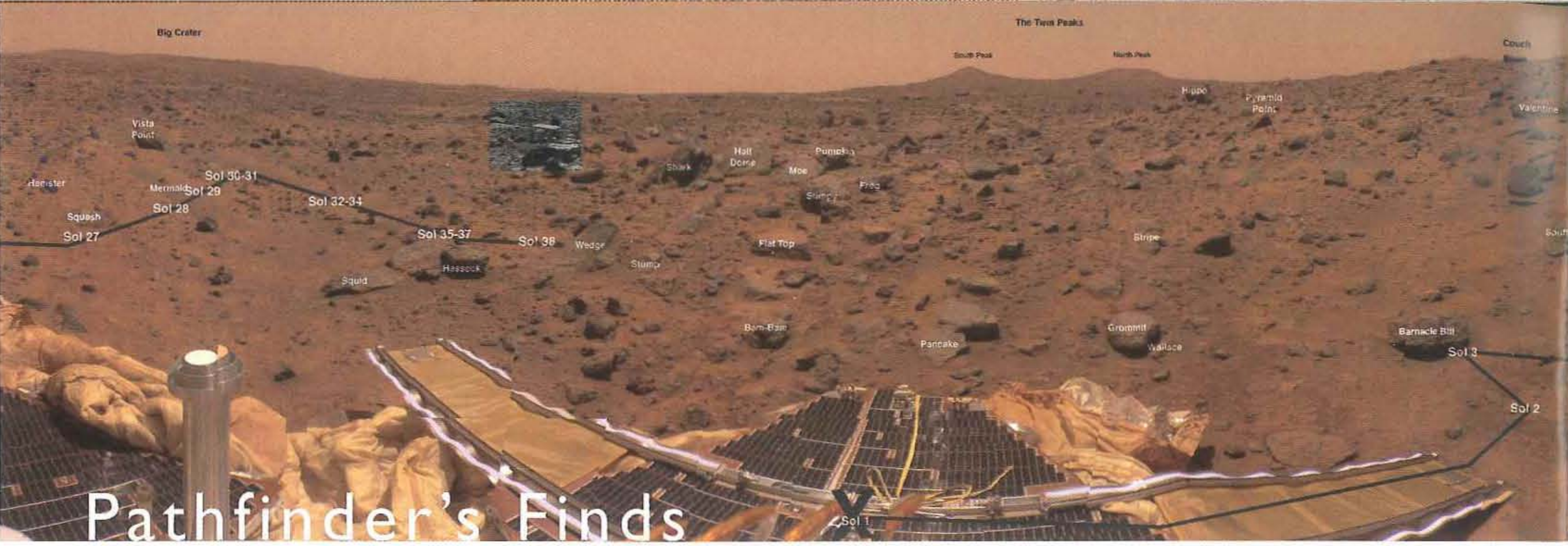
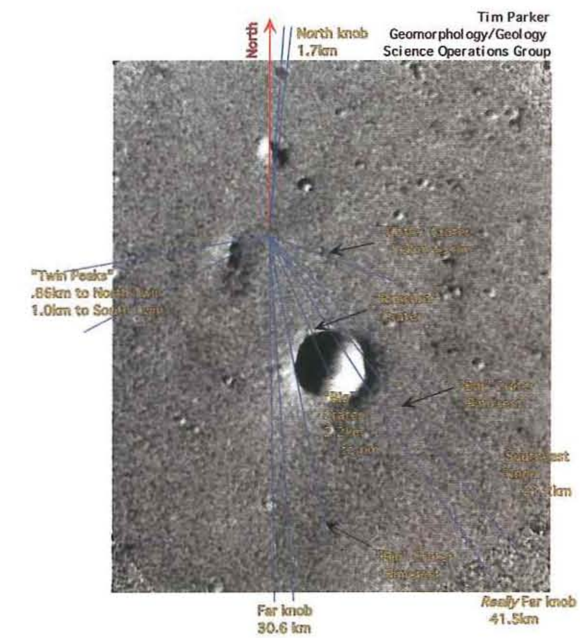


Pathfinder's Finds

by Douglas L. Smith

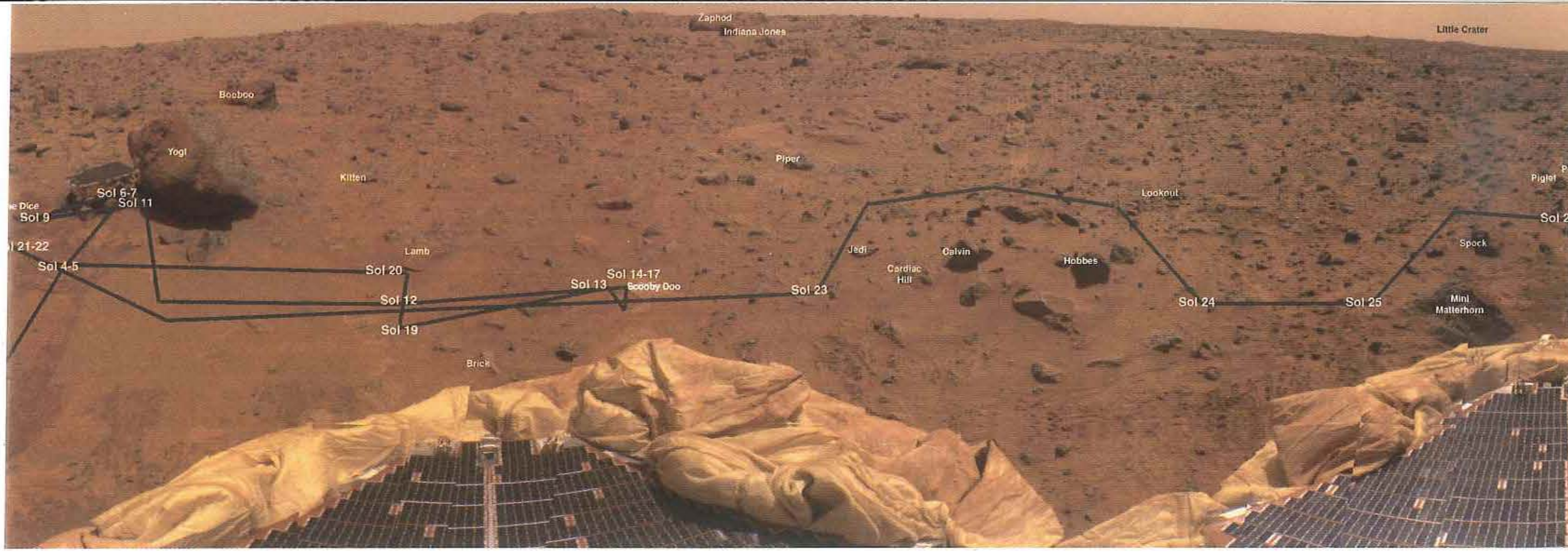
Above: The spacecraft came to rest where the floodplain of Ares Vallis, a channel carved aeons ago by the sudden release of enough water to fill the Mediterranean Sea, spills into the vast flatnesses of Chryse Planitia. This panoramic view of the landing site shows some of the names that have been assigned to rocks and other features. (None of these names have any official standing.) The rover's movements over the mission's first 38 sols (Mars days) are shown by the dark line. The rover spent the next 33 sols in the area bounded by Wedge, Flat Top, Moe, and Shark, known as the Rock Garden. As of September 26, the rover, named Sojourner, had more than 100 meters on the odometer. When last seen, the rover was in the vicinity of a rock named Chimp (gray insert).



Above: Pathfinder landed within 20 kilometers of its aim point, a feat that one member of the navigation team has likened to playing a par-four hole with the tee in Los Angeles and the hole in Houston, with a regulation ball and cup. By triangulating from the Twin Peaks and other landmarks on Pathfinder's horizon that also show up in photos from the Viking orbiters, the spacecraft's position is now known to within 15 meters.

The Pathfinder landed on the Fourth of July, and now Labor Day has come and gone. The "plucky Mars rover" has dropped off the front page of the nation's newspapers. But the mission continues, and with some three months of data in hand, the mission's scientists are beginning to take stock of their results. What follows is an amalgam of hard data, preliminary interpretations, and informed speculations on everything from Mars's air to its core.

On the meteorological front, Pathfinder started taking atmospheric data on the way in. The spacecraft's Atmospheric Sciences Instrument (ASI)/meteorological package contains instruments similar to those of the Viking missions of 20 years ago, but considerably more sensitive, says JPL's Tim Schofield, leader of the ASI/met team. And while the temperature data taken on the way down are unreliable because of the unsteady airflow around the recessed instruments, Julio Magallhães of NASA's Ames Research Center, at Moffett Field, California, has constructed a temperature profile from the atmospheric drag recorded by the accelerometer. (See picture on page 10). The data resemble those from Viking 1, which landed more than 800 kilometers away at very nearly the same latitude and elevation, albeit somewhat earlier in the northern-hemisphere summer. Pathfinder's temperature readings were, on average, 20 kelvins (K) lower at altitudes above 60 kilometers—probably because Viking touched down at four in the afternoon, while Pathfinder bounced in at three in the morning, local Martian time. From about 60 kilometers on down, Pathfinder's data match Viking's to within five or ten degrees. This leaves unresolved the debate about whether Mars is getting colder—ongoing telescopic observations of the lowest 20 kilometers of atmosphere of the planet as a whole have been reading about 20 degrees cooler than in the days of the Vikings. Furthermore, the telescopes don't see that much dust in the air—important because



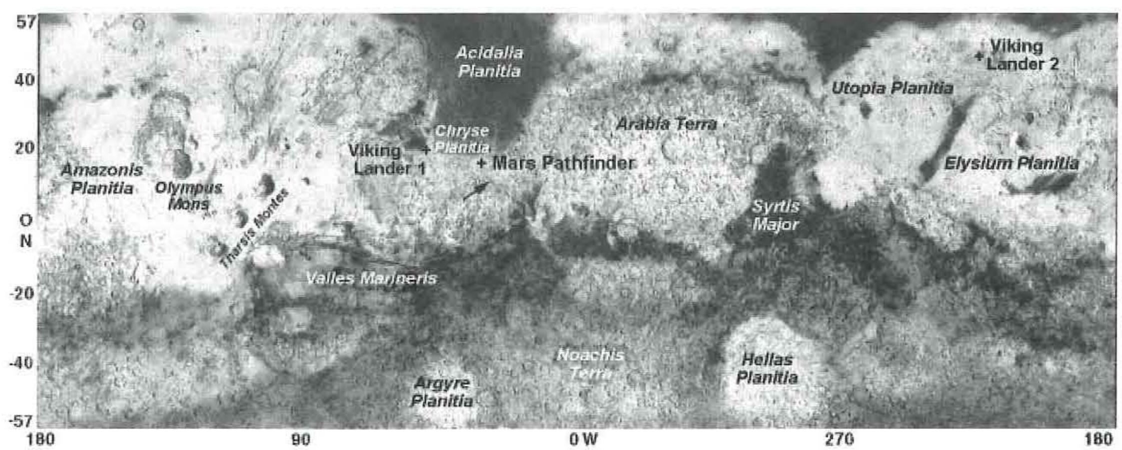
the dust is heated directly by sunlight—while Pathfinder's camera is seeing as much dust as the Vikings did.

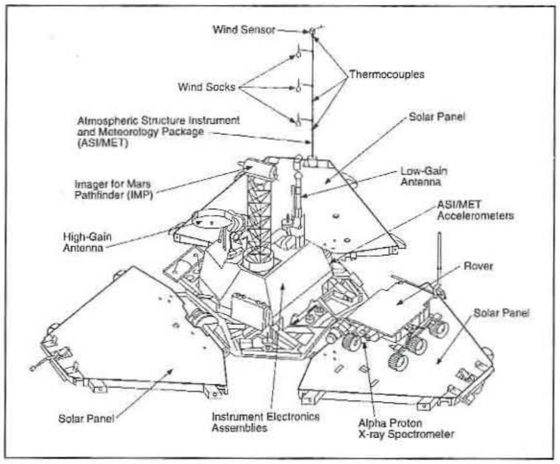
Pathfinder did find it as much as 50 K nippier at altitudes between 60 and 100 kilometers, however. This again is probably due to day-night differences, possibly accentuated by thermal tides in the atmosphere, a phenomenon seen on Earth that would be accentuated by Mars's thinner air. These tides begin at the planet's surface, where heated air expands by day. This creates a wave that travels upward, with the amplitude of the temperature variation increasing with height. At about 80 kilometers, the temperature bottomed out at 92 K—cold enough to freeze carbon dioxide, which makes up some 95 percent of the Martian atmosphere. There's speculation that this dry ice may form clouds, but if so, they haven't been seen.

Since the landing, Pathfinder's weather station has been recording barometric pressure, temperature, wind direction, and speed. For the 30 sols—as the Martian day of 24 hours, 37 minutes, and twenty-odd seconds is called—of the primary mission, it took data day and night. (On some days, in the meteorological equivalent of the panoramic views, the lander took data at four-second intervals for an entire sol.) During the extended mission, Pathfinder goes to sleep at night to conserve power, so weather data is taken during daylight hours. But once every couple of weeks or so, the scientists make the spacecraft stay up all night to see what they're missing. Pathfinder's weather reports average 10 degrees warmer than Viking 1's during the day, and 12 degrees warmer at night. Part of the reason may be that the Pathfinder site is darker and thus absorbs heat better; its rocks also retain heat longer than did the finer sand and dust at the Viking site.

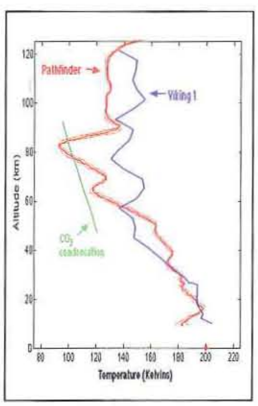
But the barometer watch is going to be the real gold. "Temperature and wind just tell you what's happening where you are," says Schofield. "But pressure readings tell you about the whole column of atmosphere from the surface all the way up." Pathfinder landed in the northern hemisphere during late winter in the southern hemisphere, when pressure wanes planetwide because some 20 percent of the atmosphere's carbon dioxide freezes out into the south polar ice cap. Pathfinder

Below: The green cross in this view from the Hubble Space Telescope marks the Pathfinder landing site. Right: The two Viking landers are also shown on this Mars map; the arrow points to Ares Vallis.





Above: Pathfinder's principal parts. On July 5, the lander portion was renamed the Carl Sagan Memorial Station. Below: During its descent, Pathfinder found the air cooler than Viking I did—cold enough to make dry-ice clouds at one point. These temperature measurements were actually derived from an accelerometer—the rate at which the spacecraft decelerates as it descends is a function of atmospheric drag, which in turn depends on the air's density. Air that's cooler than expected is denser, and thus generates more drag, than would be expected at a given altitude. The data is good down to about nine kilometers, when the parachute opens.



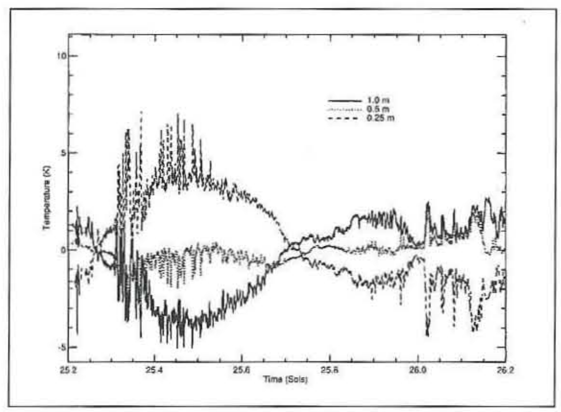
caught the depth of this cycle on Sol 20, when the pressure bottomed out at about 6.7 millibars (a millibar is a thousandth of the atmospheric pressure on Earth's surface). But the pressure is rising rapidly with the spring thaw, reaching 7.2 mb on Sol 83, and Schofield expects it to peak at about 9 mb within the next hundred sols.

Summer on Chryse Planitia is a lot like summer in Los Angeles, at least as far as consistency goes—one day is pretty much like the next. But as autumn draws on, Schofield expects to see more variety—weather fronts rolling down from the poles, just as they do on Earth. And the extra heat that Mars gets from being closer to the sun in the southern summer may bring on those famous planet-enveloping dust storms. But before these long-term patterns unfold, the day-to-day data are revealing short-term patterns of their own.

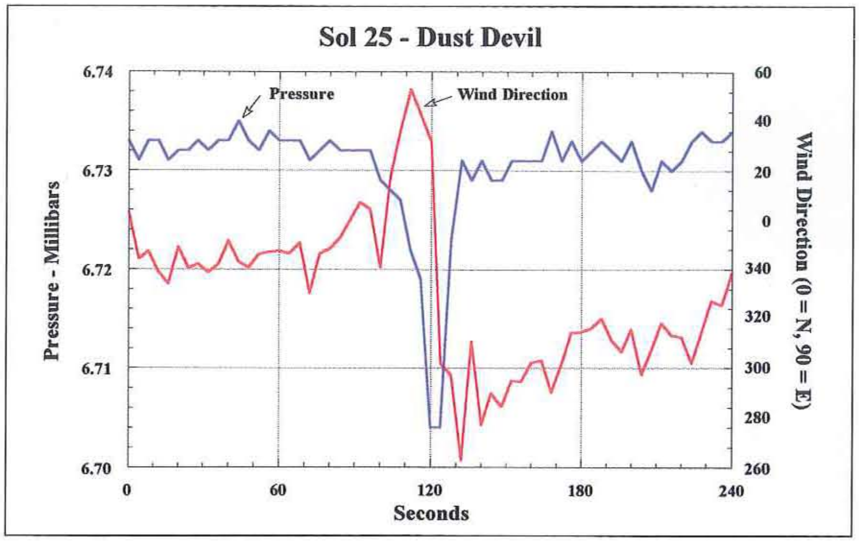
The winds in the lander's vicinity, for example, blow in a topographically driven cycle. They're called "slope winds," says Schofield, and on the simplest level they work like this: at night, cold air descends from the highlands hundreds of kilometers south of the landing site, sighing down through the canyons toward the lander. During the day, the sun heats the flatlands around the lander, and the warm air rises back up through the canyons. The upshot is that the wind makes a daily sweep clockwise through every point of the compass, lingering in the south overnight—a progression so regular during the first 30 sols that any resident Martians at the landing site could set their watches by it.

There's also cool stuff in the temperature data. The meteorology mast carries three thermometers at heights of one-quarter, one-half, and one meter. (The Vikings only had one temperature sensor each.) There's a dramatic temperature stratification—if you were standing next to the lander at midday, your shoes would be 10 degrees hotter than your belt buckle, because the sun-warmed ground heats the air in contact with it. (The pattern reverses after sundown, because the ground loses heat faster than the air, but the nighttime spread is only a few degrees.) All three sensors reach a daily peak in the early afternoon, and then cool overnight until dawn. Superimposed on this gentle swell are spiky features—15-degree variations over tens of seconds—caused by bubbles of heated, unsteady air convecting and mixing. Even after dark, when the warm air is on top and one might assume things would be calmer, the nighttime winds periodically overturn the layers.

When the bubbles of hot air coalesce into a vertical pipeline you get a dust devil, which is the weathermen's hottest quarry. The weather station



Above: A sol's worth of output from the three thermocouples (temperature sensors). In this decimal representation of time, .0 sols is midnight and .5 sols is noon. Sunrise and sunset are at roughly .25 and .75 sols respectively. The data are plotted as the difference from the mean value of all three sensors at that moment, accentuating the temperature spread between the top and bottom sensor. By day, the bottom sensor is the warmest (peaking this day at a balmy 270 K, or very nearly 0° C), but at night, the ground cools faster, and the bottom sensor is the coldest. The spikes are caused by winds mixing the air masses. The temperature resolution is 0.01 K.



Above: A dust devil's signature is written on the wind and pressure sensors. The wind suddenly changes from its prevailing direction, accompanied by a sudden, sharp pressure drop. As the dust devil passes overhead, the wind abruptly whips around to the opposite direction; the pressure and wind readings then rapidly return to normal as the dust devil moves on.

is recording an average of one devil every other day, and on a big day it will see three. These tiny tornadoes register as brief, sharp pressure drops—in the largest one to date, the pressure plummeted about .05 millibars, or 1 percent of the ambient pressure, in a few seconds. (For comparison, a terrestrial tornado causes about a 10 percent pressure drop.) If the dust devil passes directly overhead, the lander also records a sudden reversal of wind direction and a temperature drop. Dozens of dust devils had been inferred from Viking wind and temperature data, but the pressure data lacked fine enough resolution to see them. They could be an important dust-raising mechanism between local and global storms, says Schofield—a host of the little guys all over the planet could easily help keep the observed background levels of dust aloft.

They *could* be—we don't know yet whether they actually carry dust. They may not get enough oomph from the tenuous Martian atmosphere to pick up anything, in which case they'd be invisible, like the wind shear at airports. Pathfinder's camera hasn't caught one yet, but that's just a matter of time. (Schofield and his team plan to search all the images returned so far to see if they can spot one in the background.) But there are hints that the dust devils really are dusty—on Sol 62, a photocell that monitors the light striking the solar panels noted a dimming in the ambient light five minutes after a dust devil passed by. The phenomenon lasted for 10 minutes or so, and could be the receding dust devil's shadow. Schofield estimates this dust devil's diameter at about a quarter of a kilometer, based on the shoulder-to-shoulder width of the pressure minimum and his best guess at its rate of travel. This jibes with numerous transient blobs of roughly similar size seen by the Viking orbiters' cameras. Some of the blobs cast shadows indicating that they stood six to seven kilometers tall.

When the dust devils give way to a planetwide dust storm, it could endanger the Mars Global Surveyor, which slipped into orbit on September 11. MGS will spend the next several months "aerobraking"—raising its solar panels up into a V and dipping repeatedly into the very top of the Martian atmosphere, where the drag will slow the spacecraft and eventually drop it into the nice, circular orbit from which it will map the planet. But suspended dust sops up heat from the sun, warming and swelling the atmosphere. With the atmosphere extending farther out into space, MGS could be sailing through air that's three to four times thicker than expected, and the extra friction could overheat and perhaps even incinerate the spacecraft. Pathfinder's barometer should give enough advance notice, in the form of a sudden increase in the difference between the daytime and nighttime pressure, for JPL to raise MGS's orbit to a safe height, and the Hubble Space Telescope will be keeping a watchful eye as well.

The dust gives the air at the landing site an optical density of about 0.5—the visual equivalent of a smoggy day in L.A., says Mark Lemmon, a research associate at the Lunar and Planetary Laboratory of the University of Arizona, in Tucson. (The U. of A. led the team that developed the mission's camera, puckishly known as the IMP, or Imager for Mars Pathfinder.) Optical density is a measure of the number of dust particles in a given volume of air, but the math gets complicated by assumptions about particle size (believed to be a little less than a micron, or millionth of a meter, based on how they scatter light), and whatnot. An optical density of 1.0 means that if all the dust suddenly precipitated, it would cover the ground in a layer exactly one particle thick. The optical density has remained rock-steady so far, but that will change with the advent of dust-storm season. Five of the densest 10 days have been very recent, but the peak was only 0.6. "You wouldn't notice the difference visually if it was 0.5 one day and 0.6 the next," says Lemmon, "but you might if it happened suddenly." The group measures optical

"Red sky at morning, sailors take warning." Martian mariners would live in a constant state of terror, as this predawn IMP shot shows. The colors are real—the red sky is due to dust suspended in the air, but nobody knows what's in the blue clouds.

density by pointing the IMP at the sun, and comparing the apparent brightness to what it would be without the intervening dust. They also check the sun when it's low in the sky to look at layering in the atmosphere, and have determined that most of the dust hangs in the lowest 13 kilometers.

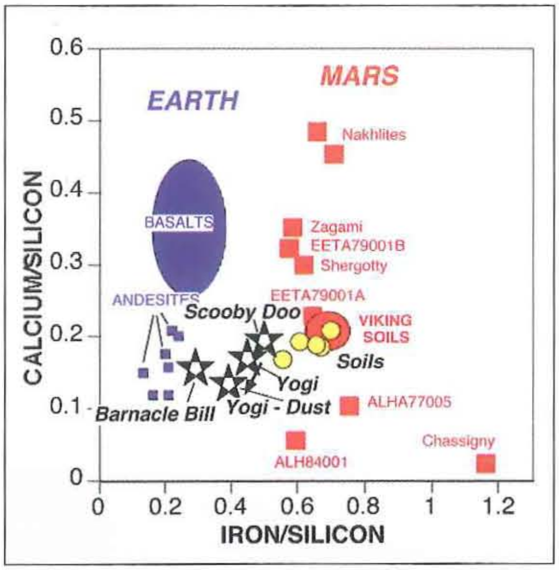
But the most remarkable atmospheric phenomenon that the IMP has captured to date is the blue clouds that are seen occasionally about an hour and a half before dawn. Illuminated by the sun from below the horizon, they burn off rapidly under direct sunlight. Nothing much is known about them, except for the inference that whatever makes them up must be about 0.1 microns in size because it scatters blue light. ("This is going to be one of the most complicated analyses we'll have to do," says Lemmon. "We'll have to model Mars's spherical form, and the sun angle, and all these other geometric effects." Lemmon plans to consult with a research group at the University of Alaska at Anchorage that, in a classic example of making lemonade when life gives you lemons, leads the field of terrestrial twilight studies.) The consensus is that the clouds probably lie at about 13–15 kilometers altitude, and that they're probably made of water. But this is based on several assumptions—for one thing, the clouds aren't reflective enough for the IMP to pick up the water's spectral signature. (The IMP *can* measure the total amount of water aloft by looking at the sun through a special filter—an exercise at the extreme limits of IMP's sensitivity.)

Sojourner does an APXS analysis of a rock named Moe. The APXS sensor head is the inverted demitasse cup pressed against the rock. It takes all sol to get a reading.

Designers of future Mars missions need to know whether the dust settles fast enough to pose a serious problem for solar-powered devices. Geoffrey Landis of NASA's Lewis Research Center in Cleveland, Ohio, principal investigator of the rover's Materials Adherence Experiment (MAE) and a photovoltaics expert, had predicted a coverage rate of 0.22 percent per day. The MAE is logging about a quarter of a percent per day, which Landis thinks is no problem for Pathfinder but could present difficulties for missions of a year or longer. The experiment consists of a glass plate covering a small solar cell on the rover. Once a day, the glass rotates out of the cell's line of sight, and the cell's output with and without the cover plate is compared. The plate is moved by a thin wire of an alloy called nitinol, which contracts when heated. Once the wire has cooled, the glass returns to its initial position. Meanwhile, an adjacent sensor weighs the dust deposited on a quartz crystal by recording its change in vibration frequency. The whole package draws an infinitesimal amount of power—the price for riding the rover—and is slightly larger than an Elvis stamp.

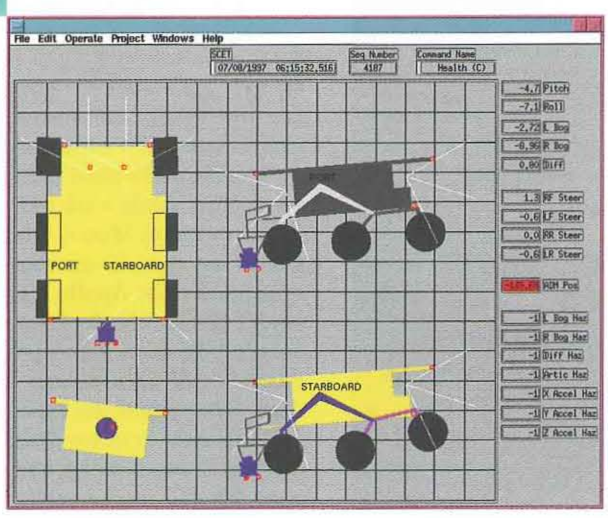
If the rover is a six-wheeled geologist, as it's frequently been called, then its rock hammer and loupe is the Alpha Proton X-ray Spectrometer (APXS). The APXS is three instruments in one, and is designed to give a complete elemental analysis of the soils and rocks the rover encounters. So far, all the results reported about the chemical composition of the landing area's soil and rocks have come from the X-ray mode because the alpha-scattering and proton-emission portions of the instrument, which analyze the light elements, are having calibration problems and will have to be recalibrated. Because nobody knows how long the rover will last, the team is focusing on collecting data rather than analysis, says Tom Economou, senior scientist at the Enrico Fermi Institute at the University of Chicago and coinvestigator for the APXS. As of September 26, the APXS has taken nine rock and seven soil samples.

The biggest surprise actually came from Barnacle Bill, the first rock to be sampled. The conventional wisdom said that Mars, being about half Earth's diameter, would have cooled fairly quickly as planets go. Therefore Mars rocks shouldn't have undergone much remelting, and were expected to be primordial basalts—like Earth's ocean floors, the rock samples brought back from the moon, and the so-called SNC



Left: The ratios of various elements to one another, rather than the elements' absolute abundances, can be more useful in comparative mineralogy. The APXS data from rocks at Pathfinder's landing site (stars) are more Earthlike than the soils (yellow circles), which resemble the Viking soil samples (red circle) and various Martian meteorites (red squares) in composition. The star labeled "Yogi – Dust" is an attempt to correct for the dust layer on Yogi's surface.

The wheel thing. The Wheel Abrasion Experiment (left) consists of 15 panels—three metals each in five films ranging from less than 100 to a few hundred atoms thick, deposited on black, anodized aluminum for contrast. The soil-mechanics experiments depend on knowing the position of the rover's suspension system (below). This tells you how much weight is resting on the wheel, and how deeply it has dug in (which gives the surface area in contact with the soil). Contact area times weight is "normal stress," which is plotted against "shear stress" (derived from the contact area and the torque needed to just begin turning the wheel) to give a straight line from whose slope the friction angle is derived.



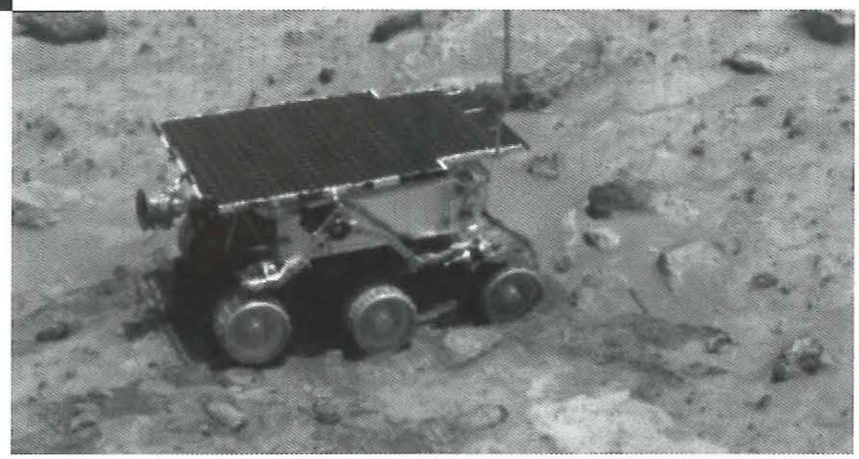
meteorites, which are believed to be Mars rocks blasted to Earth by a meteorite hit on the red planet. Instead, Barnacle Bill had way too much silica, indicating that at least part of Mars's interior had been through enough cycles of melting and cooling for some silicon to separate from the heavier elements and float like soap scum to the top of the mantle before condensing into rock. The exact mineralogy isn't known yet, partially because of the lack of good oxygen data from the alpha-scattering portion of the spectrometer, and partially because Economou would have to get a confirming set of readings from a terrestrial sample of the same mineral. "I get e-mails and samples every day from people who think they've found an Earth analog to what we're seeing," he says. "It'll take years to analyze all of them."

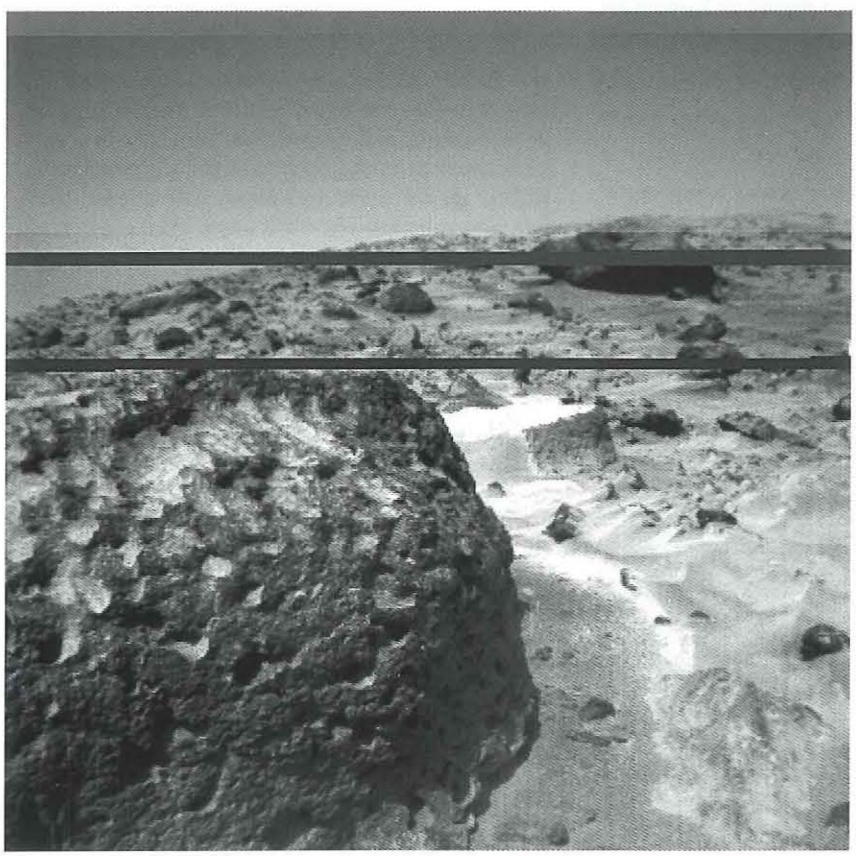
Subsequent rocks have either resembled Barnacle Bill or have been roughly basaltic. But even the basaltic rocks aren't entirely as expected, having more sulfur and chlorine than either their earthly counterparts or the SNCs. What this means is uncertain, but it shouldn't come as a total surprise, says Economou—nobody knows what part of Mars the SNCs came from, but it's not unreasonable to suppose that the rock mineralogy varies from place to place, as Earth's does. On the other hand, the soil APXS results have been identical not only with one another but with the soils at the two Viking lander sites, separated by nearly 180 degrees of longitude. This strongly indicates that the soil, presumably carried on the wings of the wind, is the same all over the globe.

As Sojourner plods from sampling point to sampling point, it takes note of what's underfoot. The Wheel Abrasion Experiment, also run by NASA Lewis, consists of a bunch of thin films of aluminum, nickel, and platinum that run in a ribbon around the middle of the right center wheel. As the rover goes about its business, the soil slowly grinds the films away. You can scratch an aluminum pan with a fingernail, and a nickel with your car keys, but platinum is pretty tough stuff, so the rate at which the various films get chewed up will give us some idea of how hard or sharp-edged the soil particles are. Twice each sol, the rover spins the test wheel to dig into the soil, and a photocell senses changes in the films' reflectivity. The wheels have accumulated a lot of dust, complicating the interpretation, but signs of wear are beginning to show, says Dale Ferguson, the experiment's principal investigator.

Locking five wheels and spinning the sixth one can tell you a lot of other things about the soil's mechanical properties, says Henry Moore, the Pathfinder Rover Scientist and scientist emeritus with the U.S. Geological Survey in Menlo Park, California. Perhaps the most important parameter that can be measured this way is the friction angle. When the soil is not cohesive—and this stuff isn't—the friction angle is nearly equal to the angle of repose, which is the angle at which the

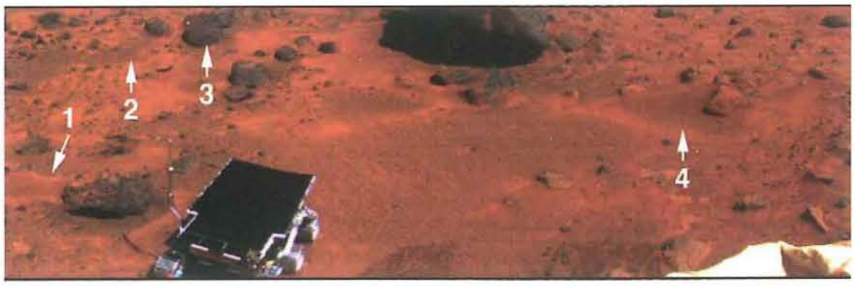
Sojourner as geologist. The rover drove over some compressible soil en route from Barnacle Bill to Yogi, as the above view from the rover's camera looking back toward the lander shows. At right, the rover digs in a wheel near a rock named Shaggy on Sol 23. And the rover's camera goes where the IMP can't, as in the rover's-eye view of Stimpy, below. Stimpy's fluted, pockmarked surface suggests sandblasting by the wind; windblown deposits of drift can be seen to the right. Flat Top is visible behind Stimpy; off in the distance, partially hidden by the top strip of missing data, is a profile of Yogi unseeable from the lander.

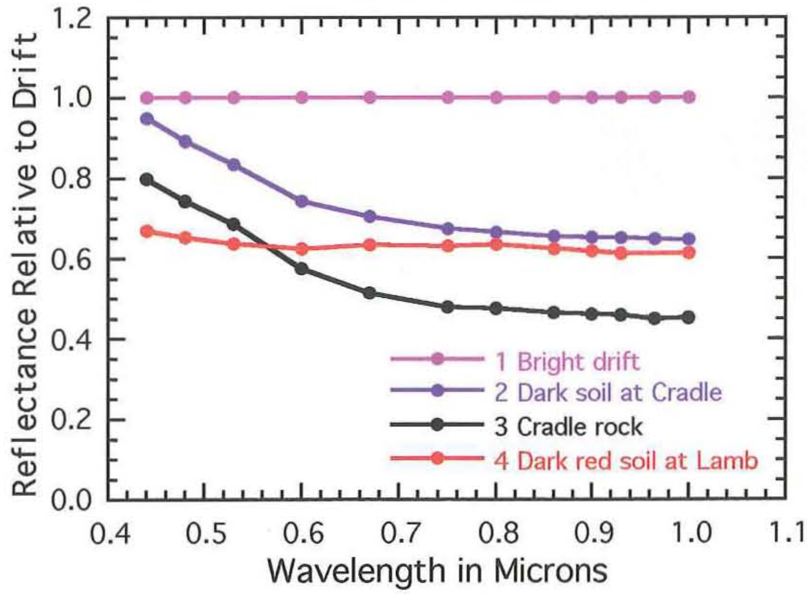




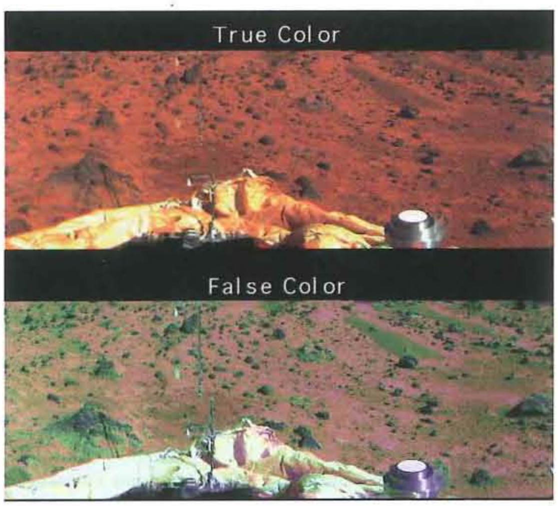
soil naturally "cones" in piles. The friction angle of a natural, dry material is related to its bulk density, which in turn underlies its radar and thermal properties as seen from afar. The rover's "ground truth" agrees quite well with the values derived from satellite and Earth-based measurements, says Moore, which is all the more remarkable in that these techniques look at average values from much larger swaths of terrain than Sojourner could ever possibly sample. But since the bulk density comes out the same either way, it inspires confidence in the accuracy of the remote methods.

Sojourner also learns about the soil by driving through it and looking at the tracks. Three basic types of soil have been classified this way. The first is a low-density, compressible soil, like the stuff near Casper. The rover leaves sharp, clear tracks there—the individual tines on the wheels' cleats are visible. Only a talclike powder will catch such fine detail, says Moore, who estimates the grain size as less than 40 microns—very like the dust returned by the Apollo missions. (The Viking 1 lander saw similar-looking soil, but of course couldn't drive on it.) A possibly identical material called "drift" accumulates in the lee of the boulders. The second soil type, which Moore calls "cloddy soil," is quite dense and is a mixture of dirt clods, small rocks, and sand- to silt-sized particles that mechanically resembles what





Left: Seen through the IMP's geology filters, the bright red drift (1), the dark gray rock named Cradle (3), and two kinds of soil (2 and 4) each have their own distinct spectral signature. (Spectra 2–4 have been plotted against the drift's spectrum in order to highlight their differences.) The strong upward kink in the two soils' spectra at visible wavelengths (less than 0.78 microns) indicates that they are more weathered and have more Fe^{+3}-containing minerals than does the rock. Soil 2, which is intermediate in color between the drift and the rock, has intermediate spectral characteristics as well, while the dark red soil (4) has a spectrum that suggests either a higher Fe^{+3} content or a larger particle size.



Left: The geology filters' output can also be converted into false-color images to summarize a region's spectral properties at a glance. In this view of the Mermaid Dune area, blue is the least weathered, green is intermediate weathering, and red is the most weathered.

Viking 2 found. Cloddy soil covers most of the area, and has been found to underlie the finer soils in places where the rover wheel has dug deeper than a centimeter or two. The rover leaves tracks in this stuff, but not crisp ones. And finally, there's the "indurated" soil, of which Scooby Doo is an example—a cohesive crust that's so tough that the rover's wheel just skitters across the surface instead of digging in.

And while the rover explores individual features of the landscape, the lander is getting the Big Picture. Literally. The IMP, as well as taking stereo pictures for the rover team to navigate by and the rest of us to ooh and ahh over, has a set of 12 "geology" filters that span the visible and near-infrared spectrum from 0.43 to 1.0 microns and are keyed to specific minerals that the scientists expected to find, allowing spectral data to be taken from anything the lander can see. According to the University of Arizona's Dan Britt, coinvestigator and project manager for IMP, the Super Panorama and the Super-Resolution Panorama now being completed are two "Cadillac data sets" that people will be studying for the next decade. The Super Pan covers the entire scene in all 12 geology filters *and* three color filters, in stereo—a compendium of the spectral characteristics of all 2,039 visible rocks (pity the poor soul who counted them!) and the intervening soil patches. And while previous images have been compressed by 6:1 or more, this color data is 1:1. (The geology data gets a very mild 2:1 compression.) The Super-Resolution Pan wrings extra detail from the camera by taking 25 lossless views of every vista, which are then combined in supercomputers at NASA Ames to sharpen the image by a factor of four to eight.

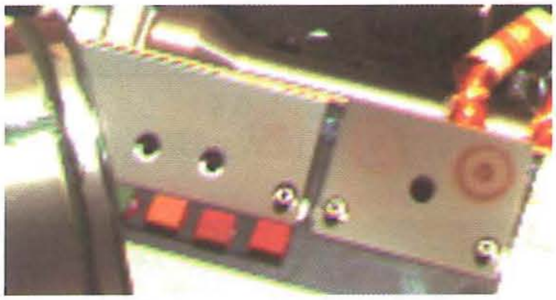
The IMP's view of the rocks dovetails with the APXS data, which means that elemental compositions can be assigned to a host of rocks that the lander can see but the rover can't reach. Yogi and the other big rocks are more weathered, says Britt,

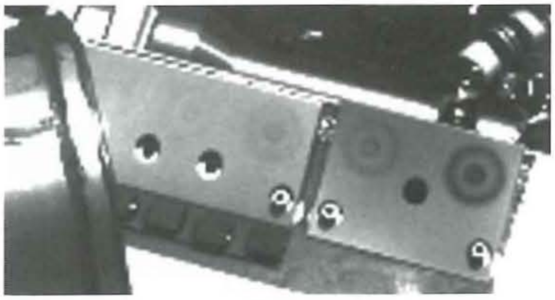
The bright object off in the middle distance of this portion of the Super-Resolution Pan isn't a data-processing artifact or a sign of an alien civilization—it's Pathfinder's backshell, which was cut loose just two seconds before the spacecraft hit the ground. The spacecraft, swaddled in its airbags, bounced from there to its present location. This image fortuitously caught a glint of sunlight off the backshell, making it easier to spot.

which means they've been sitting in their present locations for quite a while. They also tend to be rounded, like boulders in a stream, implying that they were sculpted by water—presumably while being tumbled for hundreds of miles down Ares Vallis from parts unknown. The smaller, jagged rocks like Shark and Wedge are less weathered, and thus relative newcomers. They're also higher in silica, so they must have come from a different place. One popular conjecture has them being impact ejecta from the so-called Big Crater to the south.

Britt classifies Scooby Doo and its kin as a third kind of rock that he calls "caliche-like," after a cemented mineral common in the Tucson area. When it rains in the desert, calcium-rich salts leach out of the upper soil and begin to percolate downward. But before they've penetrated more than a foot or so, the water evaporates in the scorching heat, concentrating them into a layer—caliche—that has many of the properties of concrete. Says Britt, "There's a big debate about whether the caliche-like stuff should be classified as soil or rock. The people from moist climates who have never tried digging in it call it soil. Those of us from arid regions call it rock. And since I'm the chair of the mineralogy and geochemistry science group, it's rock."

The IMP is also a vital part of the Magnetic Properties Experiment being run by the Niels Bohr Institute for Astronomy, Physics, and Geophysics at the University of Copenhagen, Denmark. Iron and liquid water are chemically the best of friends, so the state of Mars's iron can tell us a lot about the history of Mars's water and the former potential for life therein. Iron is the third most abundant element in the Martian soil (after oxygen and silicon), and the magnets carried by the Viking landers rapidly became saturated with dust. So Pathfinder carries arrays of weaker magnets, whose rate of dust accumulation should tell us how strongly magnetic the dust is. Iron comes in two ionic forms: it dissolves out of its native rock as Fe^{+2}, but dissolved oxygen converts it to Fe^{+3}. Fe^{+3} is insoluble, and rapidly precipitates. On Earth, Fe^{+3} eventually becomes hematite (a popular gemstone) or goethite (the primary constituent of rust), neither of which is strongly magnetic. Fe^{+2} can linger in solution for years before eventually settling out as the terrestrially less common iron oxides maghemite (the magnetic coating on cassette tapes and floppy disks) or magnetite (humankind's first compass, also known as lodestone). So dust consisting of clays with a strong magnetic component will imply that liquid water played a long-term role in the dust's formation. The IMP looks at the array every few days to see if the accumulating dust matches any of the patterns these minerals made on an identical array on Earth, and once a week tries to identify the minerals spectroscopically through the geology filters. The dust appears to be a composite of mainly silicate particles containing maghemite, says Jens Martin Knudsen, IMP coinvestigator from the University of Copenhagen.





Pathfinder carries two arrays of five bull's-eye magnets of increasing strength from left to right. The upper array is for airborne dust; the lower array is near the lander's base, in hopes of collecting sand grains as well. These two images of the upper array are from Sol 64. The black-and-white image has been contrast-enhanced to reveal that dust is sticking to four of the five magnets. The dust's color is suggestive of maghemite, but the fact that little, if any, appears to be sticking to the weakest magnet so far implies that there's a lot of nonmagnetic silica mixed in.

But dust devils may strip off weakly magnetic dust, says Britt, so the results have to be interpreted with care. A further complication is that some or all of the dust may be of recent vintage, as the surface of Mars continues to rust to this day. Dust inherited from the underlying rocks will contain titanomagnetite, which has been found in many Mars rocks (including the SNC meteorites). If there's titanium in the dust adhering to the magnets, it would mean that water played a smaller part in the dust's formation. The dust's titanium level should be revealed when the rover returns to the ramp it disembarked from on July 5. A magnet at the ramp's foot, placed there to answer this very question, awaits the APXS.

And finally, there's the question of what lies underground. Mars Global Surveyor's discovery that Mars does, in fact, have a vestigial magnetic field (see Random Walk) implies that Mars used to have a liquid core of nickel-iron, as Earth does. Such a core's heat-driven churnings could have sustained a magnetic field strong enough to fend off cell-damaging cosmic rays—another prerequisite for ancient life. JPL's William Folkner, leader of the rotational and orbital dynamics team, is trying to determine whether the core is still a liquid, albeit one too cool and sluggish to convect, or whether it has long since solidified. Folkner's group tracks the Doppler shift in Pathfinder's radio signals. By combining this data with old results from the Viking landers, they have been able to calculate Mars's polar moment of inertia to within 1 percent. Extended-mission data should shave off an additional factor of three, enough to distinguish between the core sizes, densities, and temperatures predicted by various geophysical models. Some models posit that the core is colder than Earth's, for example, because Mars is smaller and cooled more rapidly; others argue that the core should actually be warmer, at a given pressure, than Earth's, because the outer core, which solidified first, would insulate the interior. Folkner's group has already ruled out the models that predict a core less than 1,300 kilometers in diameter, but otherwise can't yet declare a winner.

With a little luck, a liquid core might manifest itself directly. As every fourth-grader knows, a hard-boiled egg spins differently than a raw egg. If the core happens to have a rotational period that's some whole-number fraction of the Martian year—two-thirds, say—a resonance will show up in the planet's nutation rate. (Nutation is the "nodding" of the planet's rotational axis as the axis itself precesses; think of a pleated lampshade as seen from overhead—the circle of the lampshade is the precession, and the pleats are the nutation.)

Meanwhile, as the south polar cap recedes, the gas it liberates thickens the air around the equator enough to detectably slow the planet's rotation, just as a figure skater spins more slowly with arms outstretched than with folded arms. (The same thing happens, to a lesser degree, during the northern summer.) The mass lost from the polar cap, and hence its change in thickness, can be calculated from the change in spin rate. This would double-check a calculation done using atmospheric pressure-change data from the Vikings, which indicated that the caps may be astonishingly thin: the loss of about 50 centimeters' worth of carbon dioxide "snow"—a knee-deep layer—is enough to make the cap retreat southward some 1,400 kilometers. (The northern cap gains and loses a thickness of about 15 centimeters.)

Another extended-mission gleam in the eye is to measure the masses, and hence the densities, of some nearby asteroids, from which something about their composition can be inferred. This was actually done for three asteroids in the Viking days, and involves watching how Mars's orbit is perturbed as an asteroid passes by. The ranging data is acquired by measuring the round-trip time of flight of a signal from Earth to Pathfinder and back. "This competes directly with telemetry, and so far telemetry wins," says Folkner. "But the only asteroids we know the masses of are those three and Mathilde, which the NEAR mission just visited, plus a couple more for which the data aren't very good. If we could learn three or four more densities from Pathfinder, that would double our data set." They've compiled a list of a dozen or so asteroids they'd like to try if they get the chance.

Let's hope they do. The spacecraft gave its handlers a very nasty scare by falling silent on September 28. Contact was briefly reestablished on October 7. It looks like the lander's batteries, which had lasted three times longer than their planned lifetime, have expired. This in itself is not a problem, as the lander, which also relays instructions and data to and from the rover, is designed to operate indefinitely on nothing but solar power. However, the unscheduled transition to solar-only mode appears to have caused the onboard clock to quit. If so—among other consequences—the spacecraft would have no idea when and where to aim the high-gain antenna to find Earth. Furthermore, the dead battery could be siphoning off power from the solar array. As of this writing, the flight team has successfully disconnected the battery from the rest of the power system. They think they've reset the clock as well, but Pathfinder has since gone silent again. With the spacecraft uncommunicative, nobody knows if the commands being uplinked to it are getting through, but the engineers are plugging away at the problem. Once they get Pathfinder back to its old convivial self, they'll use the IMP to hunt for the rover, which is programmed to head in the lander's general direction if contact is lost for more than five days—a precaution built into the software in case the rover inadvertently moved out of radio range. And then, with luck, Pathfinder will be back to business as usual. □