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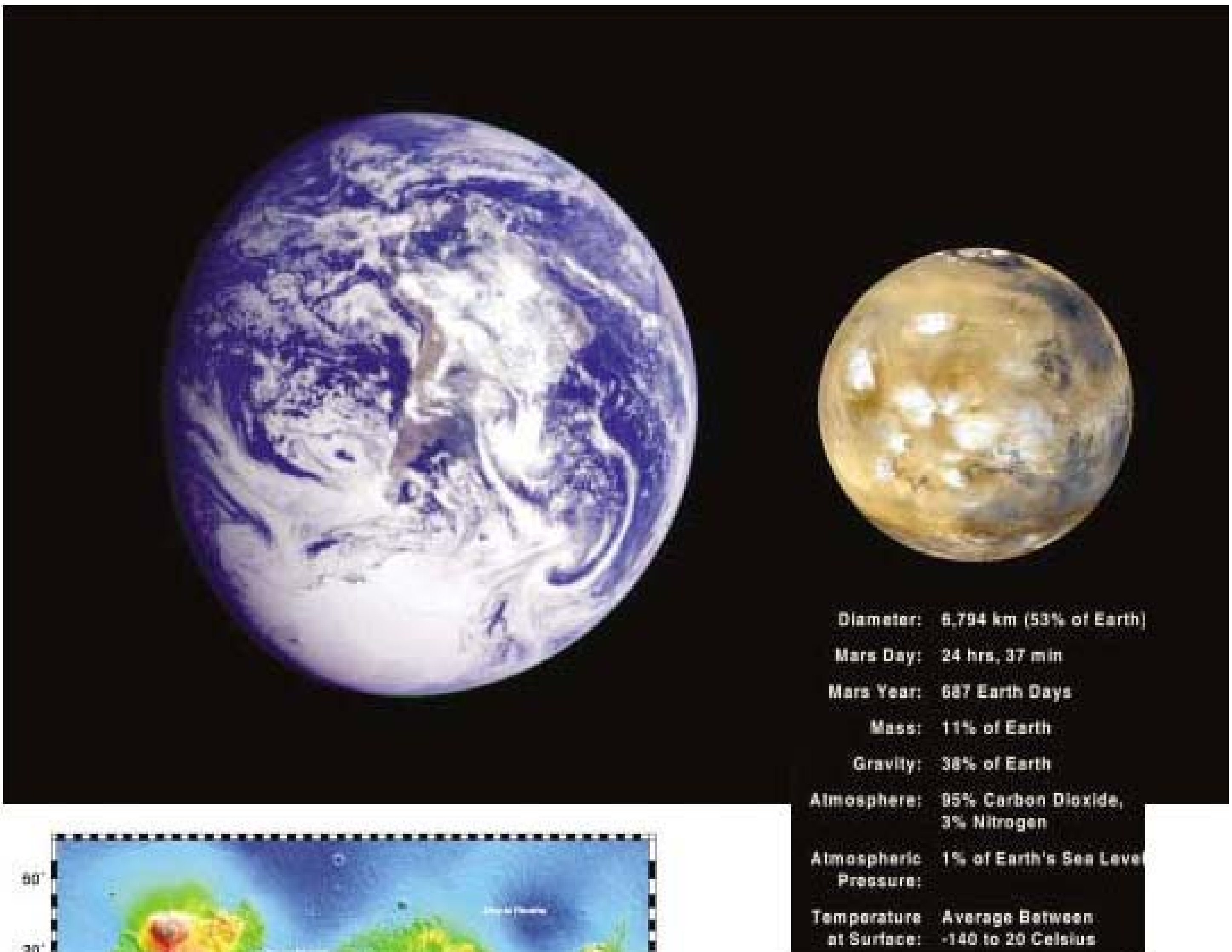
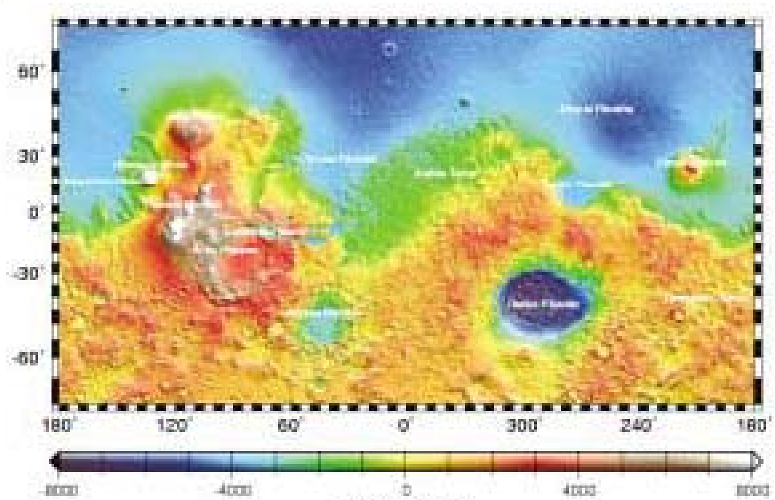




Mars Global Surveyor: A Success by Any Measure

by Arden L. Albee

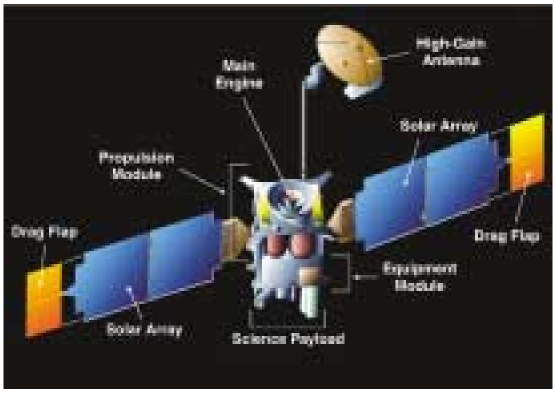
Opposite: Not quite peas in a pod, but certainly fraternal twins, Earth and Mars are shown to scale in these images from Galileo and the Mars Global Surveyor. Clouds mark the summits of several dead volcanoes, including the three Tharsis Montes, arranged in a diagonal line like the stars on Orion's belt, and the mighty Olympus Mons above and to their left. To their right the Valles Marineris canyon system slashes across the planet's belly like a giant gallbladder scar. The relief map was made from Mars Orbiter Laser Altimeter data.

Above: The Mars Orbiter Camera makes a daily weather photo of the entire planet.

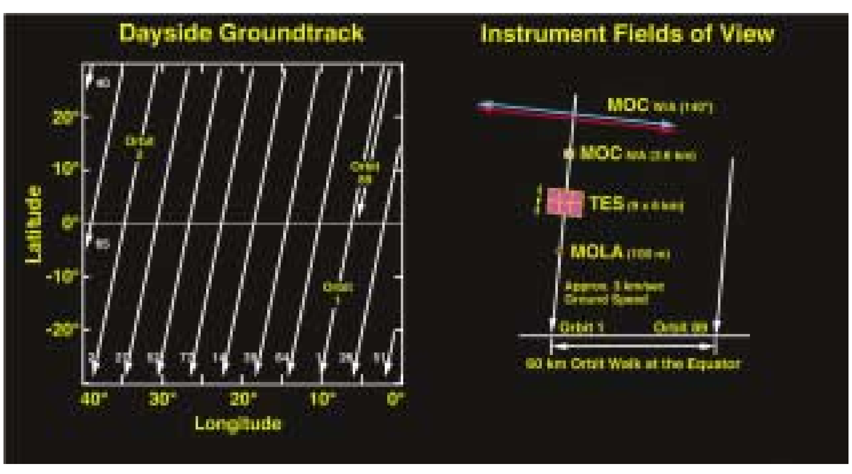
We are fascinated by Mars because it is the most Earth-like of terrestrial planets, and it's the first one humans are likely to visit. It looks familiar—it's got peaks, valleys, and clouds. The Mars day is almost the same length as our day, but the Mars year is twice our year. The surface temperature ranges from 20° Celsius, which is like a nice summer day in Iowa, to –140° C, which you don't even want to imagine. Mars has almost the same tilt on its axis that Earth does (23.98 versus 23.44 degrees), so it has seasons. They're quite pronounced because of its orbit, which is much more elliptical than Earth's, and the southern summer is shorter than the northern summer. Even though Mars's atmosphere is only 1 percent of our atmosphere and is almost all carbon dioxide (CO_2), the climate-modeling approaches that have been developed for Earth can be applied because both are rapidly rotating planets with shallow atmospheres whose winds are influenced by topography. Their atmospheres are heated similarly—sunshine warms their surfaces, which in turn heat their atmospheres. However, Earth's atmosphere is moderated by the oceans, which act as a heat reservoir and smooth out seasonal temperature swings. Mars doesn't have oceans, lakes, rivers, or rain. The Martian atmosphere is controlled by the warming of the subsolar region (the region where the sun is directly overhead), to which it responds very rapidly. Any liquid water that should happen to appear on the surface would evaporate immediately, but evidence suggests this was not always so—early Mars could have been like early Earth, with a warmer, wetter, thicker atmosphere. Since liquid water seems necessary for life to exist, we want to know, Did life develop there? If not, why not? If it did, did it die out? Or is it still there, hidden in water in the rocks? What does Mars have to tell us about what can happen to Earth's climate?

The Mars Global Surveyor, or MGS, replaced the Mars Observer, which was lost on arrival at Mars in 1993. Both spacecraft essentially combine a weather satellite and a LANDSAT into a single orbiter to get integrated global data sets—on climate, weather, surface morphology, geology, topography, the geodetic figure, gravity anomalies, and the magnetic field—to answer the big questions about Mars's history and evolution. The MGS team is also examining potential landing sites to help choose ones where spacecraft can touch down safely, yet still find interesting geology. In order to do all this, MGS moves in a nearly circular, nearly polar orbit, looking at the whole planet as it spins underneath. We orbit the planet 12 times a day, and every 89 orbits, or roughly eight days, we come back over almost the same spot. The orbit is sun-synchronous, so it's always 2:00 below us—2:00 p.m. on the day side, 2:00 a.m. on the night side—giving us a constant lighting angle. The instruments are co-aligned so that they all look at the same piece of land, and they always face Mars so that we get round-the-clock data. (It's quite a challenge for spacecraft designers to keep the instruments pointed at Mars, the high-gain antenna aimed at Earth, and the solar arrays facing the sun all at the same time—you have to use lots of wrist joints!) Each of our instruments has more computing power and more memory than any entire spacecraft that JPL had launched until then—a tremendous advance. MGS has returned more than two trillion bits of data so far, which is more than any other mission.

MGS has five instruments, each of which is operated by its Principal Investigator, or P.I. The Mars Orbiter Laser Altimeter, or MOLA, bounces a laser pulse off the planet, and the time of the pulse's flight measures the distance to the surface. (Of course, you have to know the spacecraft's location to a very high accuracy.) MOLA's global map, which has a spatial resolution of 1/64th of a degree and a vertical resolution of 30 meters, is better than our best global map of Earth at this point. This map is based on a set of laser footprints 130 meters in diameter whose positions are known to



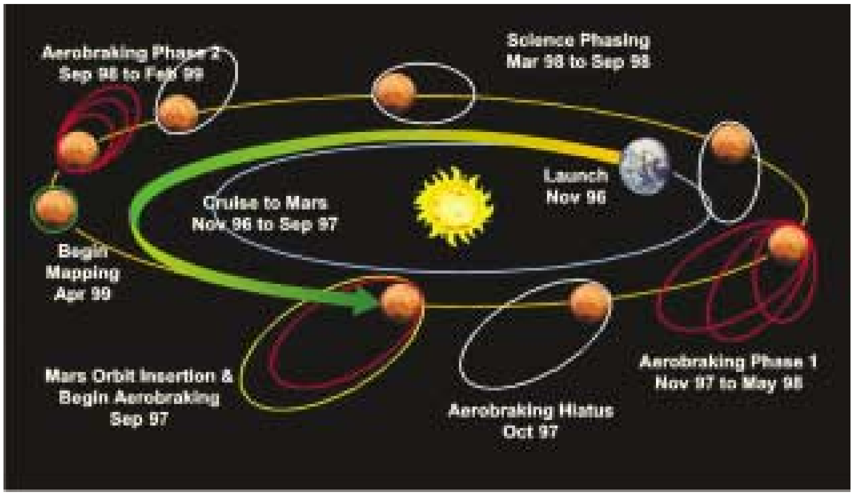
Above: The spacecraft's principal parts. Right: Most of the instruments look straight down from a platform on MGS's belly. The Mars Orbiter Laser Altimeter (MOLA) is the copper-colored mirror that's sprouting a mushroom. The tall kitchen trash can to its left is the Mars Orbiter Camera (MOC), and the mailbox below that is the Thermal Emission Spectrometer (TES). (The magnetometers are mounted on the outer tips of the solar panels.) The paper towel holder is the Mars Relay Antenna, provided for later missions. Below: The overlapping orbits and fields of view.



less than 1 meter vertically and 100 meters horizontally. The laser fired 640 million times before a chip in the firing circuit failed on June 30, 2001—the longest-lived laser ever put in space. We would not have been too surprised if it had lasted only a month, and it worked for four years! David Smith at NASA Goddard is the P.I. The Mars Orbiter Camera, or MOC, acts like three cameras in one. It has a wide-angle mode that can view the entire planet at once at a resolution of 250 meters per pixel at nadir—the point directly below the spacecraft—and 2 kilometers per pixel at the limb, which is the edge of the planet's disk. All these images are stored in the camera's computer, and once every 24 hours the camera's software edits the wide-angle strips that have been collected during each orbit, down to a resolution of about 7.5 kilometers per pixel. The data are then compressed and sent back to Earth, where we assemble them into a global mosaic to make an image much like the weather photos you see on the nightly news. The near-nadir strips are likewise edited and assembled into regional maps with a resolution of about 300 meters per pixel—not quite enough to pick out the Rose Bowl, but plenty to see the parking lot. And the narrow-angle, high-resolution mode, at 1.4 meters per pixel, can see things about the size of a Volkswagen. That's a staggering quantity of data, so we'll cover less than one percent of the planet that way over the life of the mission. Still, we've obtained more than 100,000 high-resolution images, or twice as many as the two Viking missions combined. MOC's P.I. is Michael Malin, of Malin Space Science Systems, who got his PhD from Caltech in 1976.

The thermal emission spectrometer, TES, is an infrared (IR) spectrometer that takes atmospheric data and maps the surface's composition—the latter at 3 kilometers per pixel. The P.I. is Arizona State University's Phil Christensen. The Magnetometer/Electron Reflectometer first looked for a global magnetic field, which we didn't think existed. If no such field was found, they were to make crustal magnetic maps at a resolution of 100 kilometers. Mario Acuña from Goddard is the P.I. And finally, the radio-science experiment uses the spacecraft's radio to do two other things while sending back data. First, it measures Mars's atmospheric pressure. As the spacecraft goes behind the planet, the radio signal passes through the atmosphere. By analyzing the signal, you get a very accurate profile of the atmospheric pressure in 200-meter increments all the way down to the surface. The radio also enables us to map Mars's gravity field, and I'll talk about that in more detail later. The radio-science P.I. is G. Leonard Tyler, from Stanford.

MGS is about half the size of the Mars Observer, and wasn't able to carry all of its instruments. (The others are being flown on later missions.) We also launched on a relatively small rocket, so we couldn't carry the fuel to fire the engine long



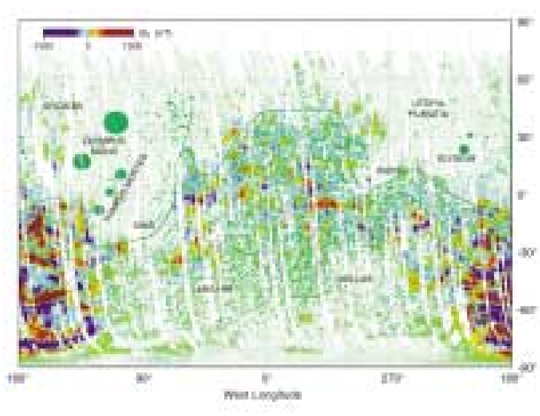
The plane of MGS's orbit remains almost constant relative to the sun, while Mars's sun-facing side slowly turns beneath. The original plan was to go from a 45-hour elliptical orbit to the 118-minute circular mapping orbit by the time Mars arrived at the right edge of this diagram. Instead, the October '97 hiatus was the month-long pause during which the team figured out what to do about the fluttering solar panel, and the March '98 – September '98 "Science Phasing" was the bonus period in which the gravity and magnetic fields were mapped.

enough to put us directly into our circular mapping orbit on arrival. So we intended to aerobrake instead, by treating the solar panels as if they were wings and dipping into the very top of Mars's atmosphere once every orbit. The drag gradually slows the spacecraft and circularizes the orbit. The original plan was to begin mapping in March 1998, but as you will see life doesn't always work out as planned. We had a perfect launch on November 7, 1996, a beautiful sunny day, after a one-day weather delay. But then when we unfolded the solar panels for the flight to Mars, there was quite a clunk, and one panel's wrist was damaged.

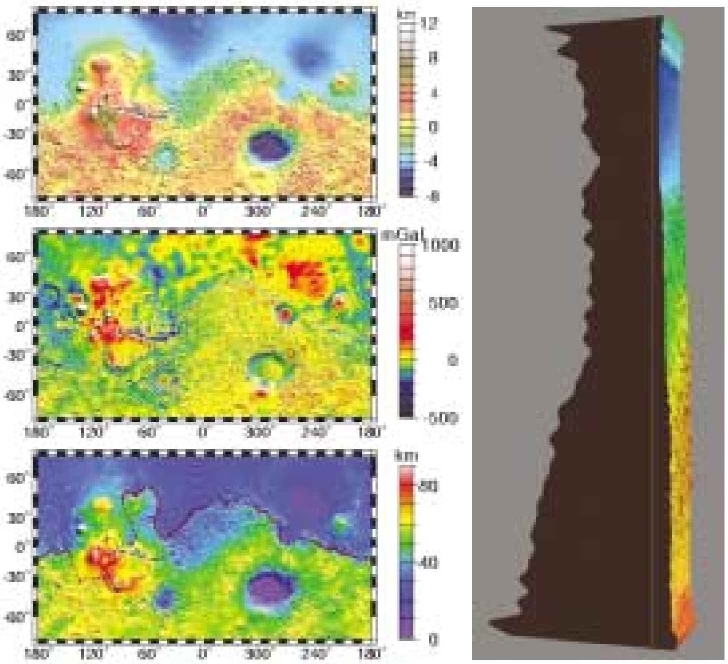
This turned out to be a blessing in disguise, though it could have been catastrophic. We weren't sure whether the weakened panel would hold, so we began aerobraking very cautiously. And then suddenly came a day when the atmosphere was denser and our broken wing began to flutter. We paused for a month to say, "What are we going to do?" I give credit here to Glenn Cunningham, a smart project manager who never forgot that the real goal of the mission was science. The plan was to go into orbit at about the 6:00 p.m. position, begin aerobraking, and let the planet gradually move under us until we got to 2:00 p.m. But because of the broken wing, we simply could not aerobrake that hard—we could not put that amount of pressure on it. Glenn agreed with the scientists to take an extra Earth year to get over to the opposite position—2:00 a.m. instead of 2:00 p.m. The illumination angle was the same, but now we were traveling *up* on the daylight side of the planet instead of *down*. In a sense, we're operating in reverse. And what turned this near-catastrophe into a scientific triumph was that we had to spend a long time in an orbit whose low point was about 175 kilometers, which is ideal for mapping magnetic and gravitational fields, because it gets in under the ionosphere. The orbit's low point slowly moved up, over the North Pole, down the back side, and under the South Pole before we got to 2:00 a.m., so we got good coverage of most of the planet. We would never have had the guts to design a yearlong delay into the mission, but when it worked out that way we got exceedingly valuable data sets.

I'd like to share with you the highlights of what we've found, which I've organized into a somewhat arbitrary Top Ten list à la David Letterman, working from the inside of Mars outward. First is the magnetic field. Earth's magnetic field keeps the tissue-damaging high-energy particles called cosmic rays at bay. We immediately found that Mars has no global magnetic field, so it doesn't have that protection. (Mars's thin atmosphere also offers no protection from the sun's ultraviolet (UV) radiation, which is even more damaging—the planet's surface gets a UV dose equivalent to what we use to sterilize operating rooms.) These cosmic-ray and UV fluxes are something to consider when looking for Martian life, or planning a human presence on Mars.

But we did find, later, that Mars has remnant magnetism—fossil bar magnets in its crust, if you will. On certain orbits we'd come down through the ionosphere and suddenly find a very large local magnetic field. In the map below, the red spots are strong upward-pointing magnetic fields and the blue spots are strong downward-pointing ones. The crust anomalies were a tremendous surprise, and we still don't fully understand them. The fields tend to line up somewhat, so many people said, "Hey, maybe this is evidence of plate tectonics, like the magnetic stripes in the spreading ridges on Earth's seafloors." But these fields are very, very old—they are concentrated in the southern hemisphere, which is much more heavily cratered than the northern hemisphere and therefore older. And the magnetism has been destroyed around Hellas, a vast impact crater that itself dates from the first several hundred million years of



The fossil magnetic features, with some topographic landforms drawn in. The line that very roughly follows the equator marks the boundary between the ancient terrain of the southern hemisphere and the relatively young north. The strongest fields are found in the old crust.



Above: Global maps of Mars's topography (top) and gravity (middle) can be mathematically merged to derive the crustal thickness (bottom). The crust is relatively thin under the northern plains and beneath the big impact basins of the southern hemisphere, but quite thick under the Tharsis uplift region. Above, right: A vertically exaggerated slice through the crust along 0° longitude, from the north pole to the south. The crust is about 40 kilometers thick under the northern plains and 70 kilometers thick in the far south.

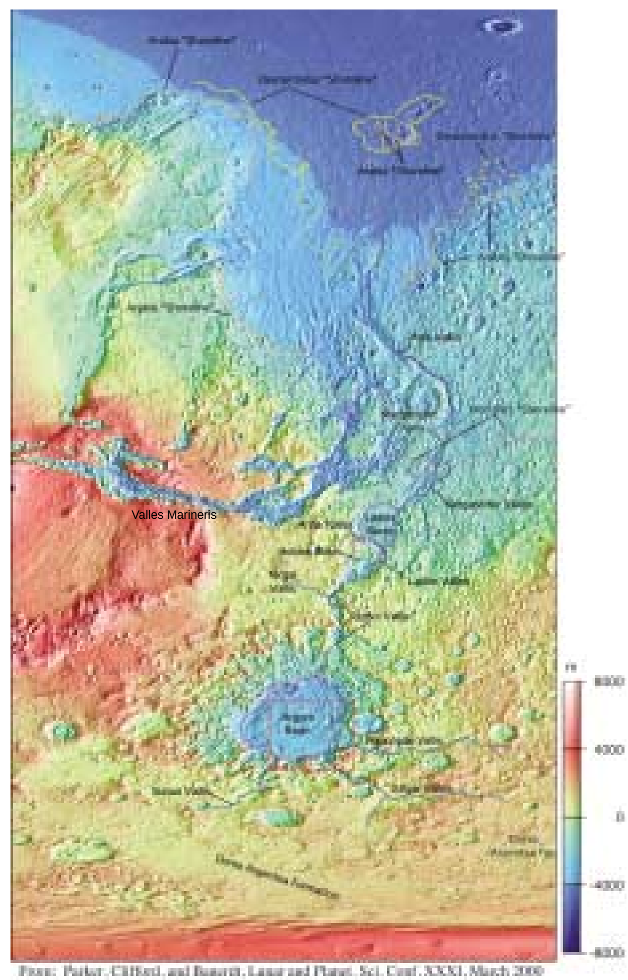
Martian history. These anomalies are 10 times stronger than any we know on Earth, and it boggles the mind as to how they could have formed—you'd need a hot, molten core with vigorous convection to create the magnetic field, but at the same time you'd need to cool the crust quickly enough to lock in the field by crystallizing the rock. We don't yet know how this might occur.

Let's turn to number two, which is Mars's figure and gravity field. By figure, I mean the planet's shape, which we now know very, very accurately. Mars is egg-shaped. The northern hemisphere is flattened, and Mars's center of figure is offset to the south of the planet's center of gravity by nearly three kilometers, so that the top hemisphere is skinnier and six kilometers lower than the bottom.

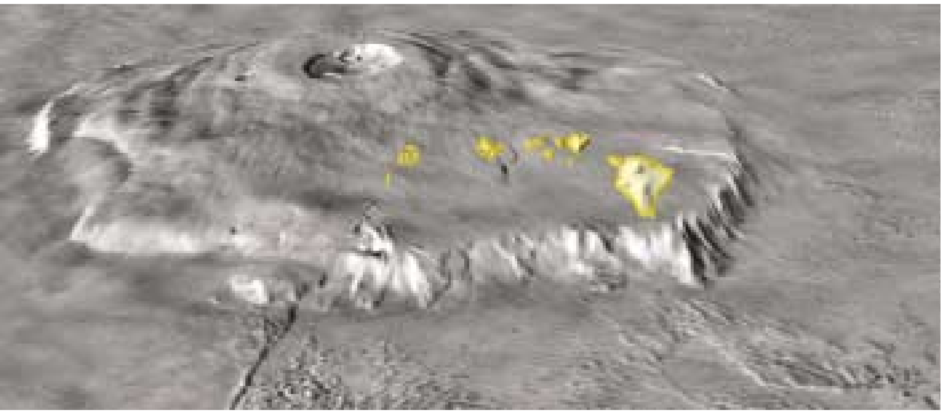
When we combine topography with gravity measurements, we begin to learn about the planet's interior. Well, how do we map gravity? Imagine you're orbiting Earth and approaching Mount Everest. Its mass is going to pull on you, and you'll speed up slightly; once you pass by, the mass will pull you back slightly. If you are emitting a continuous radio signal, the Doppler effect will shift its frequency very minutely, allowing us to measure your instantaneous acceleration and deceleration, and map the gravitational field. If we do, we'll find Mount Everest didn't speed you up and slow you down as much as it ought to. On Earth, mountains are like icebergs—light crustal rock floating on the denser upper mantle, with most of their bulk below the surface. This bulk displaces the mantle rock, so there's not as much mass as there would be if the mountain were simply piled on top of the crust. So this allows us to ask, how strong is the crust? Is it supporting these big mountains by its own strength, or do they have deep roots that help buoy them up?

It turns out that the mountains in the southern hemisphere of Mars are quite well compensated, which is to say they have deep roots, whereas in the north, they don't so much. That may just be a matter of time, because the southern hemisphere is so much older—the mountains in the north may not yet have sunk to their buoyant depth.

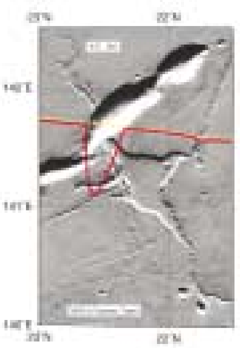
Number three on my list is topography. As I mentioned before, there's a pole-to-pole slope from the southern hemisphere downhill to the north that would have controlled the flow of water on early Mars. Besides measuring Mars's shape, MOLA has produced high-resolution topographic data that geologists can use to make detailed contour maps to interpret the landforms we are seeing. For example, coming out from the Argyre Basin there is a series of channels, many times the length of the Mississippi-Missouri river system, that has been successfully traced even though the channels are disrupted in places by later craters. The channels lead up to a vast low area in the north that could have been the site of an ancient ocean. We can draw a contour, or a couple of contours, around



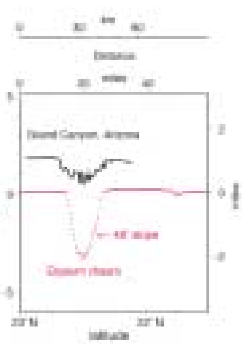
The Argyre Basin's complex drainage system, with three putative shorelines drawn in. The Valles Marineris helps drain the Tharsis region.



This 3-D view of Olympus Mons was made from MOLA topography data and a Viking image. The vertical relief is exaggerated tenfold. The state of Hawaii has been superimposed on the image to roughly the same horizontal scale.



Above: The MOLA elevation profile (red) of an anonymous chasm in Elysium Planitia. (MGS's ground track is shown in yellow.) The steep slopes indicate it may be relatively young and uneroded. Below: The deepest part of the Grand Canyon, for comparison.



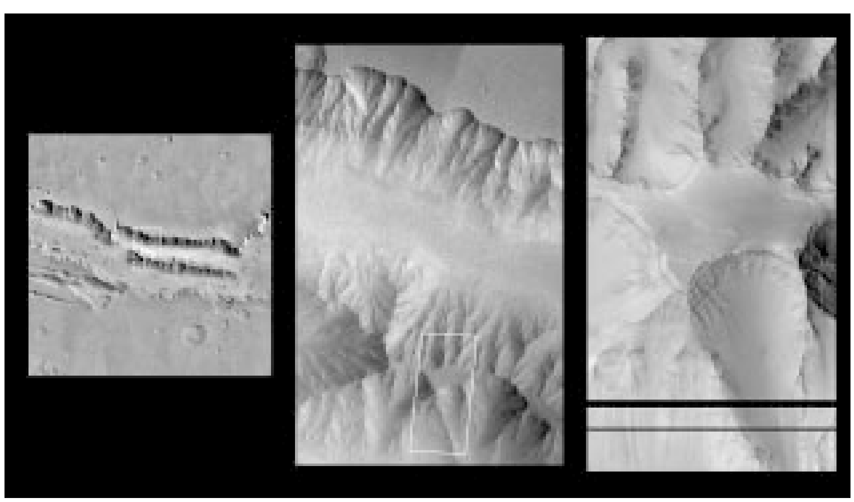
it that some people believe represents shorelines. We can also trace upslope from Argyre all the way back to the south polar cap and show that water, or some fluid at least, flowed down from the cap, filled Argyre Basin, overflowed it, and successively filled up a series of basins downstream before ending up in the north. But, oddly, the MOLA topography shows faint traces of big craters under the northern plains. We used to think that they had been resurfaced by very thick accumulations of volcanic and sedimentary material, but it now looks as if the surface layer is relatively thin. How to make the plains so flat if there's an ancient surface not far underneath is one of those mysteries we have to work on.

You have to keep the scale of these features in mind. The Valles Marineris, which is a branch of this channel system, would stretch from San Francisco to New York City. And the chasm at left is so small it doesn't even have a name, yet it is twice as deep and just about as wide as the Grand Canyon. Olympus Mons is so huge it would dwarf the entire state of Hawaii, yet once you get across the bounding scarp, its slopes are as gentle as Iowa's. How Mars came to have such large features is still an open question.

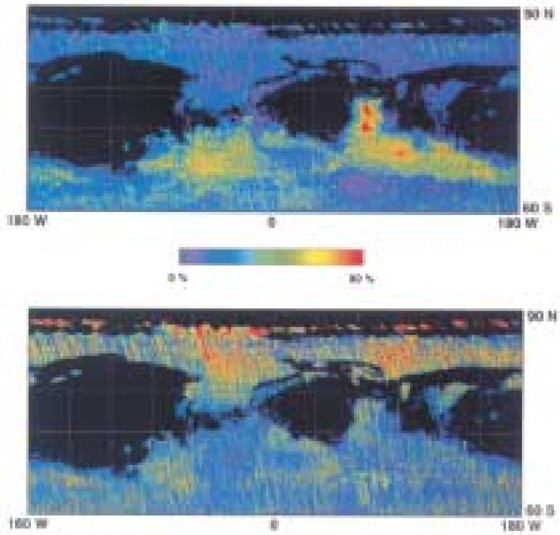
Fourth comes volcanism in the planet's early history. Mariner found Martian volcanic constructs—among them Olympus Mons and the Tharsis Montes, the latter being part of an area more than twice the width of North America that's been uplifted by some four or five kilometers. But we found thick, massive, layered beds that are probably volcanic strata in the walls of the Valles Marineris. So before the fluids carved the canyons, a sequence of volcanic rocks, probably basalts, were laid down. Such early extensive volcanism is a new element in Mars's history.

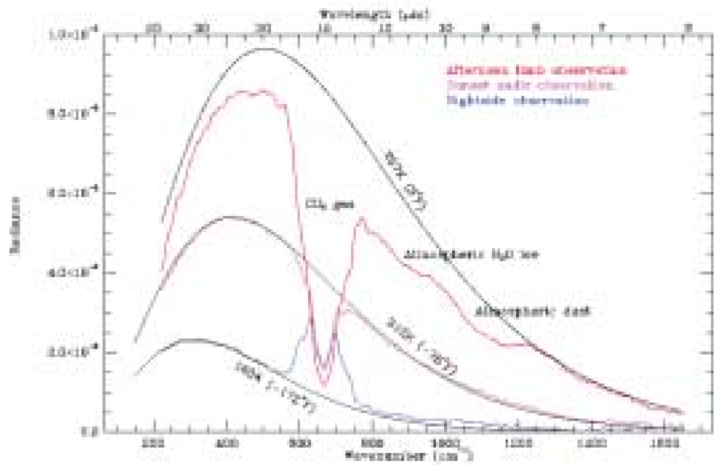
Number five is mineralogy and weathering. The TES spectra mapped on the next page show volcanic rocks over much of the planet. The black areas on the map have very weak spectral features that are difficult to interpret, and are probably regions of fine-grained dust. Dust particles do not give good spectra because of their size, which approaches the wavelength of infrared light and therefore doesn't interact with it strongly.

I need to take a moment to explain how we interpret IR spectra. If a bulk material has no absorption features—a so-called black body—it



From left: Zooming in on a section of the Valles Marineris. The white outline in each image shows the field of view of the image to its right. The closest view shows distinct rock layers ranging from a few meters to a few tens of meters thick. The resolutions are 230, 80, and 6 meters per pixel; the first two images are from Viking.





From: Christensen et al., Journal of Geophysical Research, Volume 106, Number E10, 2001, p. 23,844.

Above: Global TES maps of basalt (top) and andesite (bottom) abundances. Basalt is a dark volcanic rock formed when thin, runny lava oozes out onto the surface and hardens, as in Hawaii. Andesite is closely related to basalt, but forms from slightly more viscous lava with a higher silica content. The fact that the basalt is found in the older south and the andesite in the younger north indicates that some process within Mars altered the ratio of silicon to the other elements over time. Above, right: Some TES spectra of Mars, fitted to black-body curves. There is a peak for CO_2 instead of a trough in the nightside spectrum because the atmosphere is warmer than the surface and therefore emits, instead of absorbs, infrared radiation.

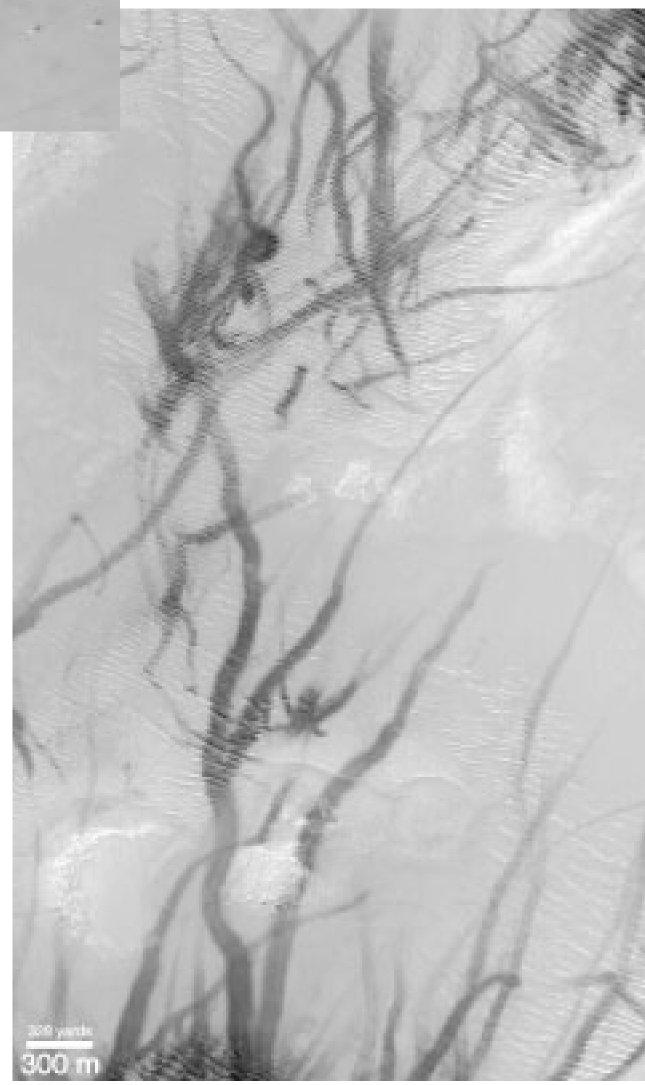
shows a nice, smooth curve whose height depends only upon its temperature. Even though it's not a black body, we can fit a black-body curve to the general shape of Mars's spectrum in order to determine its temperature. And since the smooth spectral curve has been eaten away by dust, water ice, and CO_2, all of which absorb in the infrared, we can measure their amounts by the depths of their absorptions. Furthermore, we get quite different spectra depending on whether we're looking through the atmosphere out into space or directly down toward the surface. So we can tell whether the absorption features are caused by material in the atmosphere or on the ground, and we can measure the atmospheric and surface temperatures separately. And once we subtract out the atmospheric CO_2, the water-ice clouds, and the airborne dust, the remnant spectra tell us there's basalt on the surface.

The key thing is that we don't see any products of hydrous weathering, which indicates that the rocks have not been exposed to water for any significant length of time. This is big news. After Viking, we had a picture of Mars as being covered with clays and other highly weathered material. That picture is now dead. We find volcanic minerals—plagioclase, pyroxene, and olivine—that on Earth rapidly absorb moisture and turn into hydrated clays, but we do not find the spectra of clays on Mars. Nor do we find quartz, which is the most common product of weathering on Earth and the chief component of Earth's sand; nor sulfates and carbonates, which tend to precipitate from liquid water and might indicate places where life could be or might have been. (There are probably some sulfates and possibly carbonates present in the dust, but at an abundance so low we can't positively identify them.)

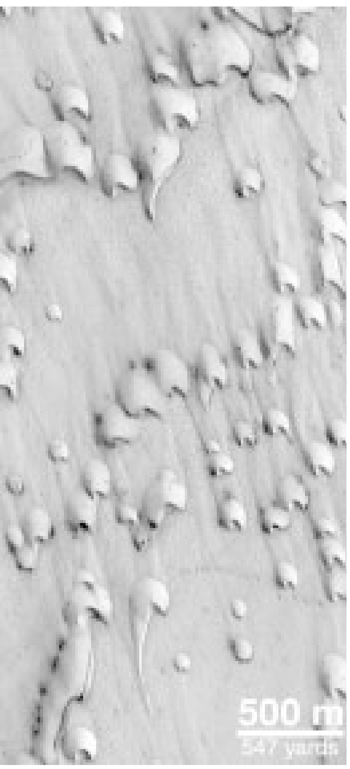
We *have* found a large area of coarse-grained hematite centered, coincidentally, at 0° latitude and longitude. Hematite forms in hydrothermal environments—hot springs, in other words, like at Yellowstone Park—and is also made by certain species of bacterial and other forms of life. So this is a prime candidate for a landing site for the '03 mission. Detecting hematite is Top Ten item number six.

Number seven is aeolian processes. Aeolus was the Greek god of the winds, and he rules Mars (or should I say Ares?). It's been known since the first telescopes that Mars has seasonal dust storms, but we found widespread layering indicative of loess deposits. Loess is a fine-grained, wind-blown material found in great quantities in China, where it started accumulating after the last Ice Age. The wind carries dust in from the deserts to the west and builds up deposits hundreds of meters thick. On Mars, the deposits have been laid down, partially eroded away, laid down again, and so on, until hundreds of layers are visible in some places. This appears to have been going on for three billion years, and the deposits can be several kilometers thick.

The wind also makes sand dunes. We find them all over Mars, and in particular they ring the north polar cap. Unlike the dust, the dunes are coarse-grained enough to give identifiable spectra, and they look like basalt, similar to the black-sand beaches of Hawaii. (Remember, Mars has lots of sand, but no quartz.) The dunes are typically dark relative to the lighter-colored, fine-grained dust, a coloration that gets exaggerated when we enhance the image contrast to bring out the details. At right are barchan-like dunes, meaning they are crescent-shaped. The crescents' horns always point downwind—a very handy meteorological tool for us! We often see small, bright ripples between the dunes, which means that there are several sizes of wind-blown features that were generated in an unknown sequence. Sometimes we see dunes going across an older, cratered surface that got worn smooth as it aged. These dunes are grooved as if all the sand grains somehow got cemented together, and the solidified surface was worn away by the



From left: 1. A field of dark dunes on the floor of Kaiser Crater, which lies at 46°S, 340°W. 2. These grooved dunes in Herschel Basin (15°S, 228°W) were overlain on an older, cratered surface. 3. Several dust devils and their shadows can be seen in this 88-kilometer-wide view of northern Amazonis Planitia. Note also the two craters that are almost filled with dust. 4. These dark streaks are caused when dust devils strip off the light-colored dust to reveal the darker surface beneath.

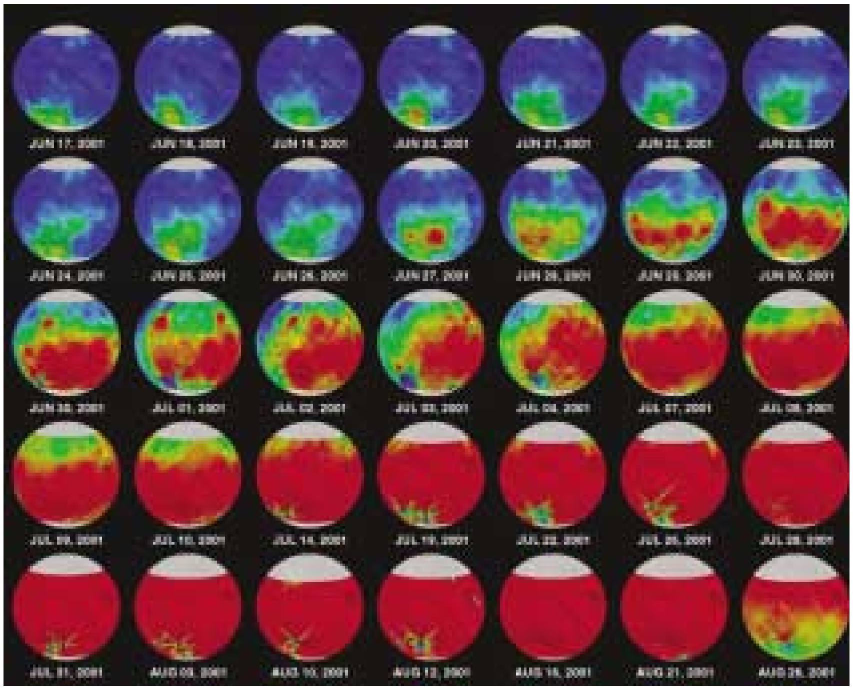


Barchan dunes, white with CO_2 frost, near the north polar cap. The dark patches in this springtime scene are sand, which is being revealed as the frost evaporates. Thus they appear to bloom, like vegetation, moving Arthur C. Clarke to suggest that they might be mangrove trees.

wind—another puzzle. Many dunes show dark streaks that look like dust avalanches, and sometimes two shots of the same area taken several months apart show differing streak patterns. The atmospheric dust slowly covers the streaks and they turn grayer and disappear, until eventually there's enough dust for a fresh avalanche.

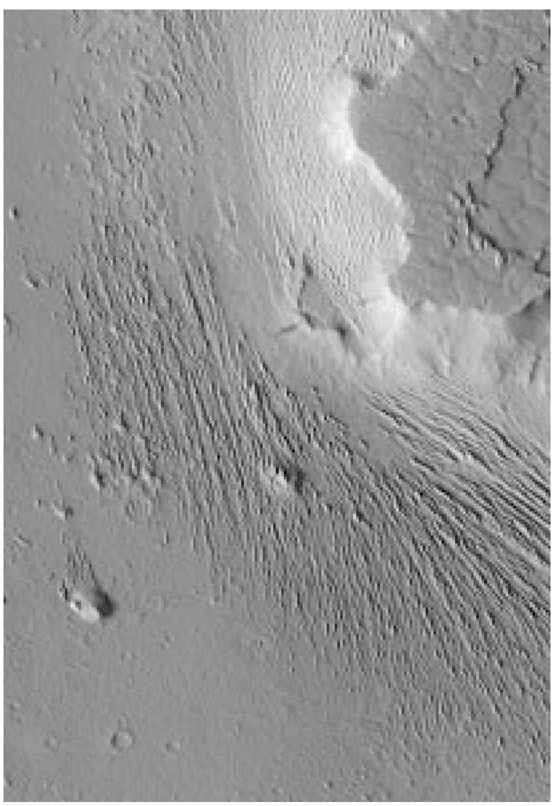
We also see dark, wandering tracks that look like seaweed on the seafloor. They're the tracks of huge dust devils, and they're just everywhere in the dune regions. In some cases, we can even see the dust devils' shadows, and because we know the angle of the sun we can measure their height. The one marked by the arrow is about 8 kilometers tall.

We've known since Mariner 9 that global dust storms also occur. The last truly big one was at the time of Viking, 20 years ago, but in June we got a whopper that formed in Hellas Basin in the south and then boiled up to the north. This is the first time we've been able to track such a storm from its birth to try to understand exactly how it begins. We don't know what the triggering mechanism is. On Earth, it takes a stronger wind to pick up dust than sand, so you start the sand blowing first and it kicks up the dust. Whether that's true on Mars, we don't quite know. It may be that there are electrostatic forces involved, so that the wind itself can lift the dust. The global storms occur only during the particular times of the year when we get violent winds—and not every year. Part of the reason we do global climate modeling is to try to understand what triggers the violent winds. Is it certain times of day? Larger than normal seasonal effects? Or is it something else? TES can measure the atmosphere's opacity, giving us detailed data on the actual amount and distribution of dust. This has shown us that although the dust storms are global events—producing planet-enveloping dust clouds—the storms themselves remain localized. Throughout the storm, the dust that fed the global plume was only being kicked up in a few isolated regions.



Above: Global TES maps of the great dust storm of 2001. Opacity ranges from clear (blue) sky to you-can-barely-see-the-sun (red).

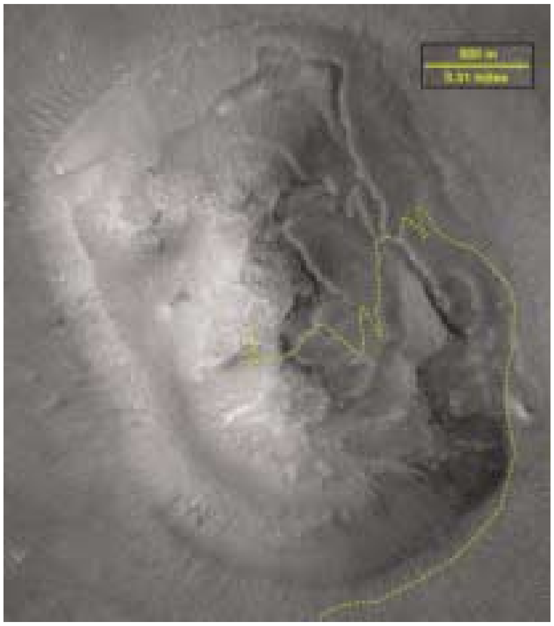
Below: Yardangs, a kind of wind-carved ridge, are particularly prominent in the Medusae Fossae, a region of easily erodable layered rock near the Amazonis Planitia. This image is about five kilometers from top to bottom.



We know that roughly half of Mars has lots of dust coating everything. We measure the albedo, which is the surface's brightness, and the nighttime surface temperature, which tells us how fast it cools off, and we calculate a property called the thermal inertia. The finer a material is, the faster it loses heat at night—if you go to the beach after dark, the big slabs of cement in the sidewalk will be warm underfoot long after the sand has turned cold. Thus, low thermal inertia indicates regions with a lot of dust. The dust varies in thickness. When you look at relatively recent features you see a rough but muted surface, as if a blanket of snow has fallen. But some craters in the layered regions are filled to overflowing with heavily compacted dust layers many kilometers thick, although some people think it's silt from little lakes that once stood in the craters. (We might find out for sure soon, as some of these filled-in craters are prime landing sites for the '03 mission.) Even in the cleaner areas, the dust obscures everything to a degree we hadn't anticipated. This has implications for choosing landing sites for future robotic, and eventually human, missions. All that dust means that even at a scale of 1.4 meters per pixel, our cameras can't really tell us what the surface looks like. It's difficult to interpret the terrain.

I find it fascinating to observe the results of wind carving. At left are "yardangs"—long, eroded features caused by blowing sand, in this case eating away a mesa whose top is protected by a more durable layer. Such features are very common. And below is a puzzle from Viking—a "white rock" that overlies a crater. Many people thought it was a soft gypsum (calcium sulfate) deposit, but it turns out again to be a fine-layered, fine-grained material—remember, we've found no sulfates of any sort. It was deposited on an old surface that had craters on it. The deposit was then dissected away by erosion, and finally the dark dunes filled in the resulting valleys. So you have an entire geological history in one photograph. Mars has a complex history, and even with 100,000 high-resolution photos, we are nowhere near understanding it fully.

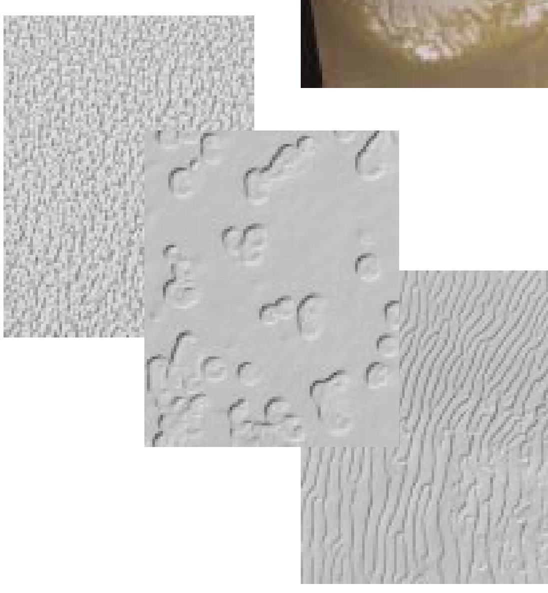
Erosion also left its mark on Cydonia Planitia, where Viking took that famous image of the Face. MGS's first look at the Face had the sun in the opposite direction from the Viking shot, so we made a negative image to mimic Viking's



The Face (41°N, 10°W) is actually a steep-flanked butte or mesa, like those seen throughout the American West, surrounded by an apron of boulders. Climbing it would make a nice outing, and NASA's Jim Garvin has already prepared the trail guide. The hike is approximately 5.5 kilometers or 3.6 miles one way, with a total elevation gain of nearly a thousand feet. It is rated easy at start and midsection, with some very steep sections in between. The time to the summit is about two hours; take plenty of water and oxygen. Begin by skirting the scree slopes at the base to the middle of the east side, where there is a breach in the battlements. Climbing through here leads to a smooth traverse that becomes a circuitous path to the summit, where there is a flat, circular patch about 100 meters in diameter from which to enjoy the breathtaking views. Regrettably, there are no picnic facilities or rest rooms.

lighting conditions. Then just this year we revisited the site, rolling the spacecraft 25 degrees to target the Face squarely. At 1.56 meters per pixel, this is our best view of the area. In fact, it's so good that Jim Garvin, chief scientist for NASA's Mars Exploration Program, has published a trail guide on how to climb it. We've also made a topographic map of it with MOLA data.

Number eight on my Top Ten is the polar caps. MOLA measured their thicknesses precisely enough to give a reliable estimate of their water volumes, and even track the thicknesses of their seasonal accumulations. (One-third of Mars's atmosphere freezes out and snows onto the poles each winter.) We've traced their seasonal changes over a full Martian year—TES mapped in detail how the caps retreated and advanced with the seasons, and, of course, MOC took pictures. Each pole changes from year to year, as you can see from these two photos of the residual north cap—the part that doesn't evaporate in the spring—taken a Martian year apart. And the two poles are quite unlike each other, so how they managed to evolve differently is a puzzle. The north residual cap has a cottage-cheese texture; the south residual cap has, in many places, a Swiss-cheese texture, and in other places a fingerprint texture. The residual cap on the North Pole is water ice, and the seasonal cap is carbon-dioxide ice. What's going on at the South Pole isn't quite as clear, but the residual cap seems to have, in addition to the water ice, some permanent CO_2 ice that might behave differently and explain those weird patterns. (CO_2 freezes into "dry ice," the stuff you use to make smoky punch bowls on Halloween.) And as this article goes to press, it's been found that the holes in the Swiss cheese are bigger this year, showing that CO_2 is being lost to the atmosphere, which may be growing thicker as a result. Whether this is a random variation or a long-term trend is a very good question.



Above: The residual north polar cap, seen here in two successive Martian summers, is about 1,100 kilometers across. Sand dunes form the surrounding ring of dark material. From left: The cottage cheese, Swiss cheese, and fingerprints are depressions ranging up to a few meters deep.

Number nine is channels and sapping, both of which are signs of liquid water. The channels are quite old, but the sapping, which I'll explain in a moment, might represent liquid water near the surface of Mars in the very recent past, and possibly even in the present day. Big, sinuous channels that look very much like they were carved by fluids were found by Mariner 9. However, on closer inspection, they lack the small central channel found in Earth's water-carved valleys and canyons down which the river actually runs. Instead, we see dunes down their centers. But MOC found a place where that central channel is still preserved.

Recently, we have seen features on cliff faces that

These gullies in Gorgonum Chaos (37°S, 170°W) were formed by water emanating, or sapping, from a prominent dark layer a few hundred meters below the top of the mesa. The close-up covers an area some six kilometers square. (The black-and-white image is from Viking, the synthetic-color images are from MGS.)

suggest sets of V-shaped gullies originating from a layer just beneath the top of the cliff. It looks as if the gullies are being cut by water emerging from that layer. This is called "sapping," and implies that there is subsurface ice that, under certain conditions, can melt and produce water. The gullies are quite widespread and found in many different environments. Unfortunately, there's no way yet to land a spacecraft in one of them, but it is certainly something we'd like to investigate. Another piece of evidence is the random pits at right. Somehow or other, material was removed from beneath the surface, which then collapsed. And we see polygonal patterns on the northern plains that look like what you find in Alaska or Siberia, which says that there's probably ground ice not far under the surface.

And, finally, number ten is atmospheric dynamics. In some ways, this may be the most important thing we've done. We've been in orbit for four Earth years, so we've acquired almost two Martian years' worth of data that we're now putting together to try to understand Mars, and, we hope, Earth. At right is an example. The top panel is a big storm front coming off the west coast of Africa. These storms move west, dumping dust on Bermuda and Florida, and then circle around and dump dust on London and Paris and Berlin. Below it is a similar front on Mars—a big, hook-shaped dust storm coming off the North Pole. Some of them are very dramatic—to their right are six hours' worth of one. And our daily planetwide weather photos show numerous water-ice cloud masses. (There really is a substantial amount of water in the atmosphere, but it's all in the form of ice crystals; we also find CO_2-ice clouds at the right time of year.) Because the water-ice clouds are at 0° C, TES can track their progress across the planet by their temperature. Twelve times a Martian day, TES gets a full set of temperature, pressure, and dust profiles of the atmosphere along our orbital track, and we interpolate between the tracks to make global maps.

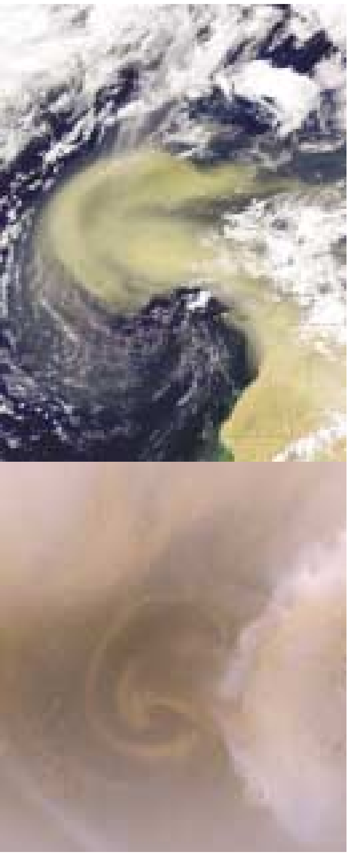
We can make movies of the images and TES maps to track the air masses and see how Mars's atmosphere operates over a long period of time, just as we're trying to make sense of the weather on Earth. And just as for Earth, much of the work is done with massive computer programs in which you include all the physics and topography you can, and then look at how points in the atmosphere move, and follow their temperatures and pressures. This gives you a forecast that you compare to the actual weather you observed, and then you go back and modify your model as needed.

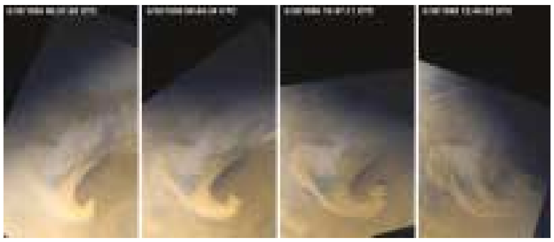
Assistant Professor of Planetary Sciences Mark Richardson used a global climatic model running on a cluster of computers to look at the motion of the air masses. The model starts with nice, even bands of color that act as tracers, and as it runs, the red gradually disperses into hook-shaped clouds like we saw on Mars.

What of the future? On October 23, Mars Odyssey went into orbit around Mars. It is now aerobraking, just as MGS did, but for various mission reasons it really needs to finish in three months, so it is being braked very aggressively. We are helping to protect it by keeping an eye out for dust storms. It's pretty quiet on Mars now, but a big dust storm would cause the atmosphere to heat and expand. If Mars Odyssey dips too deeply into the rising atmosphere, it could be seriously damaged by overheating.

In early 2004, JPL's twin Mars Exploration Rover (MER) landers and the European Space Agency's Beagle lander will go to sites our data helped to select, and we will be monitoring the bulk of their descent and landing maneuvers. Once they have touched down safely, these landers will use MGS's Mars Relay Antenna, provided by CNES, the French space agency, to send some of their data back to Earth. We will also continue to acquire scientific data of our own. Once we are done supporting these new missions (the landers' nominal lifetime is 60 days, but of course we're all hoping they'll last a lot longer then that), we'll tilt the spacecraft 16 degrees into a gravitationally stable attitude that should enable us to continue to use all the surviving instruments through 2004.

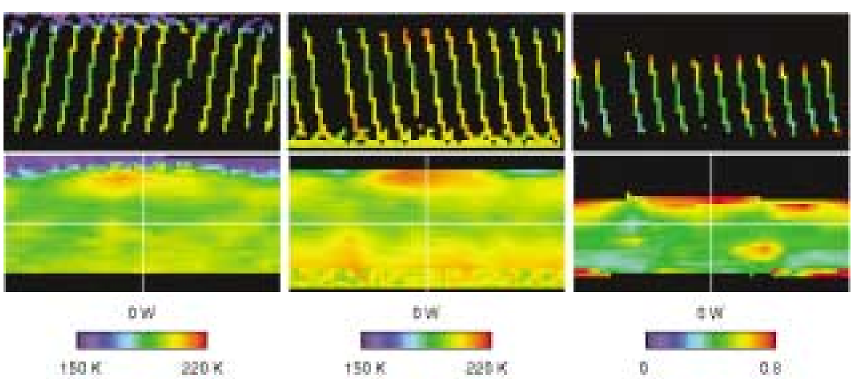
In conclusion, Mars Global Surveyor has collected more information about the Red Planet than all previous missions combined, and its discoveries show Mars to be a very different planet from what was believed at launch. The mission is an incredible success, whether measured in dollars per data bit (0.00007 cents per bit), by number of papers published (hundreds, and people are just getting started looking at the data), or by the number of times we've appeared on the cover of the journal *Science* (six, at last count). □





Left: A Saharan dust storm (top) extends 1,800 kilometers out to sea in a SeaWiFS image from February 2000; this spring dust storm on Mars (bottom) extends about 900 kilometers from the north seasonal cap. Both images are at a scale of 4 kilometers per pixel.

Above: This summer storm whipped up fast and furious, and lasted well into the next day. The white clouds are water ice; the yellow to brown clouds are full of dust.



Above: A day's worth of some TES data, from the actual orbital strips to the global maps. Shown here are the average nighttime temperature, daytime temperature, and dust opacity for September 17, 2001.

Professor of Geology and Planetary Science Arden Albee got all his degrees in geology from Harvard in the '50s and came to Caltech in 1959. He served as JPL's Chief Scientist from 1978 to 1984, and Caltech's Dean of Graduate Studies from 1984 to 2000. During his spare time, he has been Project Scientist for the Mars Observer and the Mars Global Surveyor. The Mars Global Surveyor was built by Lockheed-Martin and is managed by JPL for NASA. The MGS team, the fruit of whose hard work is described here, includes people in science, government, and industry from all over the world.

This article is based on a Watson lecture given on October 9, 2001.