# CASSINI
## Captain's Log: 2004.184

by Carolyn Porco

There are times when human language is inadequate, when emotions choke the mind, when the magnitude of events cannot properly be conveyed by the same syllables we use to navigate everyday life. Last night, the evening of June 30, 2004, was such a time.

In a history-making maneuver so flawless, so perfect it seemed dreamt, one comparatively tiny machine, along with its builders, its operators, its scientists, its well-wishers—indeed, all of humankind—fell into the embrace of giant Saturn, a place that had been a distant destination, in the mind and in the future, for nearly a decade and a half.

After seven years of design and development, *Cassini* was launched in October of 1997. Its initial years were spent cruising the inner solar system, with flights by Venus and Earth, and then a distant flight by Jupiter in late 2000, just to gather sufficient momentum to place it on its final, southerly approach to Saturn. Even at speeds approaching 6 kilometers (4 miles) per second, *Cassini* required more than three years to cross the empty abyss between the two giant planets, a distance as great as that separating Jupiter from the Sun. Then, last night, following instructions that had been uploaded into its memory two weeks earlier, the craft rose through a wide gap in Saturn's rings, glided swiftly up and over their northern unilluminated expanse, ignited its counter-thrusting main engine, and quietly took up orbital residence around Saturn. At that moment, *Cassini* became the farthest robotic outpost humanity had ever established around the Sun, a tiny but glistening newcomer to the skies of the ringed planet. We had arrived.

It was difficult to know what to say, what to feel. Fourteen years of thinking, designing, building, testing, planning, dreaming . . . fourteen years of anxious anticipation . . . had been insufficient to prepare us. Perhaps nothing could.

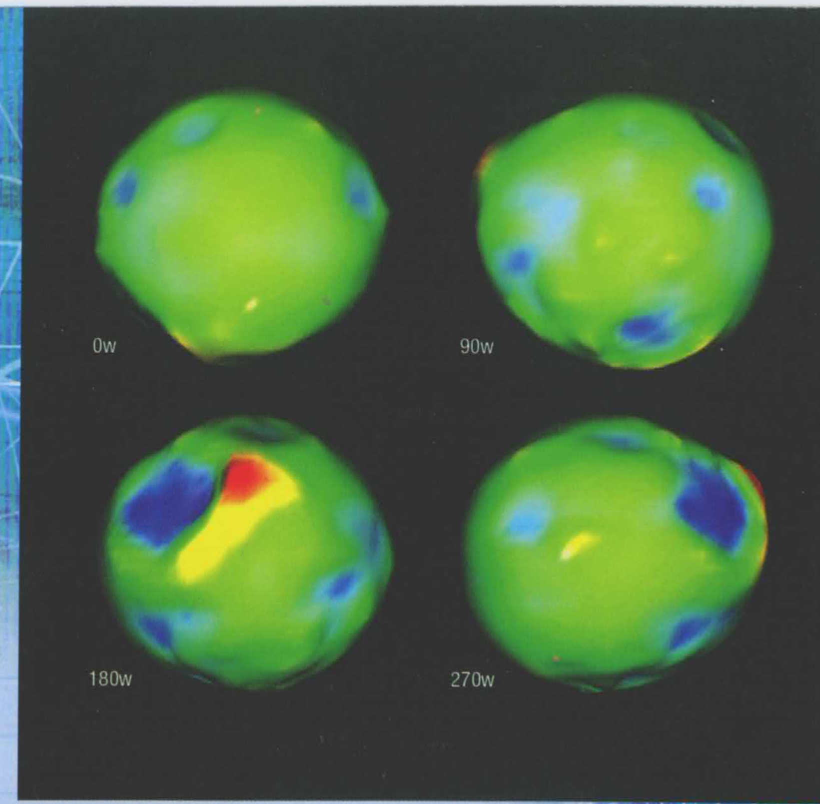
Not even Phoebe.

### Prelude at Phoebe

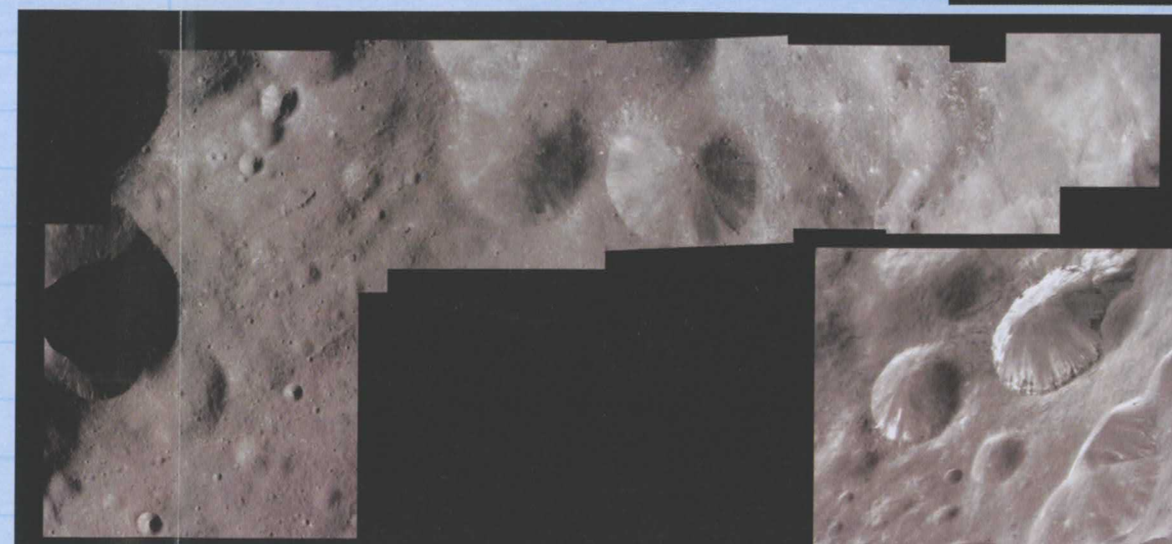
Phoebe, a moon 220 kilometers (130 miles) wide, plies the outer reaches of Saturn's gravitational influence in a retrograde orbit, a clear indication that this body is an interloper, an intruder to this particular planetary system, captured into orbit probably billions of years ago as Saturn and its moons were forming. We had buzzed this small world only three weeks earlier, coming within 2,000 kilometers (1,200 miles) of its surface, in a daring flyby that already seemed far away and long ago. At that range, the relative motion between a spacecraft and the surface of a body can be so large that it impedes the acquisition of sharp images. However, *Cassini* had been designed for such maneuvers: a staggering 53 of them have been planned over the course of its nominal four-year investigation of the Saturnian environment. It had been programmed to pivot while it flies, keeping the sights of the cameras and other remote-sensing scientific instruments staring at a particular point on the surface of a body, despite the rapid movement between the two.

Planning and programming notwithstanding, we can never fully predict what such an encounter will produce. If we could, there would be no point in conducting one.

Ground-based observers had told of the presence of water on Phoebe's surface, an observation that strongly suggested that Phoebe had its origins not, for example, in the rocky waterless asteroid belt whence the moons of Mars arose, but most likely



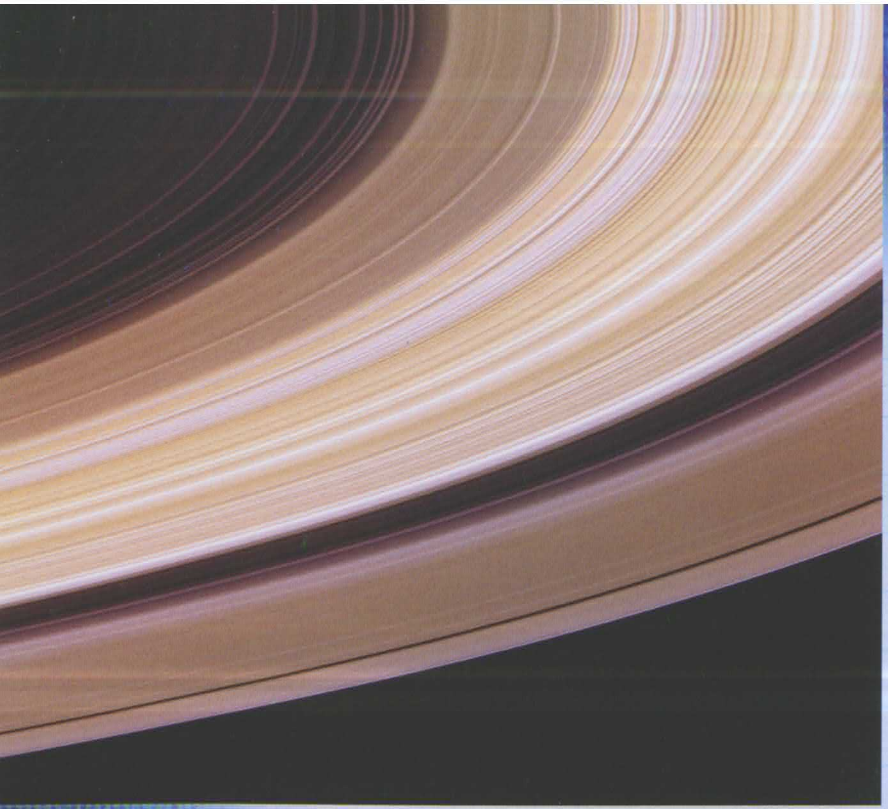

*Right: As indicated by this digitally rendered shape model, based on Imaging Science Subsystem (ISS) data, Phoebe is fairly round, despite its irregular topography. The moon's average diameter is 220 kilometers (130 miles). Phoebe's rotation is shown here, centered at four points that are separated by 90 degrees. The colors correspond to the moon's surface elevation relative to the lowest point (a range of about 16 kilometers, or 10 miles) going from blue (low) to red (high). Much of this range occurs in the large crater at lower left.* Model: NASA/JPL/Space Science Institute



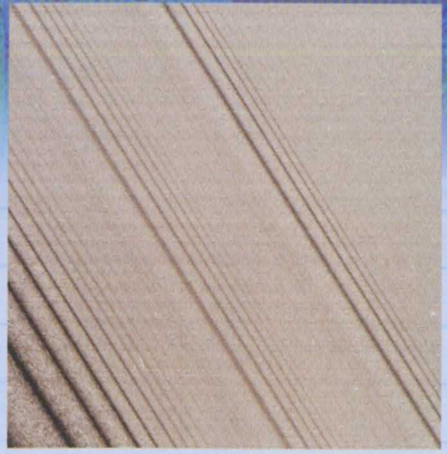
*Above: Phoebe's entire landscape is heavily cratered, which suggests that its surface is ancient. Seven of the sharpest, highest-resolution images that* Cassini *took of Phoebe during its close flyby of the moon make up this mosaic. Resolution increases from left to right, and the image scales range from 27 to 13 meters per pixel. The grooves, or chains, of pits at left are similar to those seen on other small bodies, like the Martian moons, and are of unknown origin.* Mosaic: NASA/JPL/Space Science Institute

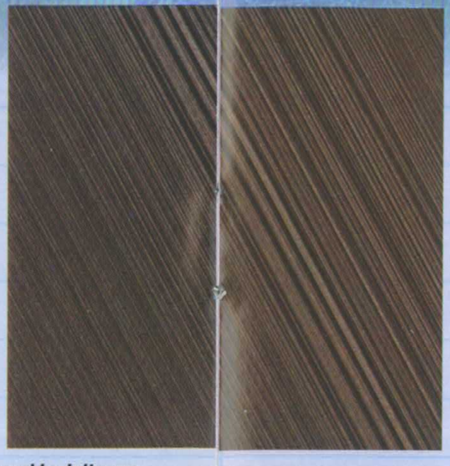
*Inset above right:* Cassini*'s observations of Phoebe add credence to the theory that the moon originated elsewhere and joined the ringed giant's family of satellites as they and the planet were forming. Saturn's oddball little moon appears to have an ice-rich upper layer overlain with a thin coating of dark material. This image was taken on June 11, 2004 from a distance of about 13,800 kilometers (8,300 miles). The image scale is approximately 80 meters per pixel.*

*Inset right: Unlike the arid denizens of the inner asteroid belt, from which Mars' moons Phobos and Deimos came, ground-based observations showed Phoebe to have water on its surface. This means that Phoebe may have originated in the boondocks of our solar system as a relative of the icy bodies that populate the Kuiper belt. Scientists think that the bright wispy streaks (which are overexposed) in this image are ice. The crater at left, with most of the bright streamers, is about 45 kilometers (28 miles) in diameter from front to back.* Images: NASA/JPL/Space Science Institute

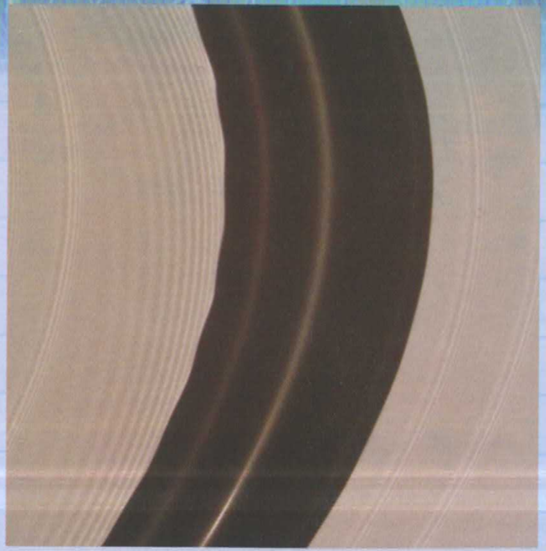


On June 21, 2004, nine days before Cassini entered orbit around Saturn, its Narrow-Angle Camera captured this natural, "watercolor" view from 6.4 million kilometers (4 million miles) below Saturn's ring plane. Because Saturn's rings are made primarily of water ice (and because water ice is pure white), scientists believe that the different colors in the rings result from differing amounts of contamination by other materials such as rock or carbon compounds. Cassini's instruments will help to identify the compositions of various parts of Saturn's ring system. Image: NASA/JPL/Space Science Institute

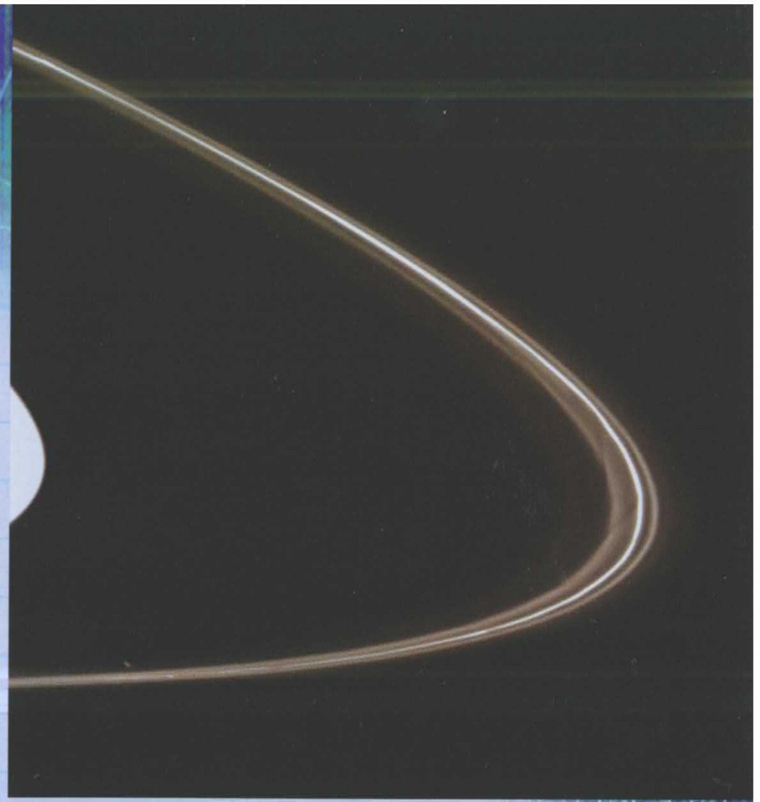




*Once* Cassini *entered Saturn's orbit, it snapped 61 images of the rings. These ring images—many times more detailed than those* Voyager *took—revealed a collection of phenomena, some of which scientists had never seen before and hadn't even predicted. The most common features were waves caused by the orbits of Saturn's moons. These Narrow-Angle Camera shots were taken from above the rings, which are illuminated by the Sun from below. The image above left shows the outer part of the A ring outside the Encke gap, with density waves created by the moons Janus, Pandora, and Prometheus. These features had been seen by* Voyager *at lower resolution, but the strawlike structure in the lower left corner was not, and it suggests the clumping of ring particles on scales not previously predicted. The image above right shows an inner and denser region of the A ring and the riot of structure that is found there. The scales of these images are about 268 meters per pixel (left) and about 338 meters per pixel (right).* Images: NASA/JPL/Space Science Institute



*The Encke division cuts a 325-kilometer (about 200-mile) swath through this image of Saturn's A ring.* Cassini*'s Narrow-Angle Camera took this picture as it looked upward at the lit face of the rings. The scallops and the white "streamers" that are visible along and interior to the gap's inner edge are caused by the perturbations of the tiny moon Pan, the gap's only known inhabitant.* Image: NASA/JPL/Space Science Institute



*This was the first shot of Saturn's rings taken after* Cassini *passed through to the illuminated side of the rings following orbit insertion. It shows, in a wide-angle view, never-before-seen features in Saturn's mysterious F ring. Perturbations caused by Prometheus (which is barely visible at lower left) as it orbits Saturn are responsible for drape-like features in the tenuous material interior to the bright core of the F ring. In this view, the image scale is about 9 kilometers (5.5 miles) per pixel.* Image: NASA/JPL/Space Science Institute

in the hinterlands of the solar system, out in the dark, cold regions patrolled by Uranus and Neptune.

However, in science, suggestions are one thing; direct, detailed evidence—the kind that speaks a thousand words—is quite another. As is often the case in the study of planetary bodies, what we found at Phoebe was similar in some respects to what had been seen on equivalently sized bodies, making what was different about Phoebe all the more intriguing.

Phoebe's landscape is cratered all over, indicating an ancient surface, one not reprocessed, as on larger moons, by internal mechanisms. This alone was not unusual. Phoebe also was grooved in places, with grooves similar to those seen on the Martian moons, including Phobos. The origin of the grooves on both bodies is a mystery, but their forms suggest cracks in the "bedrock" of the moon, filled in by loose overlying rubble. The closest images, in which details as small as 15 meters can be seen, reveal blocks 50–300 meters across—again, a circumstance similar to that observed on the Moon and asteroids such as Eros.

However, the variations of brightness across Phoebe's surface were larger than had been seen on a small body, with very bright areas exposed by large landslides and even very small craters. Furthermore, some of the larger craters revealed a layering of bright and dark material at the surface. In places, the upper layers were clearly several hundred meters thick. This was unusual. These and other imaging observations (such as a measure of Phoebe's volume) and readings from other instruments on board *Cassini*—in particular, the reading of the body's mass by Doppler tracking of the spacecraft—told of a body rich in ice though probably more rich in rock, with a mean density that could be explained best if Phoebe formed in the outer solar system. Its outer layers were clearly compositionally and spatially variable, and its surface was coated in a very thin, dark blanket of something. The Visual and Infrared Mapping Spectrometer, capable of discerning composition, found the "something" to be, in places, partly organic, also suggestive of an origin in the outer solar system.

We concluded, as Phoebe receded behind us, that we had just paid a visit to an ancient, primitive relic of the early solar system, one member of the population that formed Uranus and Neptune and a cousin to the dark bodies inhabiting the outer reaches of the solar system beyond Pluto, the famed Kuiper belt. If that conclusion is correct, we had just stared a Kuiper belt object look-alike in the eye. In our first historic episode at Saturn, we had just put a face to a name. Not bad for a prelude.

## The Moons at Saturn

The superiority of our cameras over anything previously carried to Saturn would lead to other findings, both surprising and beautiful.



Even prior to Phoebe, we imaged the Saturn atmosphere and rings with exacting deliberation to search for variations over time. We made distant approach observations of Titan and the other known moons. We searched for new moons that had escaped detection from Earth and from *Voyager*. If *Cassini* did not make it into orbit, these data collected on approach would be all that we could show for years of effort and funding; our tour of the Saturnian system would devolve to a flyby. Deciding which images to take and which to leave out was a serious matter.

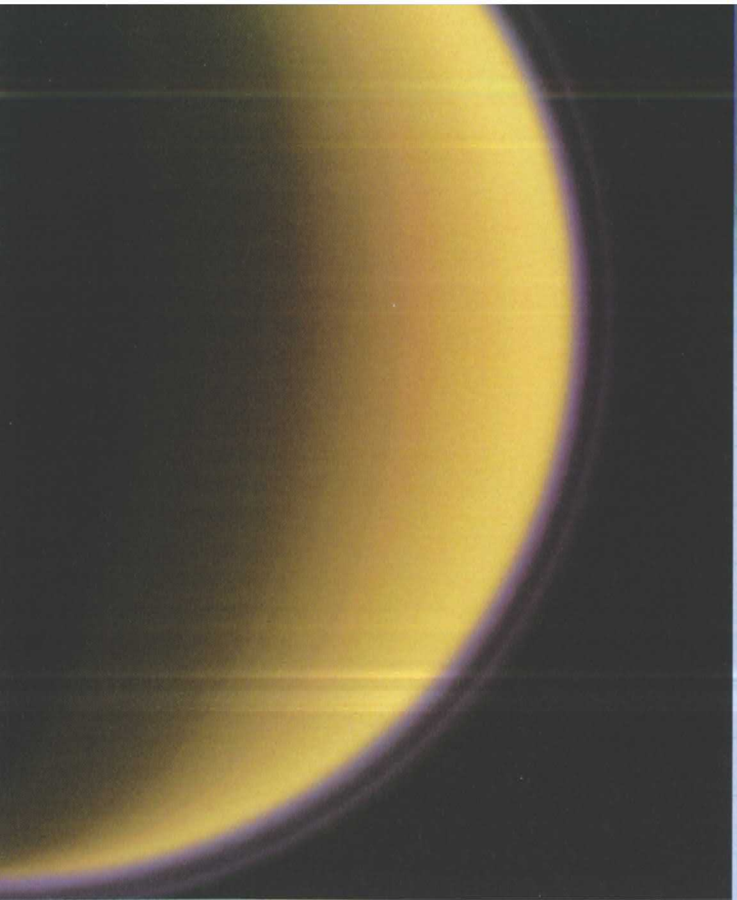
Our search for new moons was particularly gratifying. We looked among the main Saturnian moons, searched just outside the rings, and peered within the rings themselves, especially within the vacant gaps, where we surmised moons would be lurking. In doing so, we uncovered, once again, Atlas and Pan—two small bodies, about 32 and 20 kilometers (20 and 12 miles) across, respectively—orbiting just outside and just inside the main rings. These moons had not been seen by human eyes since the days of *Voyager*.

After a good deal of analysis of images taken in early June, we eventually discovered two very small objects, only several kilometers across—S/2004 S 1 and S/2004 S 2—between the orbits of Mimas and Enceladus. They had skipped around Saturn, presumably for billions of years, unnoticed until now. How lovely it was to know that our efforts to coax previously unseen bodies into view were successful and that our legacy would now include the discovery of new real estate within the Saturnian system.

These small bodies should have been broken apart easily by the great number of small, icy comets (only about 30 meters, or 100 feet, across) believed to have originated in the Kuiper belt and to have rained down on the bodies throughout the outer solar system over the course of billions of years. The very existence of these two bodies tells us either that the flux of the small comets is not as large as previously assumed or perhaps that our new finds have had a violent history of multiple cycles of collisional disruption, then re-accretion, followed again by collisional breakup and re-accretion. The answer to this riddle will be sought in images we hope to collect of the surfaces of moons such as Enceladus. These images should record, and therefore provide measures of, the flux of small comets within the Saturnian system.

## Viewing Saturn's Rings

A week after the Phoebe flyby, the planet's rings appeared to our cameras as if painted in watercolor, with subtle shades of salmon, blue, gray, and brown. They are predominantly water ice, and their colors presumably reflect varying degrees and kinds of contamination



*Titan is enshrouded in a thin layer of purple haze that appears to float above its main atmosphere in this colorized image taken one day after* Cassini*'s first flyby of the moon. The* Voyagers *also saw this haze layer as they sailed past Titan in the 1980s. This image, which shows Titan's south polar region, was taken using a special ultraviolet filter. The picture has been colorized to approximate what our eyes would see if our vision extended into the ultraviolet wavelength. The globe of Titan is the soft orange we usually see, and both the atmospheric haze and the thin detached layer have been given their natural purple color, although they have been brightened for visibility.*
*Image: NASA/JPL/Space Science Institute*

*Left: This mosaic of Titan's south polar region was assembled from images taken by* Cassini*'s ISS as it passed 339,000 kilometers (210,600 miles) from the Saturnian moon during its first flyby on July 2, 2004. Special filters allowed* Cassini *to see through Titan's thick haze and atmosphere to a surface mottled by dark and light features. The smallest features visible in this image are about 10 kilometers (6 miles) in diameter. A field of clouds near the south pole shows up as the bright spots near the bottom.*
*Image: NASA/JPL/Space Science Institute*

*Above: This series of images shows the evolution of that field of clouds near Titan's south pole over a period of nearly 5 hours.* Cassini*'s ISS captured them on July 2, 2004 from a range of 339,000 to 364,000 kilometers (210,600 to 226,170 miles). This cluster of bright clouds, about the size of Arizona, is believed to be composed of methane. Ground-based observers had previously seen clouds on Titan in the south polar region. The scale of these images is about 2.2 kilometers (1.4 miles) per pixel.*
*Image: NASA/JPL/Space Science Institute*

by nonwater components. Future color imaging of the rings, along with data collected by the spectrometers on board *Cassini*, will readily tell us the composition of the rings and its variation across them. Disentangling the composition of the original ring progenitors—those bodies whose disruption and subsequent dispersal created the rings in the first place—from the composition of the tons of meteoritic material that daily falls onto them will be a more difficult challenge.

Finally, on June 30, we found ourselves flying over the rings at a swift 25 kilometers (15 miles) per second. We were closer to Saturn and closer to the rings now than we had ever been or ever would be again during the *Cassini* tour, and maybe even during our lifetimes. This was an opportunity that could not be missed, and mission scientists had been clamoring for years to be permitted to utilize it to full advantage.

The speed of the spacecraft and the minute-long shoot-and-readout image acquisition cycle meant that consecutive images, one taken immediately after the other, did not overlap in their coverage of the rings: they were separated by about 1,000 kilometers (600 miles), several times the size of one field of view. We were not going to be able to make a complete scan of the rings. It would be hit and miss, but no one cared. Whatever we got would be the best we would ever get, and we were eager for it.

The ringscape, enormous and almost supernaturally flat, spread out beneath us; we were riveted by what we saw. For the 24 years since *Voyager 1*'s first passage by Saturn, I have carried around in my mind the geography of Saturn's rings. Their structure, their shape, and their behavior have been my profession and my life. Now, I looked upon familiar sights with unfamiliar clarity and saw something wholly new. I found myself almost without words to describe and explain.

Forty-three images, with spatial resolution some 25 times greater than we had seen with *Voyager*, were taken while the spacecraft sped in darkness over the rings, starting in the C ring, covering the inner B ring, and then beginning again at the outer B ring, continuing over the Cassini division and the A ring until we were once again staring down at empty space. We had chosen the shortest possible exposure time—5 milliseconds—to avoid any chance of smearing the images. After descending through the plane of the rings again and emerging onto the illuminated side, *Cassini* captured 18 more images—9 narrow-angle and 9 wide-angle images—from the F ring inward, terminating just interior to the Encke gap. These had a level of detail several times coarser than the dark-side views but still five times as good as anything we had obtained with *Voyager* and comparable to the closest images we will take of the rings during the remainder of our tour. They were spectacular.

It was immediately evident, upon inspection of these 61 images, that we had discovered a collection of phenomena never seen before, and some not even predicted.

We saw features without any sensible order at the limit of resolution in one dark-side image. In other



images, we saw very narrow ringlets standing apart from broader bands carved up in a profusion of seemingly incoherent structure. But mostly we saw waves, and more waves. These are the handiwork of orbiting Saturnian moons, which perturb the orbits of ring particles at the sites of gravitational resonances and force the particles into spiral patterns. Where the ring particles are perturbed into eccentric orbits, we found a density wave in which the enhanced concentration of particles takes the form of a spiral pattern wrapped around the planet; where the orbits are forced to be inclined by the action of an inclined moon, we found the height of the ring plane taking the form of a spiral pattern, wrapped round and round the planet. This latter structure is akin to a traditional wave created by a pebble thrown into a pond, only the crests are spiral and not circular.

Waves are precise but curious structures, and we don't have completely satisfactory explanations for why they look the way they do. Theories stumbled years ago, when sufficiently accurate data were lacking to guide them. Now, back at Saturn, we have collected a bounty of information we didn't have before, a circumstance that surely will advance the study of wave formation and propagation. We can expect deeper insights into the behavior of icy particles arrayed into the giant sheet that is Saturn's rings, and even into the behavior of icy particles that ultimately coalesced to form the outer planets billions of years ago. Saturn's rings are our closest analog to the great flattened structures we see throughout the cosmos: from the disks of material, being discovered as we speak, surrounding protostars in our galaxy, in which planets are forming even today, to the vast pinwheels of stars and gas we call the spiral galaxies. The scientific reach of *Cassini* and the investigations we hope to conduct with it are truly universal.

Our most artful image is surely one of the F ring, in which periodic drapelike scallops are carved by the action of Prometheus in the delicate, diaphanous material interior to the ring. But the image that kills at a thousand paces is our dayside view of the Encke gap, a 300-kilometer (180-mile) division in the outer A ring kept open by the perturbations of Pan, the gap's only known inhabitant. In this one image, we come face to face with the order and mathematical precision of countless icy particles influenced simultaneously by Saturn, Pan, and each other. The effects of Pan on the inner edge of the gap are particularly stunning and regular: scallops in the edge caused by the periodic and precisely phased in-and-out motion of many small orbiting bodies acting in unison; white streamers, marking the enhanced concentration of these bodies resulting from this phased motion, that spiral away from the edge and fade as they go; and ringlets within the gap, kept narrow by Pan's shepherding action. What a feast.

Last night, the world applauded us. We were exhausted and relieved. But our work had only begun. Titan loomed up ahead.

## Imaging Titan

We are now thirty hours from the rings, and we are staring down Titan, making our first *Voyager*-class flyby in the Saturnian system. This is the telling event.

The hazy Titan atmosphere had prevented the *Voyager* cameras, which could only "see" at the visible wavelengths of light, from penetrating to the surface. However, ground-based observers had learned to see the Titan surface by looking in specific and narrow spectral regions in the near infrared, where the transparency of the atmosphere actually begins to increase in the "windows" between those spectral regions where Titanian methane is absorbing. We had this "peering through the window" trick in mind in outfitting the *Cassini* cameras, ensuring that they had the proper narrow, near-infrared filters as well as haze-reducing polarizers needed to see to the surface. But how far would this go? We were fairly confident we could see the large-scale, 300-kilometer (180-mile) features seen by the ground observers and that we would have greater visibility of these structures, whatever they might be. But would we be able to see features as fine as the cameras and closest approach distances of the more than 40 Titan flybys could serve up—in some cases, a few tens of meters per pixel? Even in the first Titan flyby, the image scale would be 2 kilometers (1 mile) per pixel. Would we see such detail?

Available models of the Titan atmosphere covered the full range of possibilities between two extremes: on one hand, the total abundance of haze is large, in which case we would do no better than seeing features about 100 kilometers (60 miles) in size; on the other hand, the total haze abundance is modest, like a smoggy Los Angeles day, in which case we might see the finest features, assuming they exist (and are of sufficiently high contrast) in the first place. Surface contrast observed through an atmosphere will be reduced by the scattering of light from the airborne haze, and the amount of scattering, and therefore the reduction in observed contrast, depends on the abundance of overlying haze and its vertical distribution. Thus, features on the surface with greater contrast have a greater chance of being seen by a spacecraft cruising overhead.

What we see on Titan certainly lacks the clarity of the Phoebe and Saturn ring images but is perfectly within the range of expectations. Between light and dark regions, we see nebulous boundaries so diffuse that we all find ourselves fighting the impression that we are looking at clouds and low-lying fog. But we are not: many of the features seen in the south polar region looked similar in their light and dark variations and boundaries to the motionless, and presumably surface, features seen in the midlatitude regions, first by ground-based observers and now by us.

One feature immediately grabs all of us—an obvious cloud complex hovering near the south pole as big as the state of Arizona. In a series of images, taken one after the other, we can see the evolution of its structure. It is likely to be a cloud field, similar to that seen with much less detail by ground-based Titan observers. Its study over the Saturn orbital tour should provide us with a sensitive probe into the thermal inertia of the Titan surface and convective character of the atmosphere.

With a bit of work, we can also make out a few sinuous features only 10 kilometers (6 miles) wide. It is seductive to imagine riverbeds and streams or deep canyons and channels, features perhaps caused by the rain of liquid methane and ethane that Titan theorists have long predicted. At this stage, however, there is no further evidence to develop this line of imagining into fact. Scientists pride themselves on their discipline and restraint. And so we remain restrained, unsure of what we are observing, awaiting future opportunities to view Titan in greater detail and with greater coverage, and awaiting the results of the investigations of Titan by other *Cassini* instruments, before offering any conclusions about the character of the markings we have seen on its surface.

However, one thing we can readily offer is the hope that greater detail will be available to us if indeed it exists on the surface at all. The putative visibility limit of 100 kilometers (60 miles) for a large-haze-abundance scenario clearly does not apply to Titan. If we see features 10 kilometers (6 miles) across with a 2-kilometer image scale, then we should be able to see features 100 meters across with the 20-meter image scale that we will have on future Titan flybys. That assumes again, of course, that such features exist. Thus, our first flyby of Titan leaves us more excited than ever that our investigations of Titan over the next four years will bear the fruit that we have come to enjoy. We may yet learn what this deeply mystifying body has kept hidden for so long. It's only a matter of time.

And time we have. We are now in orbit around Saturn. Like Phoebe, we have come to dwell in the house of this great patriarch of a planet. Now, it is we who are the interlopers . . . looking, probing, gathering, reading, measuring—silently, methodically, without disturbance. Now, it is we who are the new Saturnians.

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