Images from Phoenix's stereo surface imager show the end of the lander's robotic arm as it digs a sample of Martian soil *(left)*. As the arm lifts up *(right)*, its instruments can be seen: an ice drill (called the Rapid Active Sampling Package or RASP) mounted on the back of the scoop, the robotic arm camera (RAC) positioned so it can see into the scoop and image soil samples and a soil sensor (called the Thermal and Electrical Conductivity Probe, or TECP) mounted next to the scoop. (Images courtesy of NASA/JPL/University of Arizona and M. T. Lemmon, Texas A&M University.)

excavation of this crater contributed soil material to the landing site. Cryoturbation processes, however, take place over a much shorter time scale, continuously renewing the landscape and making the Phoenix landing site the youngest among all other past Martian landing sites (those of Viking, Mars Pathfinder or the Mars Exploration Rovers).

Larger rocks or boulders (bigger than 20 centimeters or so) are absent at the landing site. Water ice is abundant near the surface, in agreement with Odyssey 2002 data. Perhaps the absence of larger rocks can be explained by the high concentration of condensed volatiles (such as water ice) in the subsurface that were affected by the Heimdall impact: A violent explosion would have removed and crushed the rocks that may have been at the landing site initially. A future, systematic study of the correlation between rock density and distance to the nearest crater may provide further understanding of the size distribution of rocks at the site.

The Soil Itself

Microscopic color images from Phoenix demonstrate the great diversity of particles in Martian soil. AFM scans have given three-dimensional representations of dust particles, but it is unclear how typical these particles may be of Martian dust in general. Reddish-orange dust dominates by volume. The individual dust particles cannot be resolved by the microscope and must therefore be on the order of 10 micrometers or less in size. According to a preliminary classification, two different types of grains are present in the soil: Reddish-brownish to colorless grains and dark (almost black) grains. The origin of these grains is uncertain, but a careful comparison to terrestrial analog soils may constrain the potential scenarios for the formation of these grains.

Key Phoenix instruments, such as TEGA and WCL, have provided new insights into the microscopic structure, as well as the mineralogy, of the soil. One cubic centimeter of material transferred to one of the WCL cells was mixed with 25 cubic centimeters of aqueous solution and produced a weak alkaline solution (with a pH of about 8.3) that contained

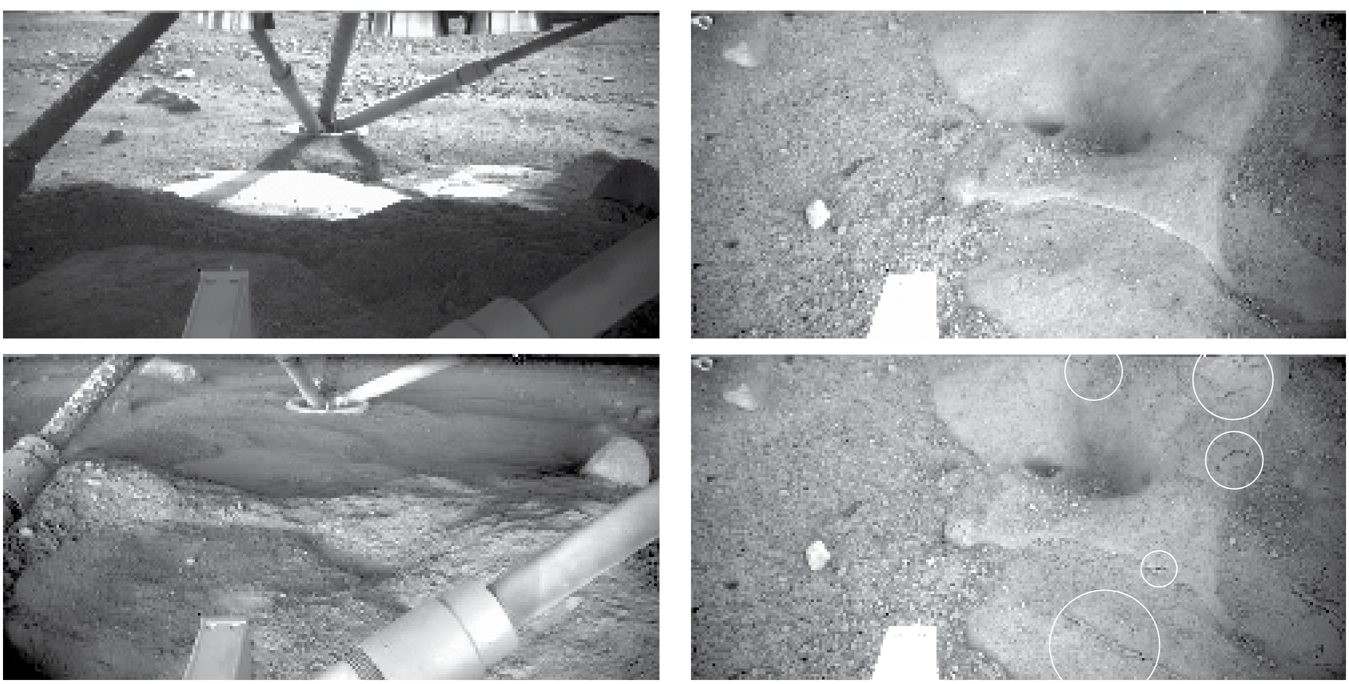


Figure 4. The icy area dubbed "Holy Cow" was swept clean by the lander's descent thrusters. It was imaged by the robotic arm camera, the only onboard instrument able to see beneath the lander; the light rectangle in all four images is the arm's soil sensor. In sunlight, Holy Cow appears bright and reflective *(top left)*, but during the reddish light of twilight, the patch is about as bright as the surrounding soil, indicating that it is not pure ice *(bottom left)*. A neighboring region, "Snow Queen," was also uncovered by the lander's thrusters. The region was initially smooth *(top right)* but showed surface fractures after about 50 Martian days *(bottom right, in white circles)*, indicating the sublimation of water ice. (Images courtesy of NASA/JPL/Univeristy of Arizona, and H. U. Keller and W. J. Markiewicz, Max Planck Institute for Solar System Research, Katlenburg-Lindau.)

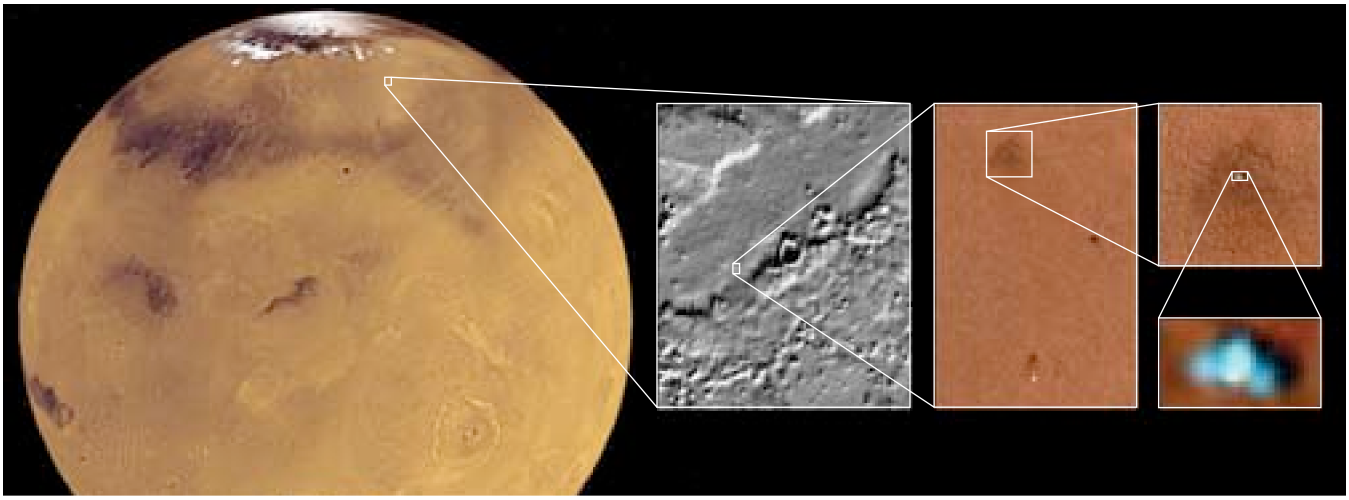


Figure 5. From global to local scale, successively enlarged images zoom in on the Phoenix lander on the Martian surface. The landing site is near the northern polar ice cap of Mars *(far left)*. A black-and-white image about 280 meters wide from Mars Global Surveyor shows that the landing site is off to the left of the circular Heimdall crater *(second from left)*. A higher resolution orbital image, taken 22 hours after landing by the HiRISE camera aboard the Mars Reconnaissance Orbiter, barely shows the lander; the black dot at the middle right of the image is the ejected heat shield, and the bright dot near the bottom center is the parachute *(middle)*. An enlargement of the middle image *(top right)* shows surface roughness and coarser-grained, darker material that was exposed by the descent thrusters. A final enlargement *(bottom right)* shows the lander deck and two solar panels, at a resolution of about 33 centimeters per pixel. (Images courtesy of NASA/JPL, Malin Space Science Systems and the University of Arizona.)

surprisingly large quantities of perchlorate (ClO_4^-), salts that could lower the freezing point of water and that have the potential to be found in a liquid-water solution under the temperature and pressure conditions on present-day Mars. This ion was by far the dominant anion (or negative ion) in the solution. Among the cations (positive ions) were, in order of decreasing concentration, magnesium, sodium, calcium and potassium.

To extrapolate from these results, one gram of Martian soil might have a perchlorate abundance of about 1 percent by weight. Such a concentration exceeds that found in some terrestrial desert soils by orders of magnitude. Finding chlorine at the highest possible degree of oxidation has significant implications for our understanding of the chemical processes taking place on the Martian surface, as well as in the atmosphere, and raises several important questions: Is the perchlorate just an exotic compound at the Phoenix landing site, or is it widespread on the surface of the planet? Is the chlorine identified by all previous Mars lander missions mostly present as perchlorate? Even the old question of life on Mars must be reformulated: Which types of primitive (terrestrial) life-forms could have evolved in the Martian soil, given the measured perchlorate concentration?

The ion-selective electrode in the WCL unit that is sensitive to perchlorate, and much less so to nitrate, provided such a strong signal that the identification of perchlorate was unambiguous (the mass of nitrate needed to explain the signal would have exceeded the total mass of the analyzed soil sample). Overall, the suite of electrodes used in

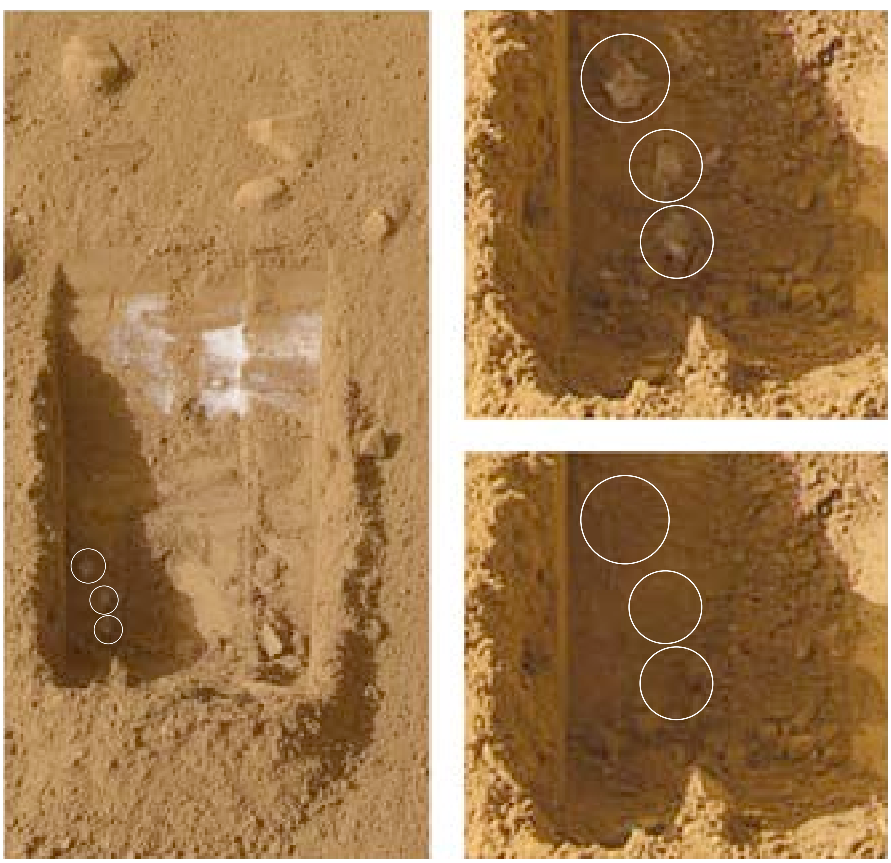
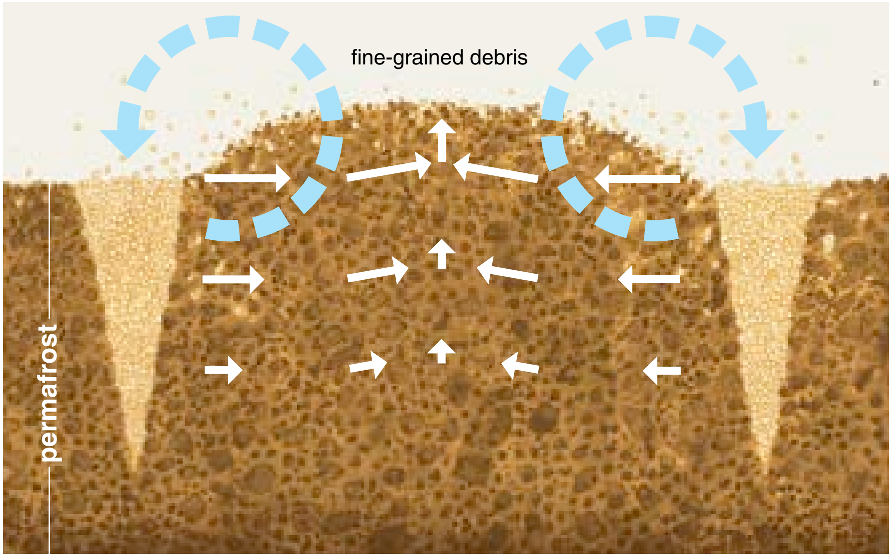


Figure 6. The trench dubbed "Dodo Goldilock" is about 20 centimeters wide. The upper part of the trench reveals nearly pure ice *(left)*. Small clusters of ice particles, about 2 centimeters in diameter, at the lower left of the trench *(white circles)* were visible when the trench was first dug *(see enlargement at top right)*, but by four Martian days later, these spots disappeared *(bottom right)* indicating the particles had sublimated. (Images courtesy of NASA/JPL/University of Arizona and M. T. Lemmon, Texas A&M University.)



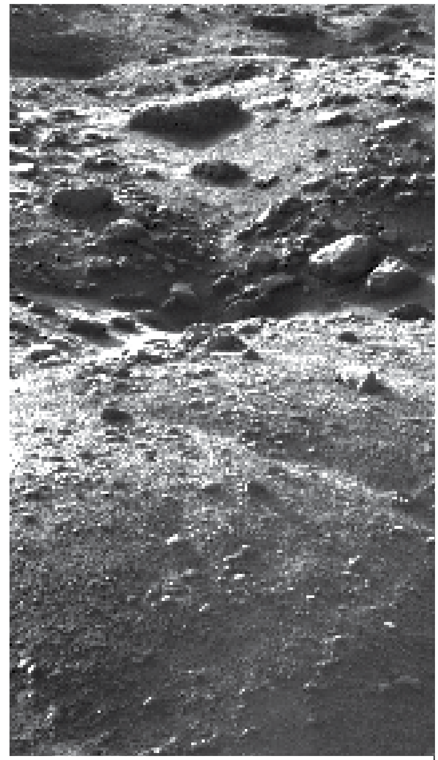


Figure 7. The Martian surface near the polar ice cap often consists of uneven mounds *(right)*, created by a process called cryoturbation. Wedge-shaped gaps form in the soil during the winter *(above)* and partially fill with fine-grained debris that prevents the gaps from fully closing during the summer. The resulting surface stress causes the motion of soil inwards and upwards *(white arrows)* creating these "polygon" surface mounds. Below the level of the permafrost and the depth of the sand wedges, the soil is not perturbed. The blue circular arrows illustrate the long-term transport of soil. (Image courtesy of NASA/JPL/University of Arizona and M. T. Lemmon, Texas A&M University.)

the WCL provided rich information on the water-soluble components of the soil, but each one is sensitive to a range of different ions at strongly different rates. The conversion of the electrode data into concentrations is therefore non-unique, and constraints from other instruments are needed.

Thermal decomposition products of perchlorates were generally not detected by the thermal analyzer or the evaporated gas analyzer's mass spectra, although this does not jeopardize the WCL identification of perchlorate. In at least one of the samples analyzed by these instruments (from a site called "Baby Bear"), some oxygen release in molecular form was observed that may be due to the decomposition of perchlorate.

Another important finding from the mass-spectroscopy studies was the release of carbon dioxide at temperatures of 800 to 900 degrees, which indicates the presence of 3 to 5 percent by weight of calcium carbonate in the soil. The result is remarkable, given that we have been on the hunt for this mineral for many years, and Phoenix found it in the soil! Carbonates are generally the products of aqueous processes, and thus their presence may be indicative of liquid water on the surface of Mars at some point in the planet's history. The inferred presence of carbonates is also compatible with WCL results and explains the alkaline pH of the aqueous solutions.

Furthermore, the absence of certain gases after heating can provide critical information on the mineralogy of the Martian soil: No sulfur dioxide has been released over the entire temperature range (from below 0 degrees, up to 1,000 degrees). This is surprising as all previous lander missions have identified substantial quantities of sulfur in the Martian soil (5 to 10 percent by weight of sulfur trioxide). The presence of sulfate ions is compatible with WCL data. Magnesium sulfate would release sulfur dioxide at temperatures below 1,000 degrees, so the absence of this gas therefore proves the absence of magnesium sulfate in the soil. In the Martian environment (with an atmospheric pressure of roughly 10 millibars, or about a hundredth of that on Earth), calcium sulfate would decompose at about 1,400 degrees, but such temperatures are not reached by Phoenix's thermal analzyer. All these facts taken together point toward the likely presence of calcium carbonate in the soils that Phoenix has analyzed. In fact, large deposits of calcium carbonate previously have been found on the surface of Mars, in particular near the north-polar ice cap.

Nice Weather

Phoenix's instruments have enabled new types of meteorological measurements at the landing site. The site has the advantage that the polar regions exhibit strong weather phenomena, especially cloud formation (as was known from orbital imagery). Also, the weathercock has returned data on wind velocity and direction throughout the mission, enabling fruitful modeling. Phoenix weather measurements were coordinated with orbital observations on a regular basis throughout the mission, strengthening the results.

Mars's atmospheric water vapor pressure, as measured by Phoenix's humidity sensor, rises between about 2 AM and 10 AM, then reaches a plateau (about 1.8 Pascals) that is maintained throughout most of the day. In contrast, atmospheric temperatures continue to rise until about 2 PM. Apparently atmospheric convection becomes very efficient and rapidly redistributes the newly formed water vapor after 10 AM. The spacecraft observed several passing dust devils at typical wind velocities (5 to 10 meters per second). Analysis of the pressure data acquired throughout the mission shows that such dust devils are correlated with brief pressure dips of 1 to 3 Pascals.

LIDAR data from the later part of the mission turned out to be particularly important: Ground fog as well as water-ice clouds near the top of the atmospheric boundary layer (at an altitude of about 4 kilometers) formed every night after sol 80. Many of these clouds had "fall streaks" formed by initially growing, free-falling, then eventually sublimating ice crystals. Such fall streaks also can be

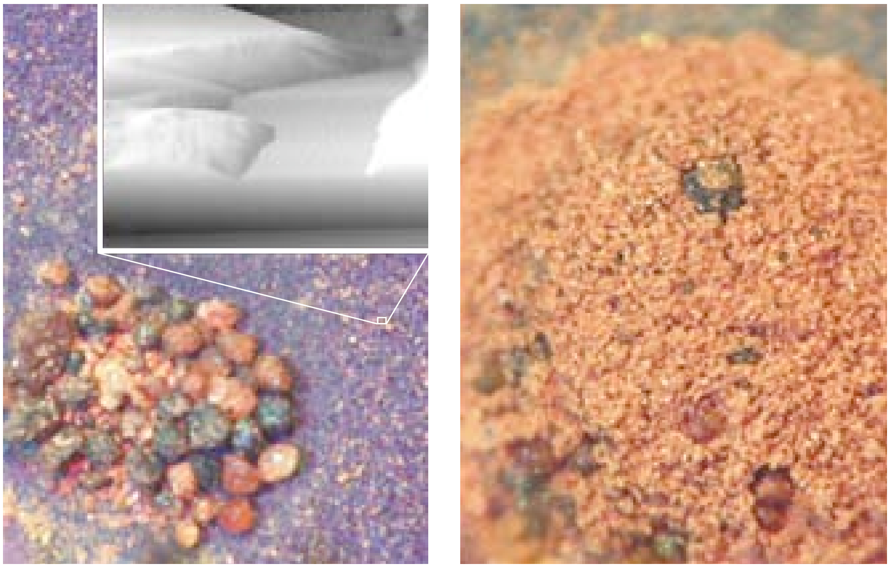


Figure 8. Images of Martian soil from Phoenix's optical microscope show a mix of lighter and darker colored grains, about 60 micrometers in diameter *(left)*, distributed through a matrix of reddish-orange dust, about 10 micrometers in diameter *(right)*. A detail of a dust particle from the atomic force microscope *(upper left)* corresponds to an area about the size of the small rectangle. (Images courtesy of NASA/JPL/University of Arizona, M. H. Hecht, JPL, and W. T. Pike, Imperial College, London; inset courtesy of NASA/JPL and U. Staufer, Technical University Delft, The Netherlands.)

observed in terrestrial clouds. Daytime LIDAR data showed mostly dust in the atmospheric boundary layer. However, SSI also documented many daytime clouds late in the mission. In some cases these clouds disappeared by sublimation over a timescale of 10 minutes.

Phoenix's instruments monitored the complete diurnal water cycle: During morning hours water vapor is released into the atmosphere. The sources for the water vapor include the shallow subsurface water ice, water adsorbed to soil grains and, possibly, crystal water in perchlorates. During the night, water vapor condenses and falls out by gravity. Most of these ice crystals sublimate again on their descent through the atmospheric boundary layer. In some cases snowfall was observed, when the fall streaks extended all the way down to the surface.

Where Phoenix Is Now

Phoenix surface operations lasted from Martian late spring to late summer—May 26 to November 2, 2008, or 152 sols. The polar night at the landing site lasted from April 1 to July 10, 2009. Since that time, the Sun has again risen above the horizon at the landing site. If the spacecraft—contrary to all expectations—survived both the low temperatures (150 kelvins) of the Martian winter and the dry-ice load built up on its solar panels, it will be able to reanimate itself through a so-called "Lazarus mode." Mars Odyssey was scheduled to search for Phoenix signals starting at the end of 2009.

Independent of its potential reanimation, Phoenix was a highly successful mission that provided on-site geochemical and atmospheric data for the first Martian arctic landing site ever explored. No organic molecules, and no traces of previous or present biological activity, were found at the landing site. Hence, the search for organic molecules will have to be continued by future missions.

It should be noted that organic molecules ought to be present in the Martian soil because of the steady influx of certain types of meteorites that contain

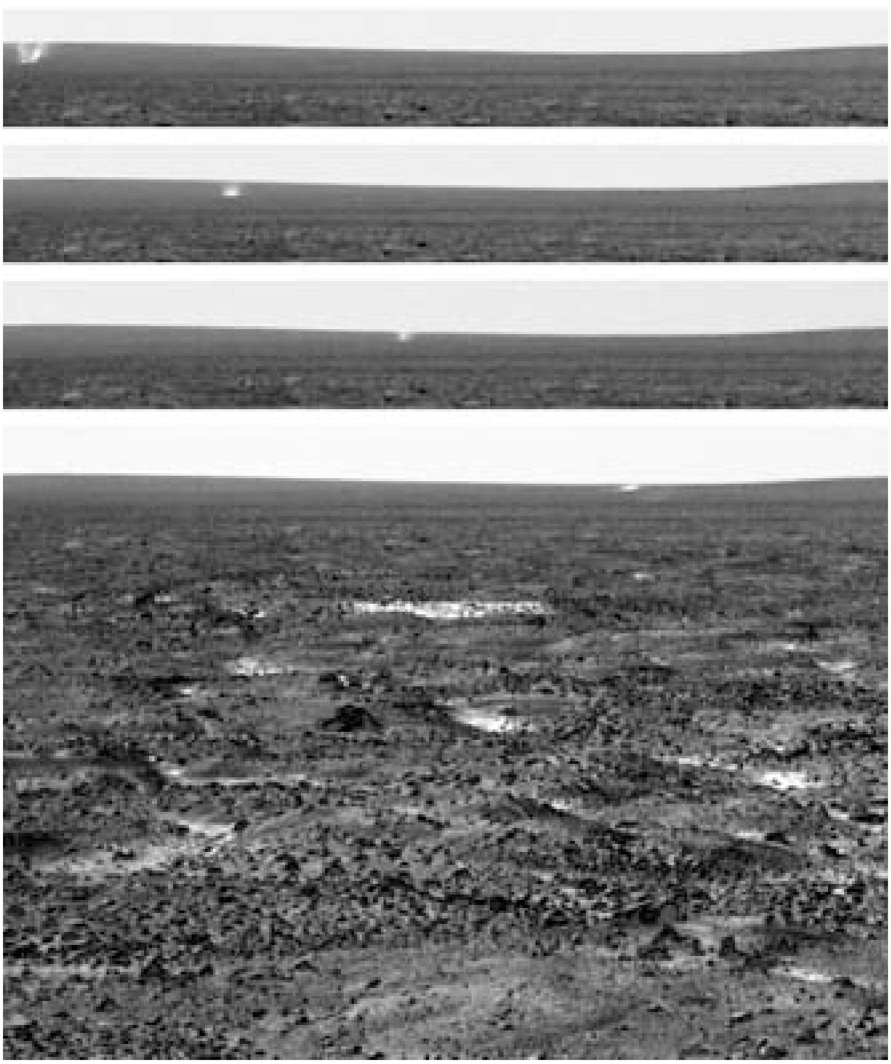
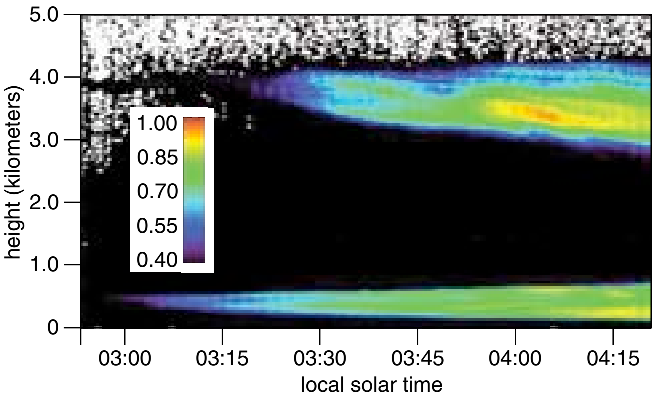


Figure 9. On day 104 of Phoenix's mission, the lander spotted a dust devil about a kilometer away *(top left)*. The dust devil movedto the right and away from the lander *(two middle images, at left)*, ending up about 1.7 kilometers away *(bottom left)*. The presence of the dust devils correlates with brief dips in the atmospheric pressure. Larger dust devils have been observed previously in Mars's Gusev crater. (Images courtesy of NASA/JPL/University of Arizona and M. T. Lemmon, Texas A&M University.)



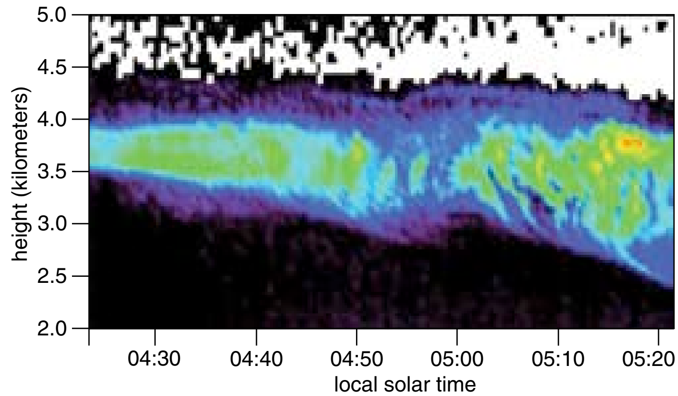


Figure 10. Phoenix's LIDAR was able to characterize the clouds and ground fog that form at night on Mars, as shown by the intensity of light backscattered from ice and other particles *(above left)*. Ice clouds at the atmospheric boundary layer, about four kilometers in altitude, often show fall streaks from the sublimation of freely falling ice crystals *(above right)*. The size of the ice particles can be calculated from their descent velocities. Similar cloud formations can also be seen on Earth *(right)*. (Graphs courtesy of NASA/JPL/University of Arizona and J. A. Whiteway, York University, Canada; photograph courtesy of Marc Thiessenhusen.)

substantial quantities of organic material. The fact that no such molecules have been found in the soil around Phoenix is indicative of fast geological degradation processes. The ever-continuing turnover of soil material (by cryoturbation) at the landing site may have favored such degradation processes.

If organic molecules are ever detected it will be a major scientific task to track down their origin: Are they imported by comets or meteorites, or do they truly attest to primitive, extinct life-forms on the surface of Mars?

Although no organics have been found so far, it is essential to continue this exploration program and search for organic material in more protected environments, such as the interior of sedimentary rocks or deeper soil layers. The next scheduled missions that are available for this task are the rovers Curiosity (which NASA plans to launch in 2011) and ExoMars (which ESA plans to launch in 2018). They will carry complex follow-up instruments that will search for organic molecules in specific equatorial regions. One instrument for ExoMars, the Mars Organic Molecule Analyzer, is presently under development at the Max Planck Institute for Solar System Research.

Curiosity's Sample Analysis at Mars (SAM) instrument has been built by the NASA Goddard Space Flight Center and is ready to go. It will be able to detect particularly low concentrations of potentially organic material. Special attention will be given to the molecule methane (CH_4) whose presence on Mars recently has been demonstrated. The instrument will be able to measure at extremely low methane concentrations (less than one part per billion) the ratio of the isotopes of carbon-13 and carbon-12 present in a molecule. Such data may shed light on the molecule's origin, favoring either geochemical or biological formation.

There is little doubt that Mars will continue to present fascinating new data, surprises and mysteries for these upcoming missions, and to ones still on the drawing board. The two new rovers, Curiosity and ExoMars, will be important benchmarks on that path. Further in the future, robotic return of samples will play a major role in the Mars exploration program. The biggest challenge—a manned mission to Mars—may belong to the distant future, but perhaps at some point such projects will be within reasonable budgets for the major space agencies.

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