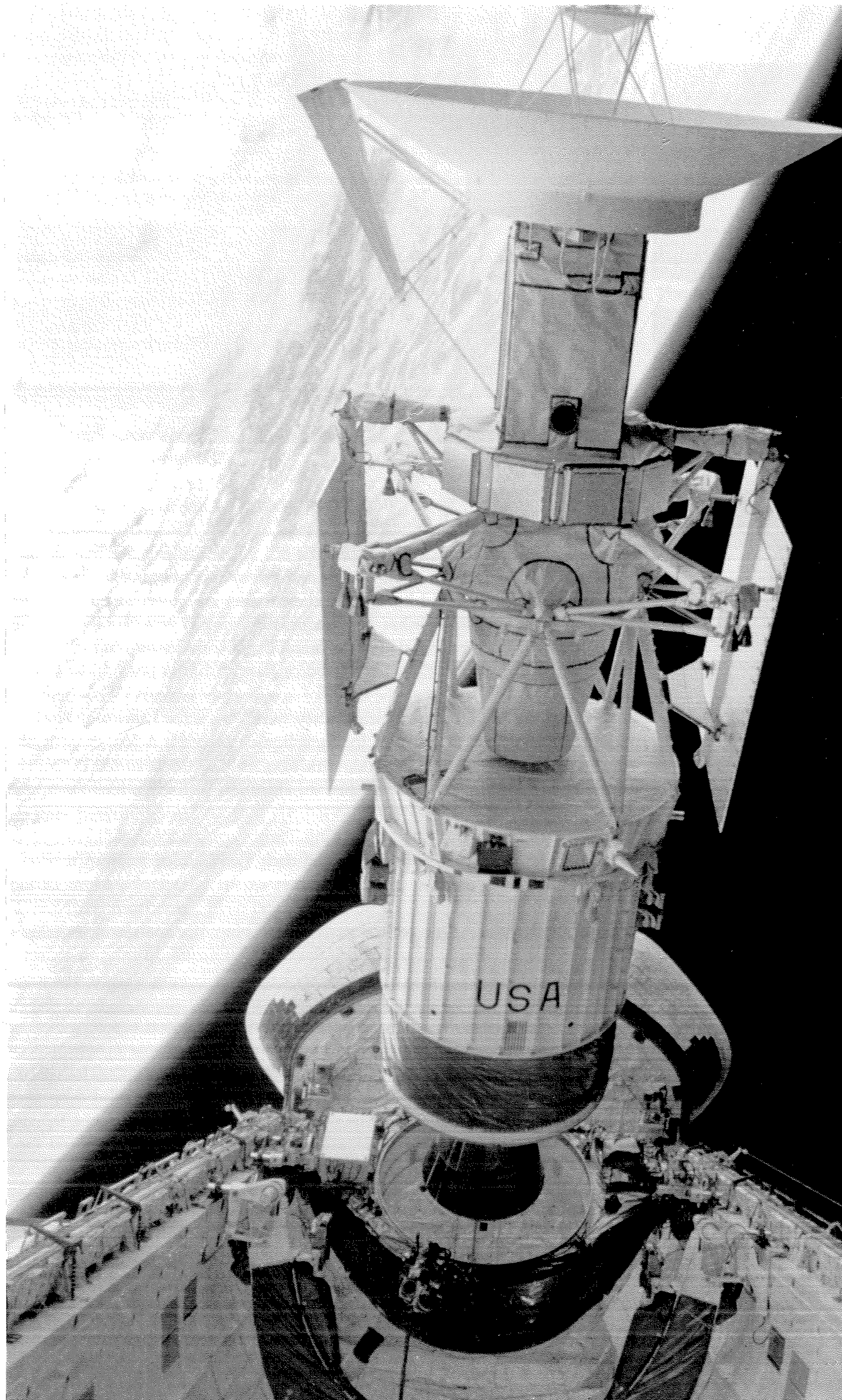

USA

Magellan: The Geologic Exploration of Venus

It's been a fantastic voyage, indeed. It's fun to go in every morning, and see new and exciting terrain that no person has ever seen before.

by Steve Saunders

Magellan just before deployment from the Space Shuttle's cargo bay. The bottom third of the spacecraft is a solid-fuel rocket that was jettisoned after boosting the mapper onto the path to Venus. The cone next to the main antenna dish is the radar altimeter. The solar panels that provide electric power are folded flat against the spacecraft's midsection, perpendicular to the camera. Magellan was built by the Martin Marietta Astronautics Group in Denver, Colorado, and the radar was built by the Hughes Aircraft Company of El Segundo, California.

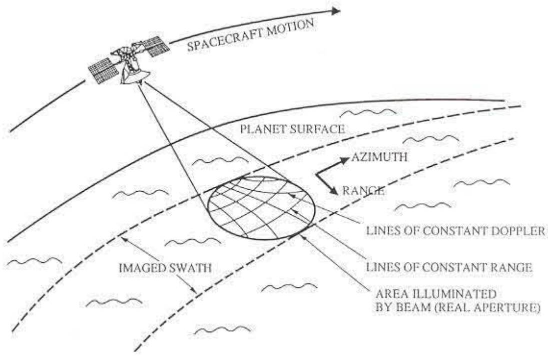
Venus is practically Earth's twin: very nearly Earth's size, just about the same density, and formed at about the same place and time. The two planets should have had a very similar early history, similar internal structure and elemental composition, and similar amounts of interior heat to create volcanoes and build mountains.

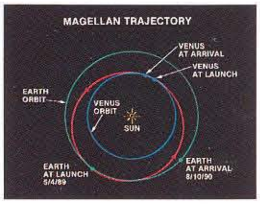
But Venus ended up very different from Earth. At the planetary surface, Venus's atmosphere is nearly 100 times as dense as Earth's, and the temperature of the rocks is nearly 900 degrees Fahrenheit—hot enough to melt lead. The difference is that Venus's atmosphere is about 97 percent carbon dioxide, versus 0.03 percent on Earth. Carbon dioxide traps heat so efficiently that Venus retains much of the heat it receives from the sun. (This "greenhouse effect," on a much reduced scale, keeps Earth warm enough to sustain life.) Venus's carbon dioxide came from its volcanoes. A similar amount has been emitted by Earth's volcanoes, but has been converted into carbonate rocks such as limestone and dolomite. Atmospheric carbon dioxide dissolves into Earth's oceans, where it combines with the eroded mineral products such as calcium that rainfall and rivers have washed out to sea, forming carbonates. The carbonates eventually turn into rocks, locking carbon dioxide into Earth's crust. So, even now, Earth and Venus really aren't as different as they seem. Venus should tell us quite a lot about how our theories of Earth's history might apply to planets in general.

Space scientists need to be very patient people. Magellan was originally approved in one form by the Carter administration in 1980. It was canceled by the Reagan administration about a year later, reinstated in a stripped-down form the year after that, and is now flying under the Bush administration.

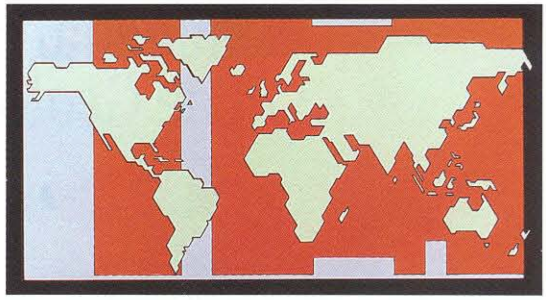
That patience has paid off. As of April 3, 1991, Magellan has achieved the minimum goals for its primary mission—mapping 70 percent of Venus's surface, an area that would stretch from Pasadena eastward to the Bering Straits on Earth. (This took 193 days of mapping, plus a 15-day shutdown during "superior conjunction," when Earth, the sun, and Venus were all in a direct line and data could not be transmitted or received.) The primary mission was a minimum performance goal—we expect to do much more during the extended mission. Magellan has already returned over 100 billion bytes of information, which equals the total amount of data from all other planetary missions to date, including the 12-year Voyager mission. It's been a fantastic voyage, indeed. It's fun to go in every morning, and see new and exciting terrain that no person has ever seen before.

We launched Magellan from Cape Canaveral on May 4, 1989, on board the shuttle *Atlantis*. We took a rather long route to Venus, going around the sun one and one-half times. (We deferred our launch in order to give Galileo the shortest path to Venus for one of the gravity assists that will send that spacecraft on to Jupiter. Otherwise Galileo would have had to wait another two and a half years before the planets got into the right positions again.) Magellan arrived at Venus on August 10, 1990. We got everything working after a few minor problems,

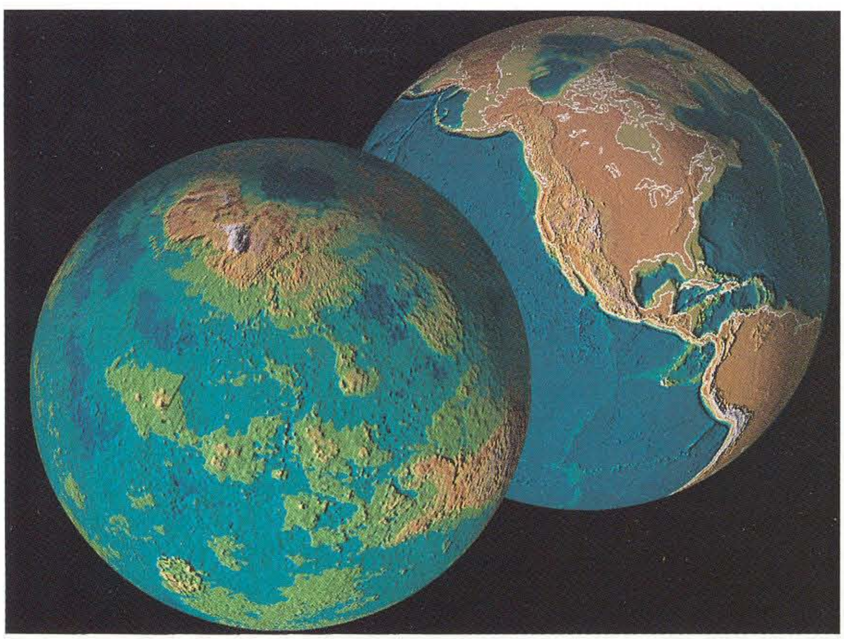




Left: Magellan's trajectory to Venus took 1¼ years—long enough for Venus to orbit the sun twice, while Magellan circled the sun 1½ times. Above: Magellan's mapping radar looks off to the side, collecting image data in two dimensions.



If Magellan had been mapping Earth starting from Pasadena, the territory covered during the primary mission would be enclosed by the orange regions. The strip running through Greenland was missed during superior conjunction.

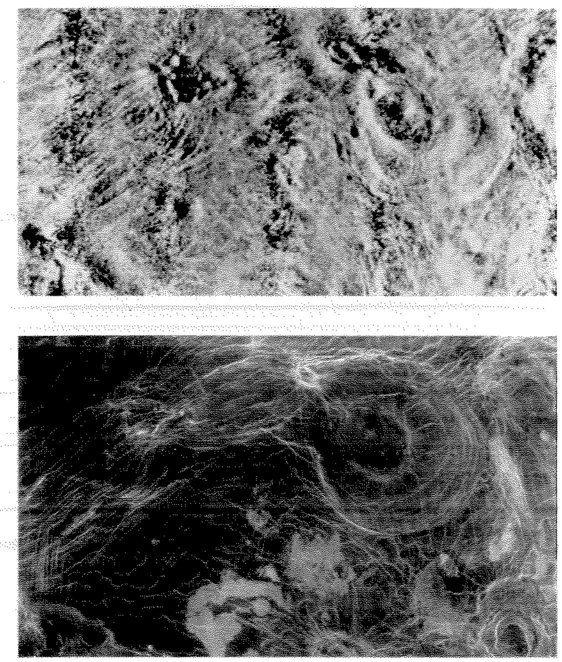


Venus is 95 percent of Earth's size.

and started mapping around September 15. Venus's surface is completely hidden behind thick clouds of sulfuric acid, so we do our mapping by radar, not photography.

Magellan's main antenna, used both for mapping and communicating with Earth, is a leftover Voyager antenna that Ed Stone was kind enough to bequeath to us. (Many components were scavenged from other missions to keep costs down.) Using the one antenna for two functions takes a lot of fancy maneuvering. Magellan's orbit is egg-shaped, with Venus as the yolk. The orbit passes over Venus's poles, while the planet turns below. (Venus rotates slowly, so its day is 243 Earth days.) Every time we go in close around the planet—every three and a quarter hours—we point the antenna at the surface and take a strip of data, slightly overlapping the previous strip, from the north pole down to about 70 degrees south latitude. Then, as we go out to apoapsis—the point in the orbit farthest from the surface—we turn the antenna toward Earth and play back the data. Magellan has a second, smaller antenna on board that serves as an altimeter, recording elevation data as we map. The two radars don't look at the same patch of ground, but we correlate their data later at JPL.

The mapping radar, called a synthetic-aperture radar, uses a very precisely tuned 12.5-centimeter-wavelength radio signal to penetrate the clouds. The signal bounces off the planet's surface, and the time it takes to return to the spacecraft is recorded. The radar looks off to the side, so the signal reflected by the features closest to the spacecraft's flight path comes back first.



Venera image (top) and Magellan image (bottom) of an arachnoid region located on radar-dark plains at 40° north latitude and 18° east longitude. Note the radar-bright lava flows at the bottom of the Magellan image. The flows are crossed by fractures, which must therefore be more recent than the flows. The two large arachnoids in the top half of each image are about 140 miles in diameter. Arachnoids are found only on Venus.

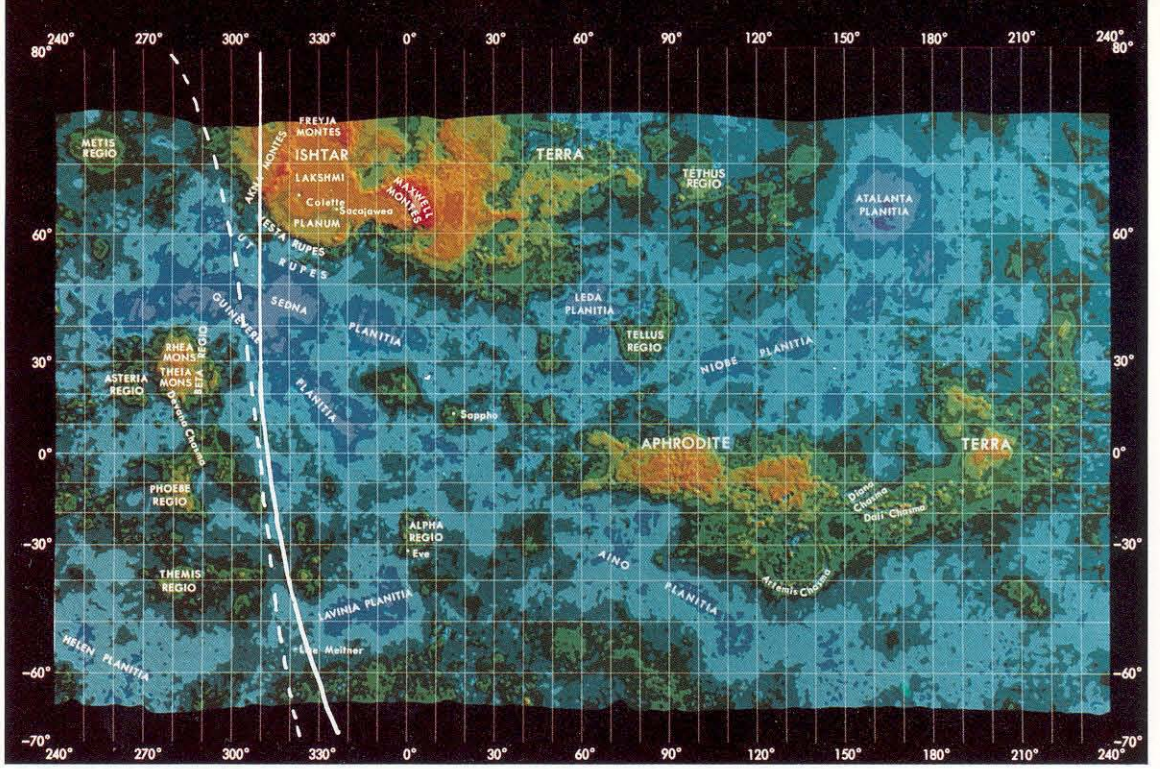
Magellan's 75-meter resolution can make out objects the size of the Rose Bowl.

Simultaneously, features ahead of us—moving toward us along the spacecraft's track—increase the reflected frequency due to the Doppler effect, and features behind us shift the reflection to a lower frequency. We actually see a whole swath of terrain with each radar pulse, because the time delays and the Doppler shifts give us information in two dimensions. We end up with an image that looks pretty much like an aerial photograph, except that the value of each pixel in the image is the ratio, in decibels, of the amount of energy returned from the surface at that location versus the amount of energy we sent. Magellan sends the time-delay and Doppler-shift data back to Earth after an on-board computer, called a block-adaptive quantizer, samples every eight-bit unit and condenses it to two bits. This computer allows us to collect and send a lot more data.

We do all of the image construction here at JPL. We make a wide variety of photo products from the digital data. The basic image strip—one orbit's worth of data—is 12 miles wide by roughly 9,000 miles long. From these, we make a standard series of mosaics. Each mosaic is 7,000 by 8,000 pixels. The first mosaic covers an area of Venus roughly 5 degrees on a side. It's a full-resolution mosaic, so each pixel covers 75 meters, about 82 yards. To make the next size up, we average each 3-by-3 pixel region to make a 225-meter (246-yard) pixel, and produce pictures that cover pieces of Venus 15 degrees square. And so on, up to 2.025-kilometer (1¼-mile) pixels. Six mosaics of pixels that size cover the whole planet. So you can start with the whole planet and then zoom in on the region you wish to study.

There are subtle differences between these images and aerial photographs. The radar illuminates the scene from the left-hand side, so slopes facing toward the radar appear brighter, and slopes facing away are darker. It's as if you were shining a light on the landscape from the left. What you see also depends on the angle of illumination, because many surfaces reflect differently at different angles. Radar also reflects a lot more readily if the surface is rough on the scale of the radar's wavelength, which in this case is a few centimeters to a few meters—terrain covered with small stones up to good-sized boulders. Terrain containing electrically conductive minerals, like iron sulfides such as pyrite or iron oxides such as magnetite, is also very reflective.

In 1984, the Soviet missions Venera 15 and 16 mapped about 25 percent of Venus's northern hemisphere with a resolution of about a mile. Magellan's 75-meter resolution can make out objects the size of the Rose Bowl. Above are Magellan and Venera images of one of the regions we call the arachnoids, because they look like spider bodies connected by weblike fractures. They're actually volcanic features, probably caused by a small "hot spot"—a place where a plume of hot mantle material has made its way up to the surface. We could barely see the bodies in the Soviet data, but the Magellan image even shows details of the web. Magellan was looking sideways at about 35 degrees, and Venera at about 10 degrees. Consequently, a lava flow that's clearly outlined in the Magellan image can't be seen in the other one.



This map of Venus is based on decade-old data from the Pioneer Venus orbiter, which mapped 80 percent of the surface at a resolution of about 30 miles. Elevation data is color-coded, from purple and cool blue lowland plains on up to yellow and red in the mountains. The solid line represents the swath mapped in one orbit, while the dashed line shows what the altimeter sees during that same orbit. The altimeter looks straight down from the spacecraft, so the dashed line shows Magellan's track as well. Magellan began mapping at Venusian longitude 330°. Venus is the only planet in the solar system that rotates from east to west, and Venusian longitude is consequently measured toward the east.

In addition to standardizing descriptive names, the International Astronomical Union has specified the type of being to be associated with each class of Venusian feature. The singular and plural forms of some common features, and their associated females, are:

chasma, chasmata—canyon: goddesses of the hunt or the moon

corona, coronae—ovoid-shaped feature: fertility goddesses

crater, craters (cratera)—crater: famous women

dorsum, dorsa—ridge: sky goddesses

linea, lineae—elongate marking: goddesses of war

mons, montes—mountain: miscellaneous goddesses

patera, paterae—shallow crater with scalloped, complex edge: famous women

planitia, planitiae—low plain: mythological heroines

planum, plana—plateau or high plain: goddesses of prosperity

regio, regiones—region: giantesses and titanesses

rupes, rupēs—scarp: goddesses of hearth and home

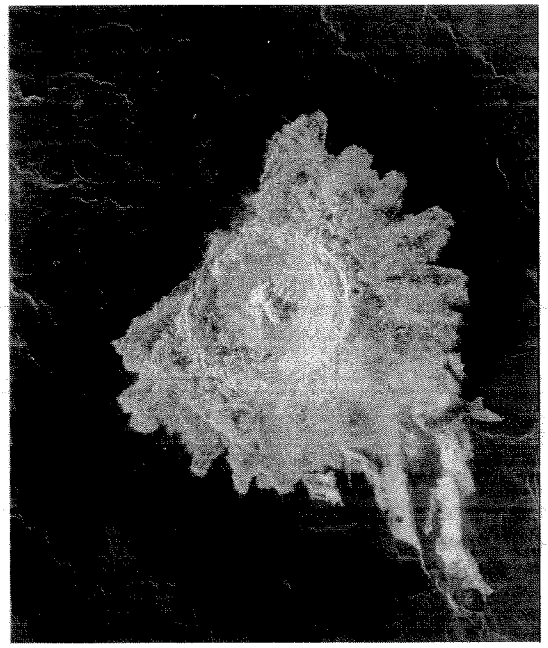
terra, terrae—extensive land mass: goddesses of love

tessera, tesserae—polygonally patterned ground: goddesses of fate or fortune

Suggestions for feature names can be sent to: Venus Names, Magellan Project Office, Mail Code 230-201, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109.

Having mapped features, we name them too. One would expect strange-sounding names on an exotic planet like Venus, but our system is really quite straightforward. We use one set of descriptive names for geographic features on bodies throughout the solar system. (See box.) Each feature gets a particular name that identifies it, plus a descriptive name that says what it looks like. The term *tessera*, in particular, was applied to a number of terrains that looked alike in the low-resolution Venera data, but which are proving to be different at high resolution.

Venus is the Roman goddess of love, so we've chosen our particular names from the ranks of famous females. Most of the large features, terrae in particular, have been named for love goddesses from other cultures. I don't get too involved in this, but some scientists get a real kick out of it, and go to the library and dig out names to use. Most of these names are provisional, and won't become official until they're approved by the International Astronomical Union. That will take some time. The IAU meets in July to consider some of the names proposed up to that time, and then doesn't meet again until 1993. We're open to suggestions, particularly for crater names. We've mapped about 400 craters so far. I expect we'll end up with about 900. You can nominate someone by sending us a note with the name and why the person should be so honored. Nominees must be famous women who've been dead for at least three years. The one exception to the females-only rule is James Clerk Maxwell, whose 19th-century theories about electromagnetism made



Right: Aurelia (20° N, 332° E) is surrounded by a radar-dark halo, as are about half of the craters Magellan has seen to date. The crater floor and the ejecta are very radar-bright, indicating rough terrain. North is to the top in all Magellan images. Far Right: This image, centered at 27° S and 339° E, shows the crater Danilova, its southern neighbor Julia Ward Howe (the author and suffragette), and Aglaonice (an ancient Greek astronomer) to the east. All three craters' interiors are nearly completely flooded by smooth, radar-dark lava. (For comparison, Aurelia is slightly smaller than Howe.) Large flows of very fluid melt issue north from Aglaonice and south from Danilova. The small domes seen in the southeast corner of the image are found all over Venus's plains and number in the hundreds of thousands. A 10- × 12-foot copy of this image, called "The Crater Farm," hangs in the Smithsonian's Air and Space Museum.

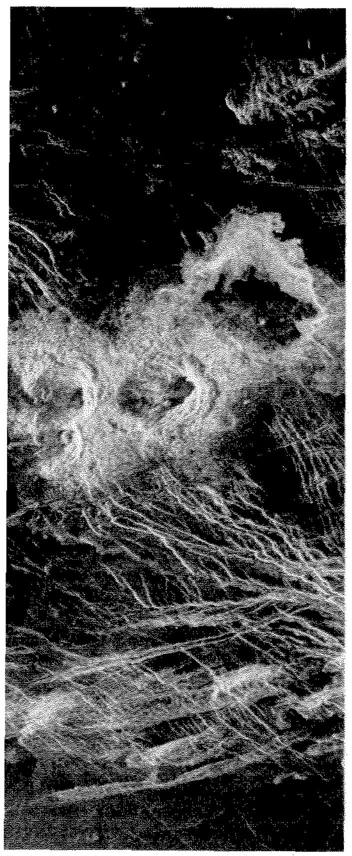
radar possible today. We've honored him with Maxwell Montes, the largest mountain on Venus. At about 36,000 feet, it's higher than Everest.

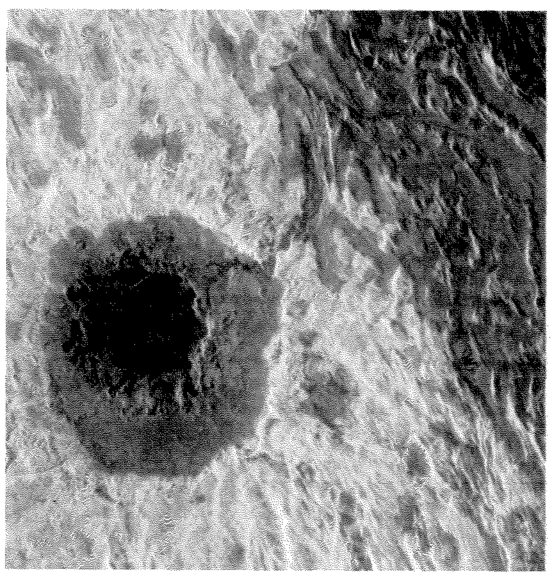
This article will take a quick look at three types of terrain. First, we'll look at impact craters, and see how their features vary with their size. Then we'll look at two highland regions: Ishtar Terra, which includes Maxwell Montes, and Aphrodite Terra. These highlands may help explain how Earth's continents formed. And finally, we'll look at a volcanic province. Throughout our tour, we will see how Venus's high surface temperature—and, to a lesser degree, its thick atmosphere—have affected the processes that shaped its surface.

Venus, like all the planets, has been subjected to meteorite bombardment over the eons—by the rubble of planetary formation, by asteroids jarred loose from the asteroid belt, and by comets. Impactors hit Venus at something like 12 miles per second, and they release a tremendous amount of energy. The impact vaporizes the object and the surrounding crust, blasting out material—ejecta—at very high velocities in all directions, and forming a "transient cavity crater"—a bubble in the crust. The bubble bursts instantaneously, throwing out more ejecta at lower velocities, and folding the adjacent crust's upper layers back over on top of themselves to form the crater's rim. The rim's inner face is very steep and partially collapses under its own weight, forming terraces. Meanwhile, the crater floor rebounds, throwing up the central peak. Impacts can cause volcanism in two ways. The collision creates heat directly. Forming the transient cavity also causes adiabatic heating, by suddenly releasing the pressure on rock that's been at very high pressure miles below the surface. It's like taking the top off a beer bottle. The material expands, releasing heat, and it's pretty hot to start with.

Aurelia (named after Julius Caesar's mother) is a beautiful, 20-mile-diameter crater. It has the central peak, the basin with a rim crest, and a flower-petal-like ejecta pattern around it. The flower-petal pattern is seen only on Venusian craters. It's caused by Venus's atmosphere, which is so thick that ejecta doesn't travel very far. On other bodies, like the moon, ejecta can travel for hundreds of miles. Aurelia also has a little kite tail of what is probably impact melt—rock melted by the heat of the impact—that flowed out into the surrounding plains. We see that in many areas. There are also exterior flows of impact-induced melt from within or beneath the ejecta that look somewhat like lava flows. When the ejecta lands, part of it apparently keeps flowing, probably because the surface is hot enough to keep it liquid. These flows are another feature we see only on Venus. Some craters this size have had their floors at least partially flooded by impact melt, or perhaps later volcanism. Danilova (named for a Russian ballerina) is somewhat larger, about 30 miles in diameter. The central peak has become more complex, and the floor is almost completely flooded. Danilova also has a large lobe of what was probably an extremely low-viscosity melt that behaved very fluidly, flowing around little prominences in its path like a brook flowing

Clockwise from left:
1. Gertrude Stein (30° S, 345° E) is three craters, each 5½ to 8½ miles in diameter, formed by chunks of an object that broke up in the atmosphere. The outflow is probably impact melt.
2. Cleopatra is about 1½ miles deep. The rough ejecta around its rim shows it is an impact crater. Lava breached the rim, flooding the valleys to the northeast.
3. Three dark splotches on a 180-mile span of Lakshmi Planum. One contains a small crater. The other two impactors didn't make it down. Dark streaks at left could be wind-blown splotch material drifting northeast against a ridge.





around rocks lying in its bed.

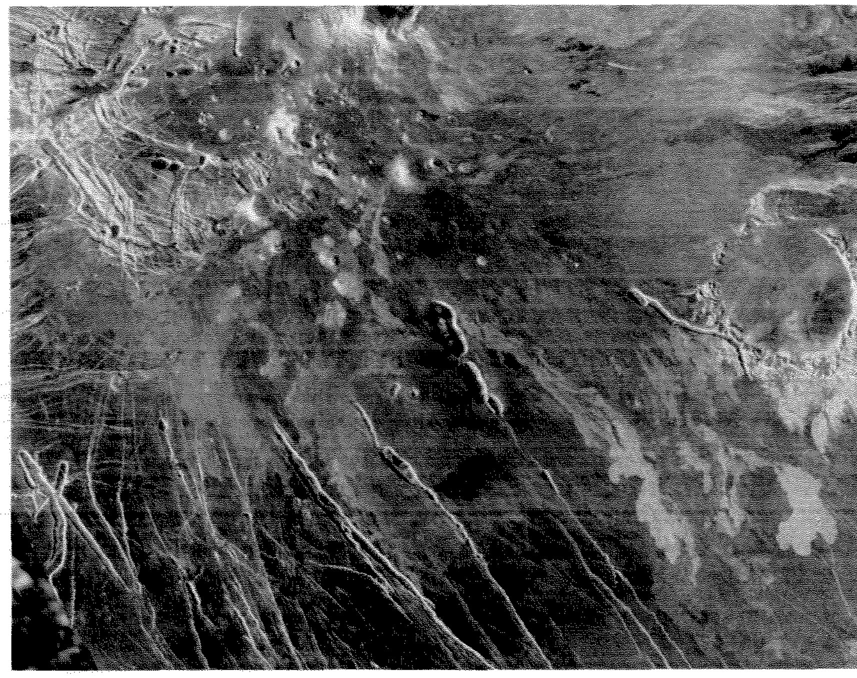
Cleopatra, on the flanks of Maxwell Montes, is a 62-mile-diameter crater surrounded by rugged ejecta. We couldn't tell from Venera data whether Cleopatra was a giant volcano or an impact crater, but it's now clear that it's the latter. Volcanism was either induced by the impact itself, or later volcanism seeped through the crustal fractures that the impact created. The crater's interior is filled with lava, some of which flowed out through a channel and filled in the nearby valleys. Cleopatra's double-ringed crater is typical of the enormous, multi-ringed impact basins that we see on many bodies in the solar system. We believe the rings are part of the surface's hydrodynamic response to an impactor many miles in diameter. The outer ring is roughly the square root of two times the diameter of the inner ring, which may be a relic of the transient cavity. The outer ring might be some kind of later collapse, or a product of the interference pattern between the very intense surface waves and body waves that the impact generates. It may also be the shock wave reflecting off another layer in the interior.

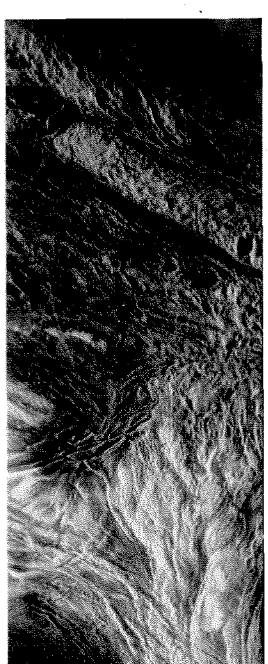
Impactors also interact with the atmosphere in some very curious ways. Objects less than about 100 yards in diameter don't make it all the way through Venus's dense atmosphere. They're pulverized, literally burned up, on the way down. Some make it almost to the surface, and may set up enormous supersonic shock waves and high winds. (Something similar happened over Siberia in the early part of this century. That object didn't hit the ground, but it laid a huge forest waste, flattening trees radially outward for miles in all directions.) We see dark splotches all over Venus. Some of them have a little crater in the middle. Dark lines trailing out radially from the splotches could be wind streaks. We interpret these splotches to be smooth areas, caused perhaps by the deposition of fine material, perhaps by pulverization of the surface by the shock wave that came along with the meteorite. These craters are never smaller than about a couple of miles in diameter. Impact craters can be quite a bit smaller on Earth, because its atmosphere is thinner and smaller objects reach the surface. Venus's atmosphere can break up friable objects half a mile or so in diameter, whose chunks then hit close together to form multiple craters.

In some places, we see what are almost certainly wind streaks where sand is being deposited or scoured away, causing the radar to read the surface texture differently. (Wind streaks are also visible in radar images of Earth.) These

Right: The crater Alcott (60° S, 352° E), 39 miles in diameter and originally about 1300 feet deep, has been almost completely obliterated by bright (rough) and dark (smooth) lava flows emanating from the collapse features at the left of the image. These collapse valleys range from 650 feet to 3 miles wide, and up to 60 miles long. They may have formed when subsurface magma drained away along crustal fractures, allowing the surface to collapse. The complex of intersecting valleys in the lower left-hand corner is informally called Gumby, after the animated character it resembles.

Below: A portion of the Freyja Montes, with the smooth, dark plains of Lakshmi to the south. Sinuous lava channels are visible in the dark zigzag valleys at the top of the image, indicating that these valleys are at least partially flooded by lava. This image is about 100 × 340 miles.



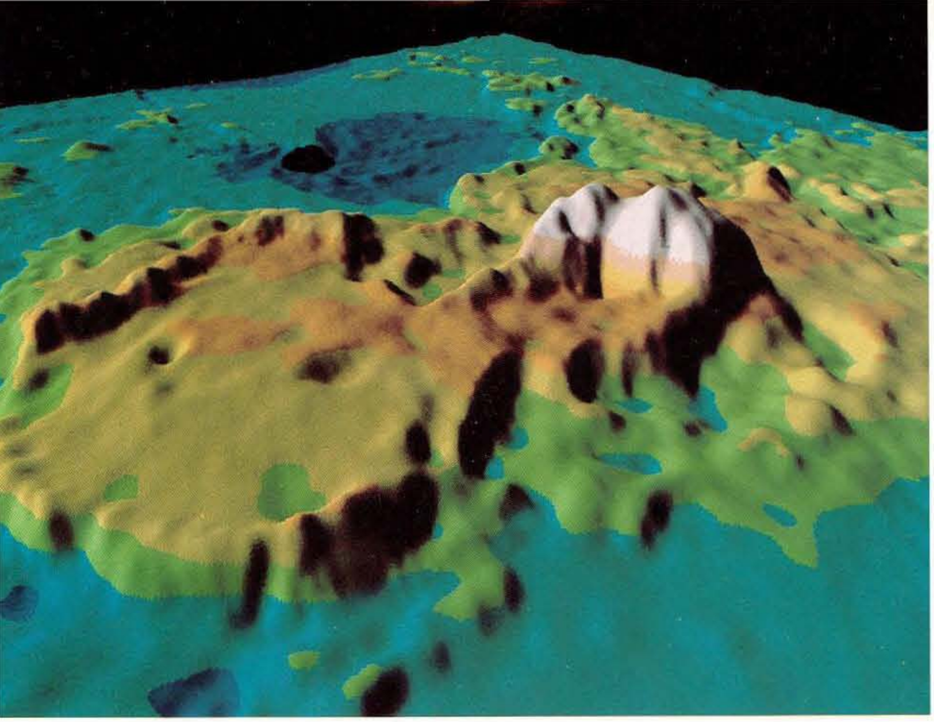


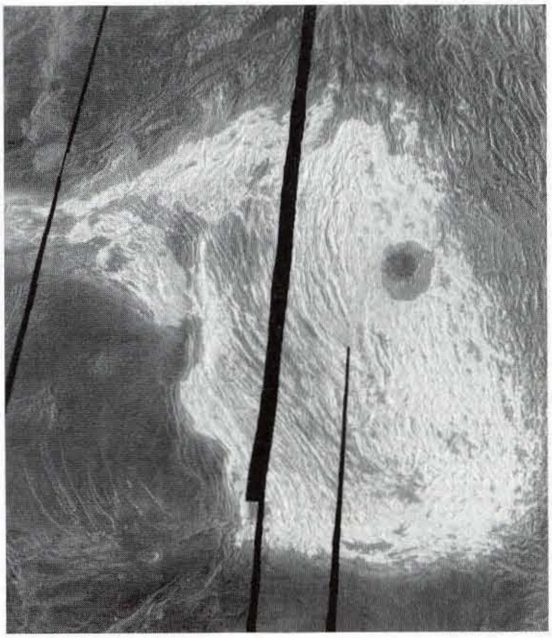
streaks will eventually give us a global map of the wind directions on Venus and hence the weather patterns. I had predicted that downslope winds should dominate, but these wind streaks go in the opposite direction. This may indicate a young, mobile surface, or old wind streaks. The surface winds aren't really very strong. At about 30 miles above the surface, the winds blow east to west at several hundred miles per hour, much faster than Earth's jet stream. But down at the surface, the atmosphere is so thick and sluggish that the wind is no faster than walking speed. This is just enough to move sand grains without giving them much erosive force. In fact, experiments in a Venus-simulation chamber at NASA's Ames Research Center show that the surface rocks are hot enough that windblown sand tends to stick to them. So the wind may be consolidating material rather than eroding it.

Speaking of erosion, when we look at Mars, or the moon, or especially Earth, we see craters of all ages, from ones that look like they formed yesterday, to old, beat-up ones that have practically disappeared. But all the craters on Venus look extremely young. We didn't see any evidence of crater degradation until we found Alcott (for Louisa May), which has been flooded by volcanic material and almost completely obliterated. Only some of the ejecta is still preserved. So it may be that every few hundred million years large regions of Venus get covered by enormous volcanic extrusions that simply erase everything, and the slate starts clean. Very little happens between those episodes of violent, extensive volcanism, except perhaps on the margins to craters that didn't get completely destroyed.

The first highland region we'll look at, Ishtar Terra, dominates Venus's northern hemisphere. (Ishtar is one of the names of the Babylonian universal goddess, the goddess of love—and, incidentally, the "Mother of Battles"—who was identified with the planet Venus.) Ishtar's western half is an elevated plain, the Lakshmi Planum, which stands about a mile above the average elevation of Venus, and is a very smooth highland. (Lakshmi is an Indian goddess of prosperity, a consort of Lord Krishna.) Lakshmi is surrounded on all sides by extremely steep mountains and scarps.

The Freyja Montes, which form Lakshmi's northern rim, are reminiscent of some large mountain ranges on Earth, with visible folds and fractures. (Freyja is the Nordic goddess of fertility and love, who weeps tears of gold as she seeks her lost husband.) I believe the zigzag valleys in the mountains' interior are pull-apart structures caused by gravity slumping. Crustal compression piles these mountains up to such a bulk that their own weight pulls them apart. This is fairly rare on Earth, but on Venus, the rocks are at about half their melting point and they tend to behave plastically. They bend and flow like taffy instead of breaking like peanut brittle. (We do see brittle deformation as well, fracturing that was probably accompanied by Venusquakes.) It's a real puzzle how Venus can have such large mountainous regions unless they're actively maintained. Some of what we see is doubtless very young. On the other hand,





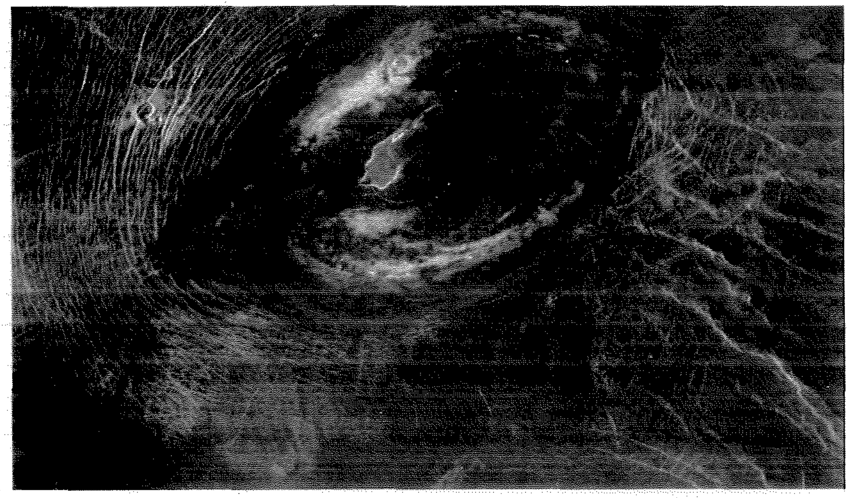
Above: A three-dimensional view of Ishtar Terra, looking northeast across Lakshmi Planum toward Maxwell Montes. The vertical scale is exaggerated. Sacajawea Patera is the rightmost depression on Lakshmi. The rugged highlands beyond Maxwell, called Fortuna Tessera, make up the eastern half of Ishtar. Right: Maxwell Montes. The black vertical bands are strips of missing data. Maxwell covers an area larger than Washington and Oregon, and stands almost 7 miles above the mean planetary radius. Maxwell's western slopes are very steep, while it descends gradually into the highlands of Fortuna Tessera on the east. The linear pull-apart features cover much of Maxwell's western half. Cleopatra is just to the right of center.

craters the size of Cleopatra don't form frequently, so the odds are good it isn't very young, yet it doesn't appear to be deformed.

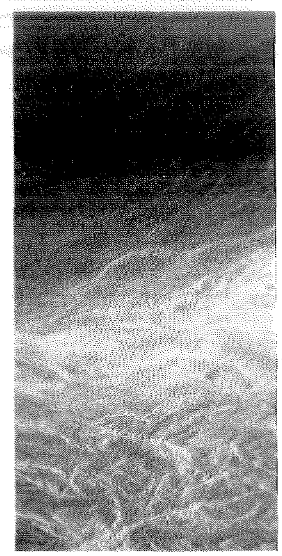
To the east, Maxwell Montes is very radar-bright. This may be a mineralogical phenomenon. As altitude increases, temperature and pressure decrease. It may be that a particular mineral assemblage is stable on the mountaintops, but not at the higher temperatures and pressures below. It could be a mineral like pyrite, magnetite, or pyrrhotite—a more complex iron sulfide than pyrite—any of which would be very radar-reflective. Maxwell's margins are steeper than the San Gabriel Mountains north of Pasadena. In places the terrain rises about a mile in a span of less than four miles. Maxwell's flanks also display linear features we think are caused by gravity tectonics. They look very much like what you see if you try stretching an old, dried-out piece of chewing gum.

Lakshmi's southern mountain belt is called the Danu Montes. (Danu was the great goddess of ancient Ireland, ruler of a tribe of ancient divinities who were later demoted to fairies.) Again, the highest regions of these mountains are more reflective than the plains. It looks as though Lakshmi's plains are somewhat folded where they abut the mountains. The plains were formed by lava flows that lapped up against the mountains, so they must have been deformed by compression later on, as if they were carpet being pushed up against a wall.

There are two very large volcanoes on Lakshmi Planum. We've only mapped one so far, called Sacajawea Patera. Sacajawea (named for the Indian woman who guided the Lewis and Clark Expedition) is a caldera—a wide crater caused by a volcanic explosion or collapse—that's about 100 miles from side to side and a bit more than a mile deep. It's surrounded by fractures that form graben. Graben are troughs bounded by vertical faults—long, linear valleys whose floors have sunk, or whose sides have risen. The East African rift valleys are graben, and there are many good examples of graben in Arizona. Sacajawea's graben are concentric rings that record a complicated history of magma withdrawal from below, perhaps accompanied by eruptions on the flanks and the collapse of the central caldera. The result looks somewhat like a multi-ringed basin, but this is a slower process caused by removing support from below, rather than digging a hole from above. Sacajawea resembles some volcanic features on Earth, but is much larger. It's very exciting for volcanologists because of its size, and we're seeing many others like it.



Above: Sacajawea Patera. The fractures that cut across the concentric graben run southeast for nearly 90 miles, and may be a rift zone through which magma drained. A small shield volcano with a prominent central pit sits on one fracture at right.
Upper Right: Smooth, dark Lakshmi Planum ripples against the radar-bright Danu Montes.
Lower Right: The Appalachian Mountains.
Below: Ovda's folded mountains are 5 to 9 miles wide and 20 to 40 miles long. They apparently formed by compression along a north–south axis. The dark plains are lava-filled basins. This image is centered at approximately 1° N, 81° E.



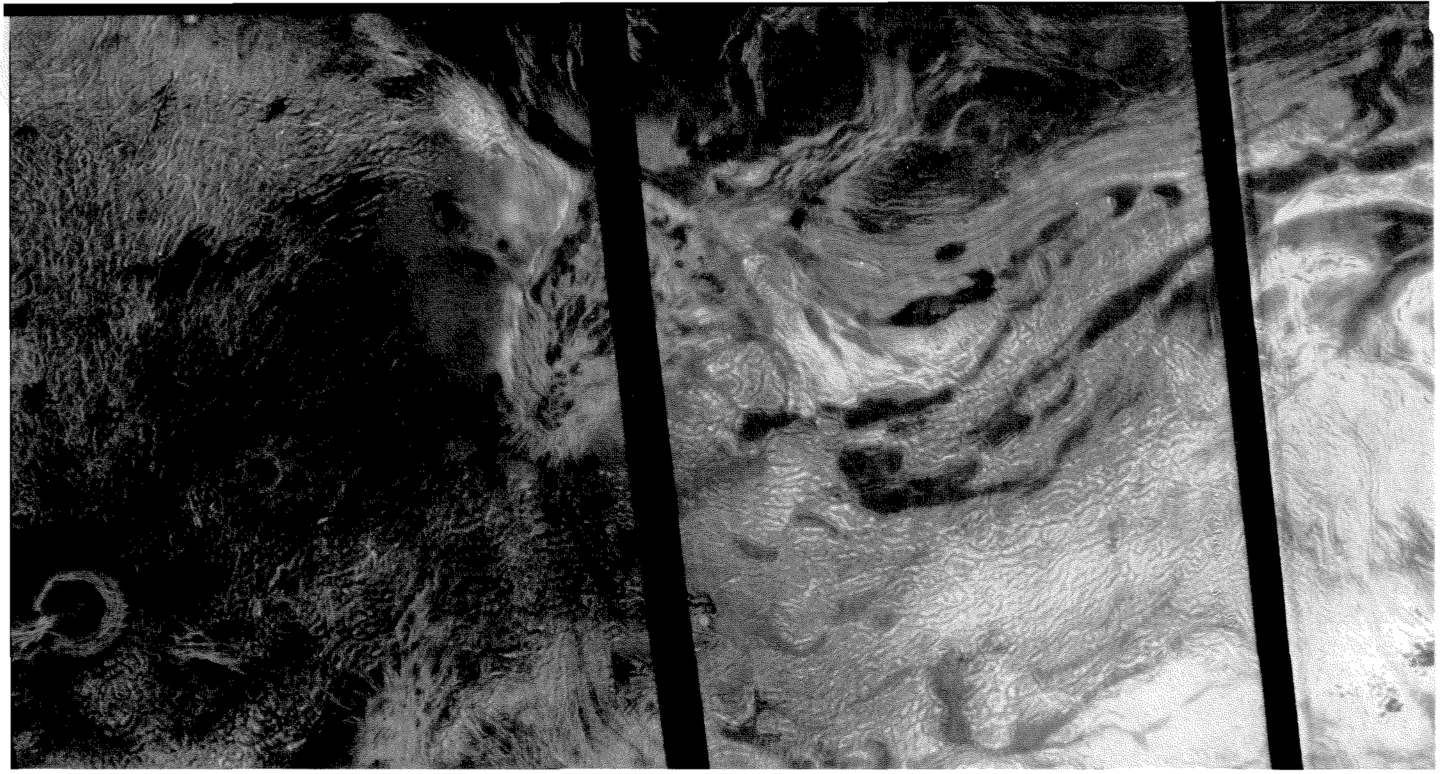
At one point, between the Danu Montes and Maxwell Montes, Lakshmi Planum isn't bounded by mountains. Instead, there's a scarp that just drops off into the plains. There's one feature about 50 miles across that looks a bit like a caldera but is probably a collapse scar. The unsupported margin simply slumped into the valley below, accompanied by fractures.

The second highland region, Aphrodite, extends about halfway around Venus's equator. Aphrodite is shaped a little bit like a scorpion, with claws, a body, legs, and a tail—a string of small volcanoes—that arches back toward the body like a scorpion's stinger. The claws, and the region inside them, may be a highly evolved Lakshmi—a volcanic plain surrounded by mountain belts. If we are seeing similar processes at different stages, it would tell us how these things evolve.

So far, we've mapped only the west end of Aphrodite, but we know already that, geophysically and geologically, it isn't one unit. It changes in its gravity signatures, its topographic signatures, and its geologic aspects. The western part of Aphrodite is called Ovda Regio for a violent, ill-tempered spirit of the Finnish forests who wandered her property naked, her long breasts thrown back over her shoulders, looking for trespassers to tickle to death. The terrain on Ovda's northern margins is very steep, just like the terrain surrounding Lakshmi Planum. The ground drops roughly two miles over a distance of some 50 miles. The plateau has pull-apart basins filled by lava flows.

If we compare Ovda's mountains with a radar image of the Appalachian Mountains, which are also folded, we see that they're superficially similar. In Pennsylvania, alternating beds of sandstones and shales lying deep within Earth have been folded by plastic deformation. Miles-deep erosion has etched away the soft shales, leaving nubbins of resistant sandstones as ridges. That simply hasn't happened on Venus, as we see very little evidence for erosion of any kind. These folds are the original surface of the compressed material, without any modification. So we get similar-looking folding patterns that were probably formed by similar processes, but are revealing themselves by quite different means.

Ovda's interior is tessera terrain. These particular tessera are mountainous massifs, or blocks of rock, that are tens or hundreds of miles on a side. The blocks are roughly equidimensional. The spaces between them are flooded by lavas. The region has clearly undergone a lot of compression, expansion, and folding. It's been there for a long, long time and has really been



This image encompasses most of Ovda Regio. The area shown is roughly 1200 × 600 miles, and spans nearly 30° of longitude. The lava-filled basin in the bottom half of the previous page's image is visible here just to the right of center. (It resembles a recumbent seahorse.) In the lower left corner, a large caldera shows against the background of smooth dark lava. Tessera—bright blocks of rock surrounded by dark lava—extend for hundreds of miles to the caldera's north and east. The bright highlands that resemble Maxwell Montes cover the right half of the image. The very highest elevations, where the terrain turns dark again, are at the edge of the image in the lower right corner. Each pixel in this image covers an area 2215 feet across, a 9× reduction from full resolution. The black bands are missing data.

kicked around quite a bit.

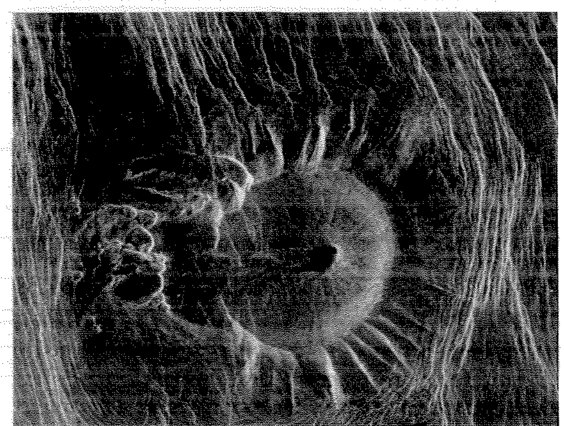
The highest parts of Ovda are similar to Maxwell in that the surface is very radar-bright, but its linear features—Maxwell's pull-aparts—are much more complex. This area has little chevron-like folds, instead of simple linear structures—a product of multiple deformations. Another interesting thing is that the lower region is dark, the middle elevations are bright, and then the very highest areas are dark again. So if we invoke some pressure- or temperature-dependent mineralogical process, it appears to form something that's stable only within a limited range. Other very high massifs in Ovda show this dark-bright-dark pattern, too.

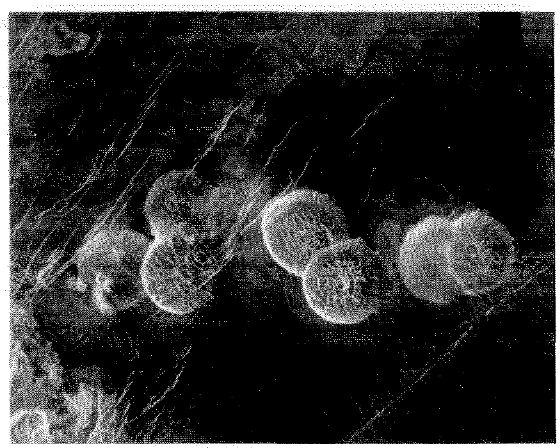
The origin of Venus's highlands is central to the whole idea of where Earth's continents came from and how the tectonics—the crust's motions—interact with what's going on in the interior. There are several models for Aphrodite's genesis. A simple one is that Aphrodite is a piece of ancient continental mass, composed of lighter, lower-density, higher-silica material, like the highlands of the moon. But this begs the question—it just says Aphrodite *is* there because it *was* there.

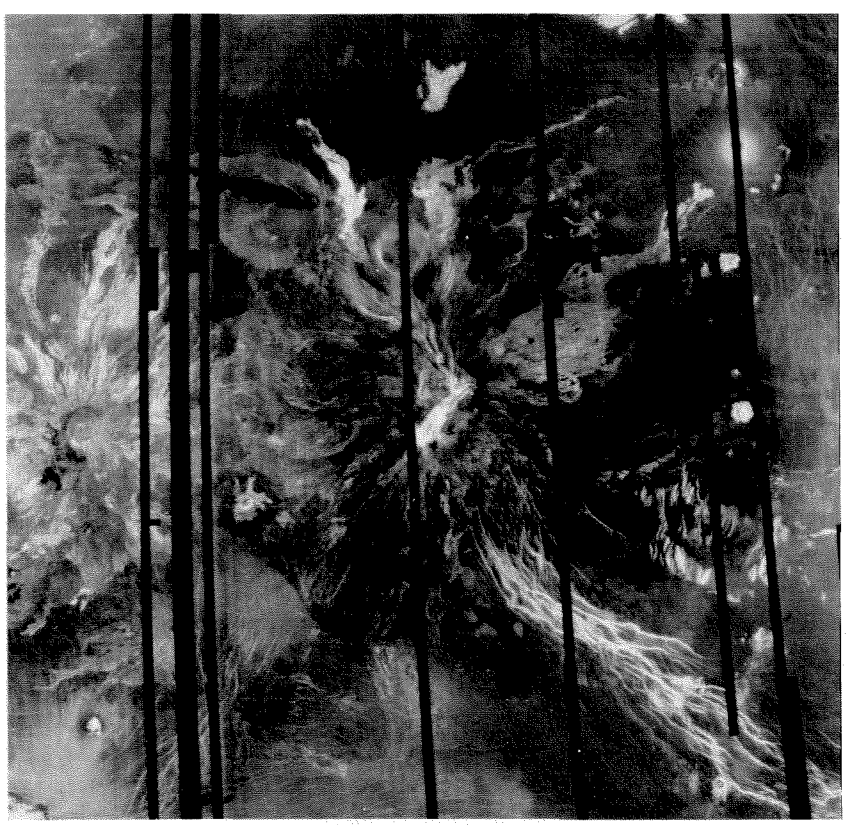
Another model says that Aphrodite was formed by a process like the seafloor spreading we see in the ocean basins on Earth. Earth's crust and mantle are closely linked, so convection cells in the mantle move pieces of crust like packages on a conveyer belt. New crust forms continuously along lines, called spreading centers, located atop rising sheets of hot mantle material. The fresh crust rides the mantle away from the spreading center. These centers are marked by mid-ocean ridges, which have a very characteristic shape: a main ridge or a trough along the center flanked by lesser, parallel ridges, and the entire ridge system crossed at right angles by parallel fractures marking transform faults along which segments of the central ridge are offset from each other. We can pretty much rule out this model now, because we don't see these features on Aphrodite. It doesn't look like the Mid-Atlantic Ridge, a relatively slow spreading center with a big rift valley down the middle; or the Pacific ridges, which are fairly fast and tend to have little ridges running down their spines.

Yet another model suggests that we're looking at a "hot spot"—a stationary mantle plume that has forced its way up to the surface. A large, long-lived hot spot could dome up a large area. The dome's own weight would cause it to push out sideways from the center, producing mountainous tectonic features on the margins through thrust faulting and crustal thickening. That's still a good possibility. But that model has an opposite twin, called downwelling. If this region of mantle is relatively cold, it would sink, drawing the crust above it in toward the center and thickening the crust into mountains. This could result in very similar surface features. One of these two models is probably the right one, but we haven't yet analyzed the detailed tectonic relationships that would allow us to distinguish between them. This part of Aphrodite is the size of the continental United States, so we're not going to be able to work out its geology in a few days.

Top: The tick (18° S, 5° E).
Middle: Pancake domes at 30° S, 12° E.
Below: This image of Sif (left) and Gula (right) Montes is centered at 22° N, 358° E. The mountains stand amid layer upon layer of bright and dark lava flows. Fractures run north-northwest from Gula to a low corona skirted by lava flows. The fracture zone running off to the southeast extends to Sappho. Several impact craters are visible, all with bright rings of ejecta, some with flooded floors and lava flows. One crater, southwest of Sif, is surrounded by a prominent dark splotch, while another crater north of Gula lies at the end of a dark streak hundreds of miles long. Dozens of small volcanic domes can be seen on the plains north of Sif, while the onset of tessera terrain is visible at the edge of the image north of Gula. Black bands are missing data.

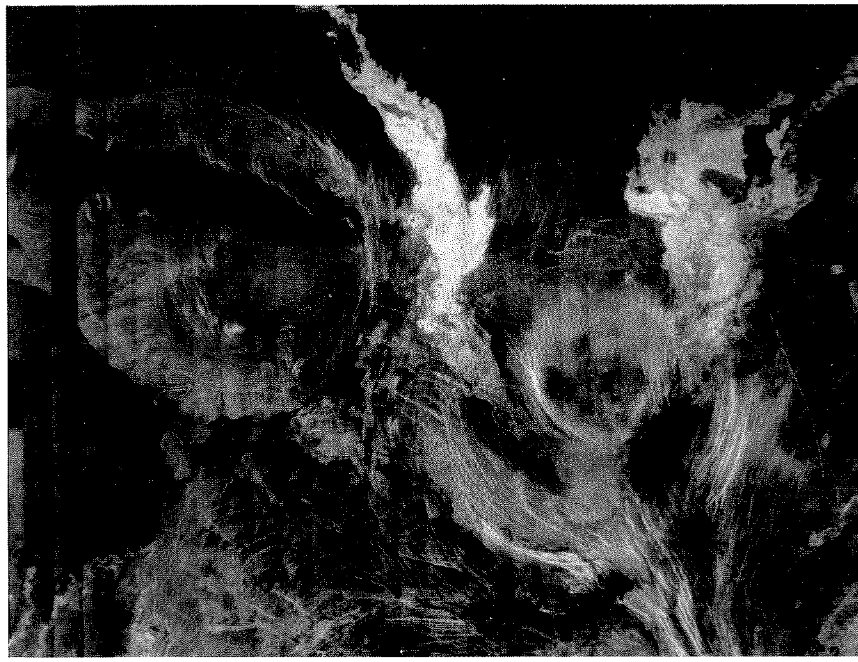






I also want to show you some strange and wonderful volcanic features. One that we call "the tick" is about 20 miles wide at the summit. It's a bottle-cap-shaped structure, somewhat concave on top, with ridges radiating out from it. On Earth, something like that could form by differential erosion, but, as I remarked before, we see very little evidence of erosion of any kind on Venus. We also see little pancake domes. They're typically less than a mile high, and about 15 miles across, although they come in various sizes. They sometimes overlap each other, like pancakes on a platter. On Earth, these are associated with magma that has a higher than normal silica content, making it a much stickier, thicker, more viscous material. There are pancakes of this type around California's Mono Lake. Those on Venus, however, are much larger than anything we see on Earth. I've seen perhaps a couple of dozen of them scattered over the Venusian surface. They may be a clue as to the distribution of early continental masses—which would have contained a higher percentage of silicates—if it turns out that they formed when later, more basaltic magma penetrated up through the continent and was contaminated by remelting silicates. But you can also make this stuff by differentiation in a purely basaltic magma. Very siliceous magma has a lower freezing point. Since it stays molten longer, it tends to come out later in a volcanic sequence. If you have a big body of subsurface magma, some of which is squirting out through volcanoes while the rest cools slowly, the last stuff to emerge will be highly siliceous. Conversely, if you're melting rock, it's the stuff you'd expect to erupt first.

I'll briefly mention two volcanoes called Sif and Gula. (Sif is the Scandinavian grain goddess, Thor's lover, whose long golden hair is the autumn grass. Gula is an Assyrian "great mother" goddess, sometimes rendered with a dog's head.) Each is a couple of hundred miles in diameter, but stands only one to three miles high—they're rather low features. They look like the Hawaiian volcanoes, which are shield volcanoes caused by a thin, runny lava building a very broad, flattish, gently domed mountain. They, like Hawaii, are probably associated with hot spots. Sif and Gula are linked by a complex of fractures, part of a rift system that extends several hundred miles southeast to another volcano called Sappho, for the poet. Gula is a little bit higher than Sif, getting just up into that zone where the brighter surface starts to form. There are lava flows hundreds of miles long—probably longer than any on Earth—extending out north-



A closeup of the plains north of Gula. The corona—the circular structure between the lava flows—is about 60 miles in diameter. The multiple crater at the end of the dark streak lies on the bright lava flow extending northwest from the corona.

The sulfuric-acid clouds filter out every color but orange. At ground level, the sky is one diffuse light source, sort of like a dark, smoggy day in Los Angeles.

ward from Gula. There's a corona—a dome—surrounded by fractures, with lava flows from its flanks out onto the plains. Coronae appear to be tectonic instead of volcanic features, although they're often associated with lava flows. They're more or less circular rings of what look like low-relief folds. There are probably hundreds of them on Venus. They most likely formed when a blob of hot mantle rock pushed its way up to the surface from its own buoyancy, making a little dome. As the blob cooled, it lost buoyancy and the dome collapsed, leaving behind a ring that looks like a fallen soufflé. This contrasts to paterae, which are caused when subsurface magma migrates, allowing the surface to subside.

On Sif's northern flank, there's a dark streak associated with an impact crater. The streak could be the record of a traveling line of shock, sort of a sonic boom, caused as the impacting object came in at a low angle. There are other dark streaks that suggest that the dark splotches around impact craters are a ground effect and not a shock wave, but this one is certainly continuous over a very long distance—hundreds of miles. The object broke up just before it hit, leaving two main craters that are younger than the lava flows. I'd hoped that Sif and Gula might be active volcanoes that we could come back and look at again during the extended mission. But this lava flow can't be all that young, because of that impact crater sitting on top of it. This is an example of how you deduce a sequence of events from stratigraphy—whatever lies on top is younger than what's below it. As yet, we haven't found any volcanoes that we can say with certainty are active right now.

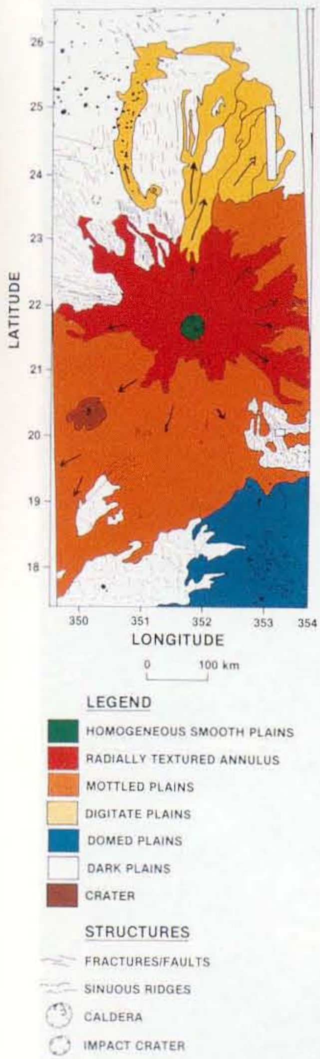
There are also hundreds of thousands of very low domes, little shield volcanoes a mile and a half or two miles across and a few hundred feet high. They tend to have central pits. We see them all over the plains. They're apparently associated with the plains' formation. The plains are a kind of background that covers about 80 percent of Venus. They apparently resulted from a very fluid lava that formed a flat, level surface, like the sea's surface. Venus, having no oceans, has no sea level, so the datum—the elevation defined to zero—is the mean radius of the whole planet. These plains are close to zero elevation.

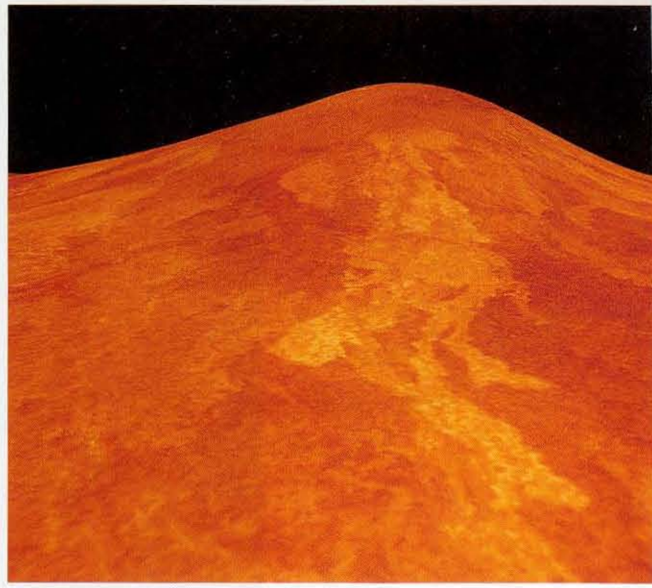
We made a three-dimensional colorized image, showing what an astronaut would see looking at Sif Mons from the north, which served as a key frame in a video we put together. The Soviet landers Veneras 13 and 14 sent back color images from the surface. The landers carried lights on board, because nobody knew if any light made it all the way down. In fact, the sulfuric-acid clouds filter out every color but orange. At ground level, the sky is one diffuse light source, sort of like a dark, smoggy day in Los Angeles.

The video combines topography, derived from Magellan altimeter data, and radar images into a three-dimensional model through which we can "fly" our video camera. The video was produced by a computer at JPL's Digital Image Animation Laboratory. To compose a frame, the computer has to decide whether each pixel in the radar image is visible to the camera or is hidden by intervening terrain. When we first started doing this, a couple of months ago, it took all day to make one frame. The video runs at 60 frames per second, so it would have taken months to create even a few seconds' worth. We've learned how to do better. We can almost do it in real time, now, by using cleverer and more efficient processing algorithms and by running several computers in parallel. We hope to be able to make videos for very large regions of Venus, and actually use them as a tool for visualizing the relationship between topography and geology.

Now that we have achieved our primary mission, we expect to operate for about six more 243-day cycles. We'll finish off the rest of this 243-day cycle, then we'll fill the major gaps in our map—the south polar region and the area we had to miss during superior conjunction. We'll point the radar off to the right instead of the left to get stereo views of the surface, and do interferometry, which will allow us to obtain very high-resolution topography. We'll search for changes. If the wind is moving sand dunes, for example, we'll see it. We'll look for volcanic eruptions. There's an excellent chance that at least one volcano is active at this very moment. We'll eventually attempt to put Magellan into a close circular orbit—still well above the atmosphere—where we can do much better gravity experiments, and some very interesting high-resolution imaging experiments. (We're doing gravity experiments right now, actually—Magellan speeds up and rises a few meters in its orbit whenever it flies over a high-density region, and when it passes over a less dense, low-gravity region, it slows and gets pulled a little closer to the planet's surface. But in order to make a really sensitive gravity map, Magellan has to be closer to the surface and has to keep its antenna pointed at Earth full time.) Circularizing the orbit is a very risky thing to do, so we're saving it for last.

The detailed exploration of our nearest planetary neighbor is now just beginning. Some of our questions are being answered, but, as is always the case in scientific endeavors, more questions have arisen. We haven't yet found evidence for Earthlike plate tectonics, nor have we found any evidence for ancient oceans or running water. However, we see many familiar volcanic and tectonic landforms. It's too early to guess how our explorations will lead to a better understanding of our home planet, but I feel certain that great and valuable insights of relevance to the geological evolution of Earthlike planets will emerge from our detailed study of the Magellan data. □





Left: A stratigraphic map of Sif Mons, showing the interrelationship of various types of terrain. Above: The three-dimensional colorized view of Sif Mons from the north. The vertical scale is exaggerated.

Steve Saunders is the project scientist for the Magellan mission. He is responsible for coordinating the actions of the science team, drawn from JPL and other institutions, and the JPL engineering team that's flying the spacecraft. Saunders earned his BS in geology from the University of Wisconsin-Madison, and his PhD in geology at Brown University. He came to JPL in 1969, just as Mariner 9 became the first spacecraft to orbit Mars, and he made the first geologic map of Mars from Mariner 9 images before turning his attention toward Venus. He joined the Magellan project about 20 years ago, back when it was the Venus Orbiting Imaging Radar, and stuck through its cancellation and eventual reinstatement as the Venus Radar Mapper before it was rechristened Magellan in 1986. Saunders's own specialty is stratigraphy—the analysis of the layering of materials on a planetary surface in order to deduce its history.