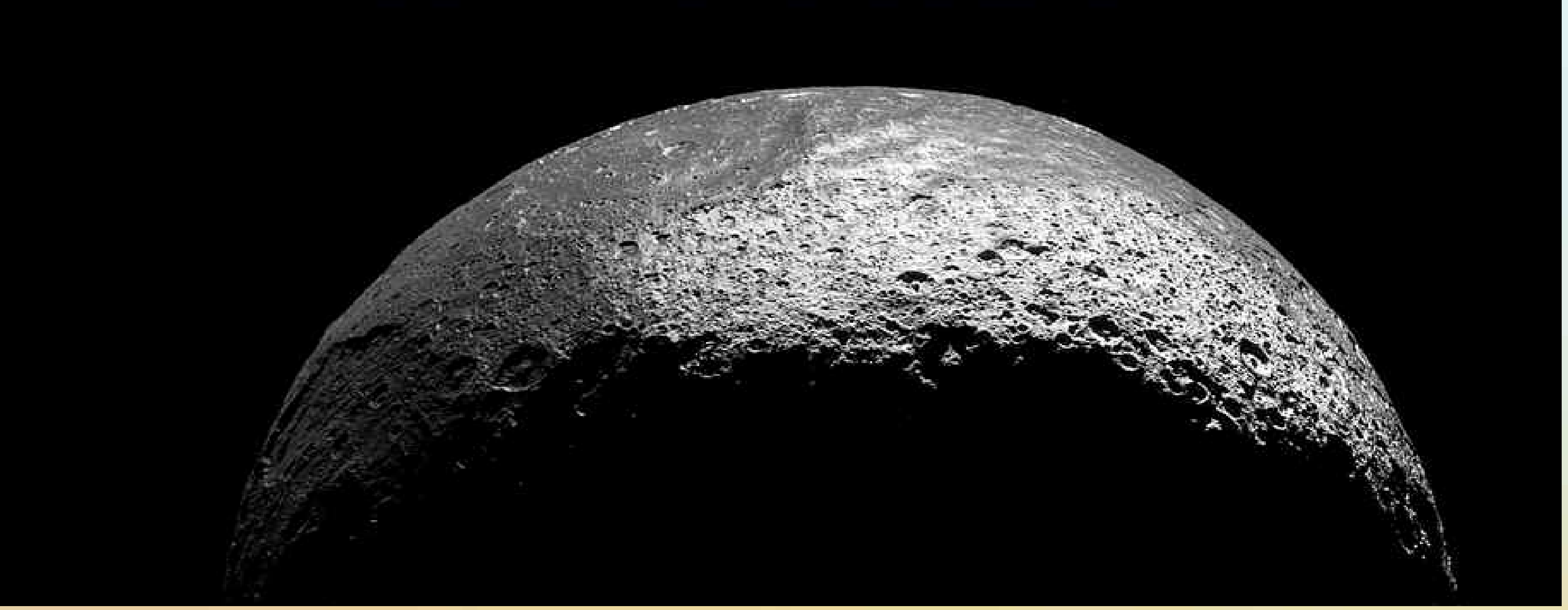
Cassini at Iapetus: A Bumpy but Successful Flyby



BY TILMANN DENK

Saturn's far-flung moon Iapetus is unique among solar system bodies for its stark, black-and-white visage. Although Cassini*'s path to Iapetus often resembled an obstacle course, the close scrutiny of this odd, yin/yang world was one of the spacecraft's most important goals. It achieved that goal beautifully.This mosaic of Iapetus is constructed of [eight?] images captured by* Cassini *on the morning of January 1, 2005 from a distance of 140,000 kilometers (87,000 miles).* Image credit: ANY DIFFERENT?

Monday, September 10 2007, was a special date for space exploration: on that day, the *Cassini-Huygens* mission performed its first and only targeted flyby of Saturn's unique moon Iapetus. With a closest approach of only 1,620 kilometers (970 miles), the *Cassini* spacecraft came to within about two radii of the moon.

Accomplishing this complicated feat was a challenge for all parties involved in directing the spacecraft. Orbiting at an average distance of 3.56 million kilometers (2.14 million miles) from Saturn, Iapetus is relatively far from the planet and is outside *Cassini*'s orbit for most of the mission's duration. Iapetus's orbit, furthermore, is currently inclined 15 degrees relative to Saturn's equatorial plane, where the rings and all the other regular satellites reside. Reaching such an object while remaining on a Titan-return trajectory is a difficult and tricky task.

Why Iapetus?

Investigating Iapetus is among *Cassini*'s most important scientific goals. This unusual moon is important because it harbors what might be the oldest unresolved mystery of planetary science: why is Iapetus' leading side (the side that faces in the direction of its orbital motion) dark while the trailing side (the side facing away from the direction of motion) is bright?

Jean-Dominique Cassini, the discoverer of Iapetus, first spotted this moon more than 336 years ago, in the fall of 1671. In 1672, he had to "rediscover" it after an extensive search because he couldn't find it at the precalculated position. (Cassini discovered Saturn's moon Rhea as a by-product of that search.) After finding Iapetus again, Cassini realized why he had so much trouble: he could see this moon only on the right side of Saturn but not on the left side. He correctly claimed that Iapetus must be in synchronous rotation, and that one hemisphere (the leading side) is much darker than the other.

Cassini probably did not consider trying to find an explanation for this unusual dichotomy in brightness. The first serious attempt came nearly 300 years after Cassini's discovery. Harvard-Smithsonian scientists Allan F. Cook and Fred A. Franklin, in an article that appeared in the journal *Icarus*, suggested that Iapetus had been covered by a layer of thin, bright icy material, but impacts by "micro-meteorites" had erased this feature on the moon's leading side.

Since the publication of Cook and Franklin's paper, multiple other hypotheses have been developed. In particular, images from the *Voyager* spacecraft showing the northern side of Iapetus on the side opposite from Saturn at a resolution of about 9 kilometers (5 miles) per pixel and the Saturn-facing side at a resolution of about 20 kilometers (12 miles) per pixel inspired myriad imaginative suggestions from researchers. None of these proposals, however, has satisfied the majority of planetary scientists.

Considering all this, it is not surprising that the investigation of Iapetus has remained a top priority for a Saturn-orbiting spacecraft. Nevertheless, when mission planners realized how difficult it would be for the *Cassini* spacecraft to reach Iapetus, they limited their plans to only one single targeted flyby of this moon during the four years of the spacecraft's primary mission. *Cassini*'s orbital trajectory had been more or less fixed in 2000, and since that time, we have known that the close encounter with Iapetus would occur, if all went well, on September 10, 2007. The spacecraft would approach the moon from its unlit leading side and depart from the illuminated trailing side, with its closest approach taking place at a low latitude over the anti-Saturn hemisphere.

Planning the Encounter

Once the timing and trajectory of the flyby were set, *Cassini*'s Satellite Orbiter Science Team (SOST) began to negotiate how to distribute the time near closest approach among the various instruments on the spacecraft. SOST includes representatives from the science groups of each of *Cassini*'s instruments. Working through regular telephone conferences, the team is responsible for preparing the observation strategies, timelines, and spacecraft attitudes for all satellite flybys.

In 2000, three competing requests were on the table: optical remote sensing (ORS) of the surface, *in-situ* measurements by the fields-and-particles instruments such as the cosmic dust analyser or the magnetometer, and an observation of a stellar occultation—a geometry in which Iapetus blocks out the light of a known star in the background. This last option would use *Cassini*'s Ultraviolet Imaging Spectrograph (UVIS) instrument to help determine whether Iapetus possesses a (very) thin atmosphere.

In the end, SOST decided to proceed with the UVIS stellar occultation experiment, but with a star that would have been occulted while the spacecraft was "inbound;" that is, before closest approach to the moon, when only the crescent would have been visible. The star Zeta Ophiuchi was found to be in the right position and best suited for conducting the experiment. A few minutes after closest approach, the ORS instruments were to take over and begin collecting data from the surface. Unfortunately, the requirements of these two experiments were incompatible with the spacecraft attitudes required by the fields-and-particles instruments, and SOST decided that they would not get their preferred spacecraft attitude.

Even so, without taking the requirements of the fields-and-particles instruments into account, certain issues were left unresolved temporarily, including the crucial question of how the spacecraft could return from inertial stellar pointing back to surface tracking within the required short amount of time.

As the person responsible for imaging observation planning of Iapetus on behalf of the *Cassini* imaging team, I was not at all happy with this compromise, because the UVIS stellar occultation was to take place just before closest approach. This would exclude the possibility of ISS (Imaging Sub-System) observations of the dark terrain at very high spatial resolution during the spacecraft's approach to the moon. In particular, we wouldn't be able to observe the Voyager Mountains rising above the horizon with this plan. Nevertheless, I was comforted by the knowledge that the orbit of Iapetus was not known well enough for detailed planning and by the hope that things might be improved when the time came for the final flyby preparations.

The Quest for the *Voyager* Mountains

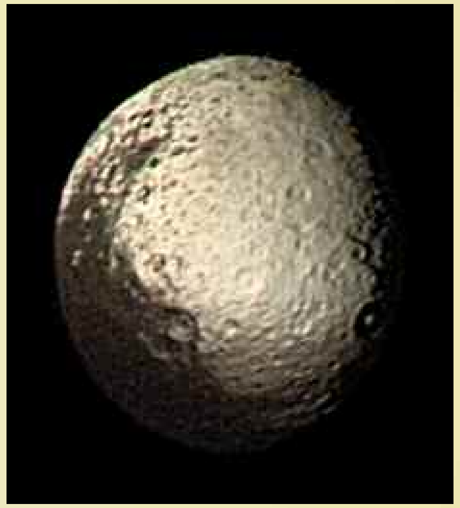
The informally named Voyager Mountains are several huge, isolated mountains near Iapetus's equator on its anti-Saturn side. They were discovered by our group in 1999 in *Voyager 2* data, where they show up nicely at the horizon. We estimated that they were more than 20 kilometers (12 miles) high, keeping in mind the huge margin of error when using images with resolution of nine kilometers (about six miles) per pixel. Initially, we had no really useful ideas of how the mountains had formed, but this changed on Christmas Day of 2004.

On December 25, *Cassini* took images of the leading side of the moon at a resolution of six kilometers (four miles) per pixel, which showed a faint linear streak running exactly along the equator, including a very pronounced bump at the western limb that was about 20 kilometers (12 miles) high. It now became apparent that the Voyager Mountains are part of a much larger equatorial ridge or chain of mountains that spans at least one third to one half of Iapetus's circumference.

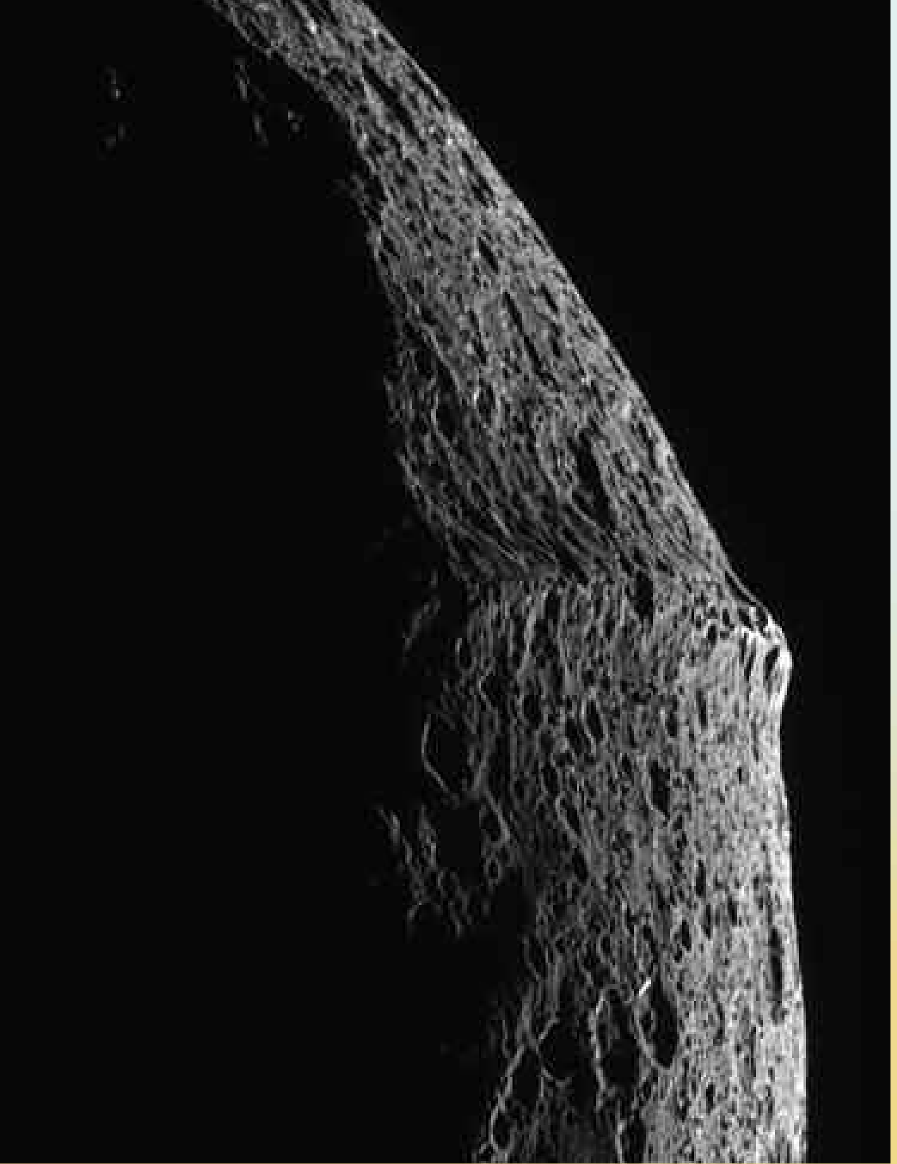
This discovery took place just seven days before the so-called B/C flyby of Iapetus, when *Cassini* passed within 124,000 kilometers (74,000 miles) of the moon. This gave us one week of pleasant anticipation, because we knew that we would get spectacular images of the ridge at a resolution better than just one kilometer per pixel.

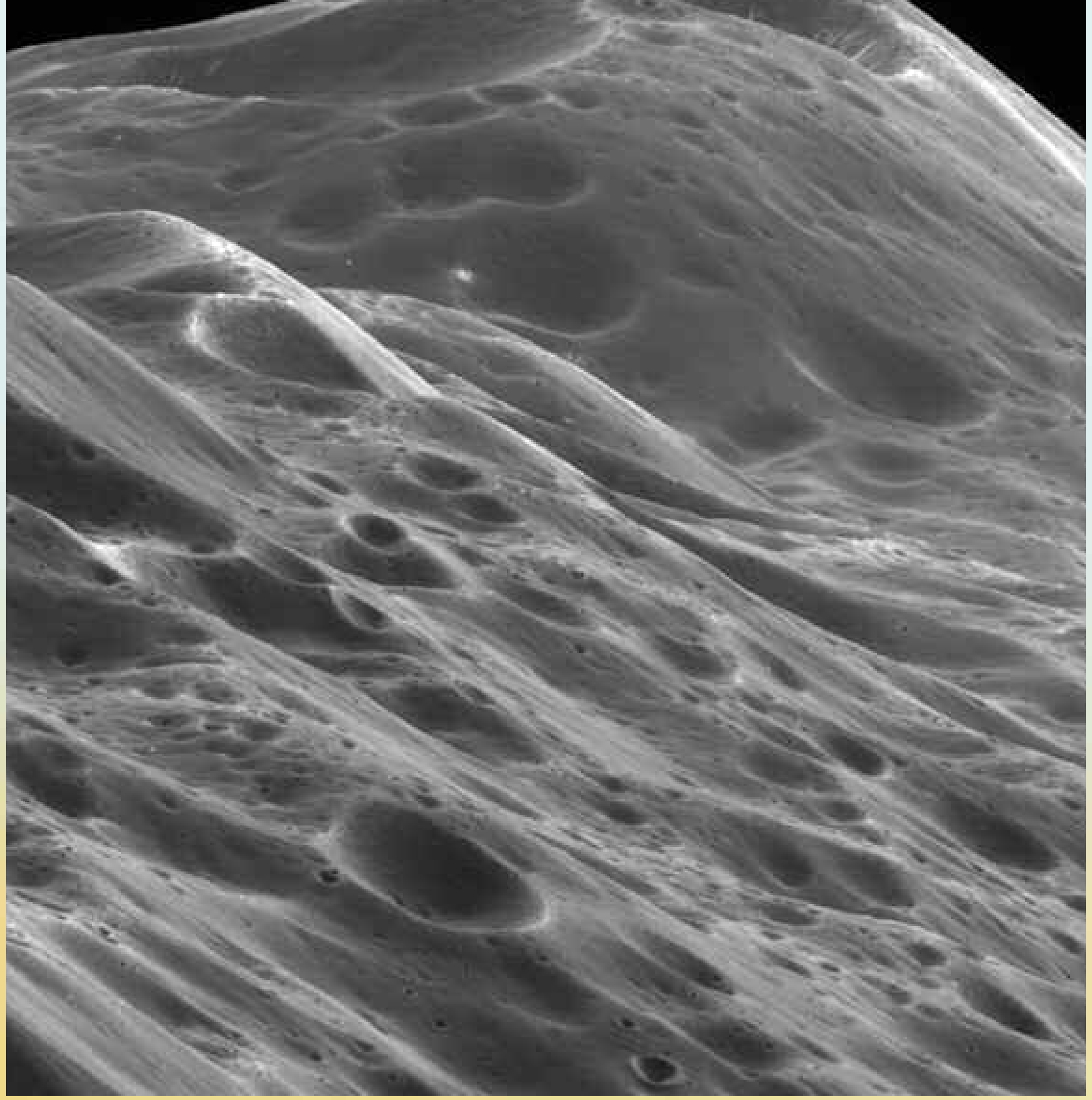
The B/C flyby is so named because it took place near the apoapsis—the position farthest away from Saturn—at the end of orbit B and the beginning of orbit C. After the targeted flyby, the B/C flyby remains the best ever of Iapetus and was by far the closest approach at the time.

The story of this unexpected flyby would warrant an article on its own. It was, in a way, a "gift from heaven", because it took place only because of certain communica-

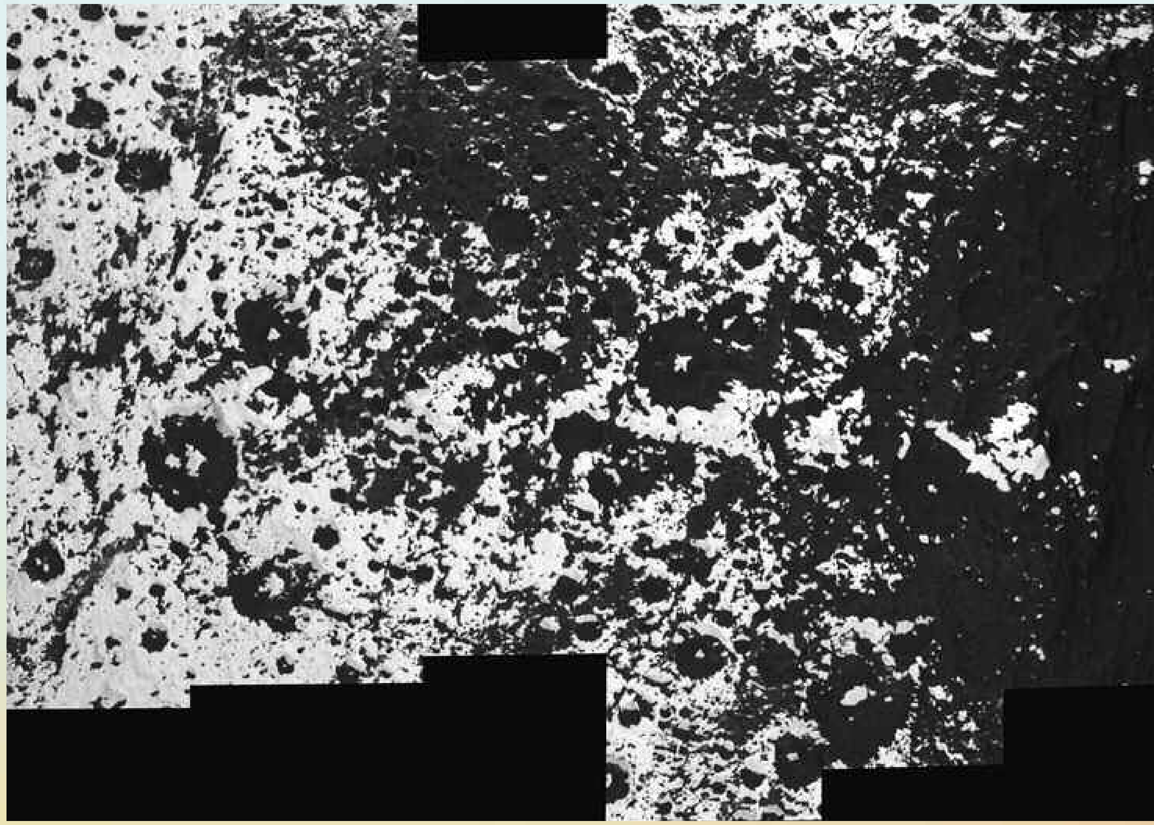


The first serious attempts to explain Iapetus' two-faced nature would not occur until more than 300 years after the moon's discovery in 1671. Voyager*'s groundbreaking i mages of Iapetus inspired many theories, but none has gained acceptance by most planetary scientists.* Voyager 2*'s closest approach to the satellite was 966,000 kilometers (600,000 miles). It took this picture of Iapetus on August 22, 1981.* Image: NASA/JPL





On Christmas day of 2004, Cassini *imaged a feature that added to Iapetus' mystique—a mountainous, equatorial ridge that circled one third to one half of the moon's diameter. The feature was quickly nicknamed "the Belly Band." It would be almost three years before* Cassini *could return to take a closer look. Above left: This raw, unprocessed image is one of the many that* Cassini *captured during its close approach on September 10, 2007. It was taken by the spacecraft's narrow-angle camera from a distance of about 77,000 kilometers (48,000 miles). Above: Later that day,* Cassini *swooped in to take this shot from a distance of about 3,870 kilometers (2,400 miles). The Belly Band breaks up into individual mountains that reach heights of about 10 kilometers (6 miles) along the equator.* Image: NASA/JPL/Space Science Institute



The transition from Iapetus' dark leading side to its bright trailing hemisphere does not appear in subtle shades of gray, but instead is a complicated patchwork of craters filled with dark material and highlands that are bright. The area shown here is 711 kilometers (442 miles) by 417 kilometers (259 miles). At center right of this view, taken near Iapetus' equator, are the large mountains mentioned in the image at left. Their western flanks are bright, but the surrounding lowlands generally are dark. Image: NASA/JPL/Space Science Institute

tion problems between the Huygens probe and the *Cassini* orbiter that became apparent in 2000. At the time, it was realized that during Huygens' descent onto Titan, the Doppler effect would push its radio signal outside the range of *Cassini*'s onboard receiver. The eventual solution was to add an extra orbit to *Cassini*'s flight plan, which would include an additional, but very high-altitude flyby of Titan and would reduce the Doppler effect to within the margins of the *Cassini* receiver. This extra orbit around Saturn led—by pure luck—to a passage near Iapetus with a closest approach distance of about 124,000 kilometers (77,000 miles) instead of 670,000 kilometers (415,000 miles) in the original plan.

The B/C flyby led to several important discoveries. The equatorial ridge was observed as hoped, but there was more: in bright north-polar terrain, we saw craters with dark rims that face toward the equator, and in the dark terrain of the midlatitudes, we found craters with bright rims facing the poles. From *Voyager* data, we had known of the existence of craters whose walls differ sharply in their brightness, but we initially thought that this contrast was correlated with the movement of Iapetus within its orbit around Saturn. The discovery that the relative brightness in fact depended on polar orientation proved to be a significant clue in resolving the dark/bright dichotomy riddle.

The B/C flyby also produced the best-ever imaging of the "moat crater" lit by "Saturnshine"—reflected sunlight from the planet. This feature received its nickname from low-resolution *Voyager* images, in which the crater appears as a dark ring, giving Iapetus the appearance of a white astronaut helmet with a black visor and a large hinge—the moat. In *Cassini* images, we identified the moat as an unusually fresh-looking crater with a very complex dark-bright pattern.

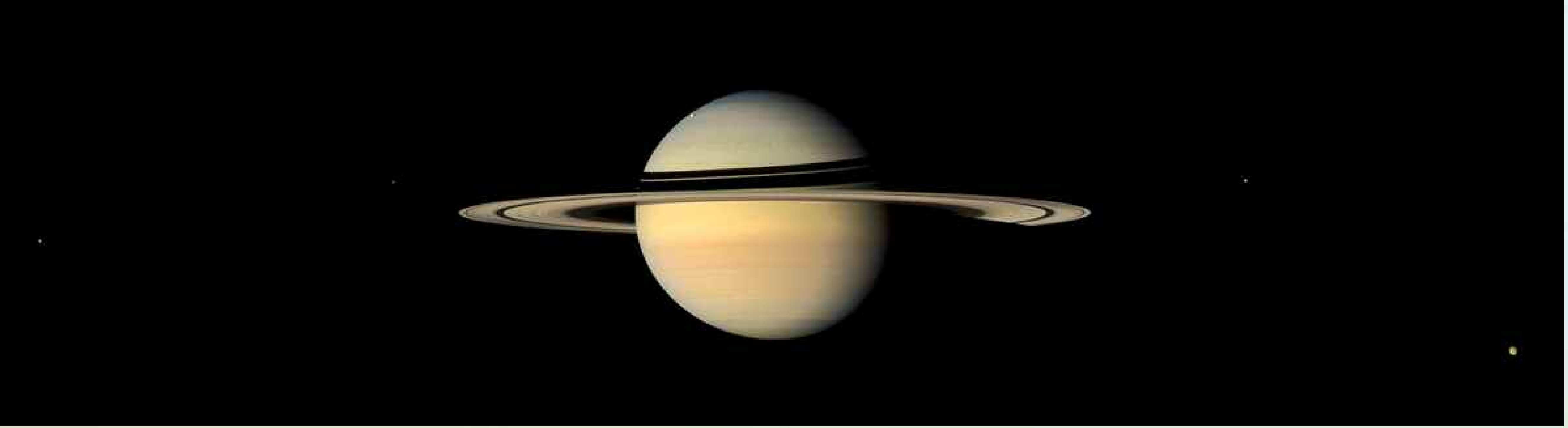
Planning, Negotiating, and More Planning

At an April 2004 meeting at the ESA center in Noordwijk, Netherlands, the *Cassini* ISS team and the *Cassini* VIMS (Visible and Infrared Mapping Spectrometer) team reached a vital agreement in terms of how to handle the closest approach part of the flyby. The two teams had been at odds because they have very different needs for their instruments to work optimally. Imaging requires a lot of shifting the spacecraft back and forth to create image mosaics, but short periods of actual exposure over the targets, whereas the VIMS spectrometer benefits from long "sit-and-stare" periods.

At Noordwijk, we agreed that during the three hours after closest approach, we would spend at least two thirds of the time in "sit-and-stare" mode and no more than one third of the time slewing between different targets on the surface. During this meeting, we also presented the broad outlines of our plans for observing the Voyager Mountains at high resolution: this would enable us to create detailed mosaics of the equatorial transition zone and the western terminator, as well as produce a multicolored image of the dark-floor crater Hamon.

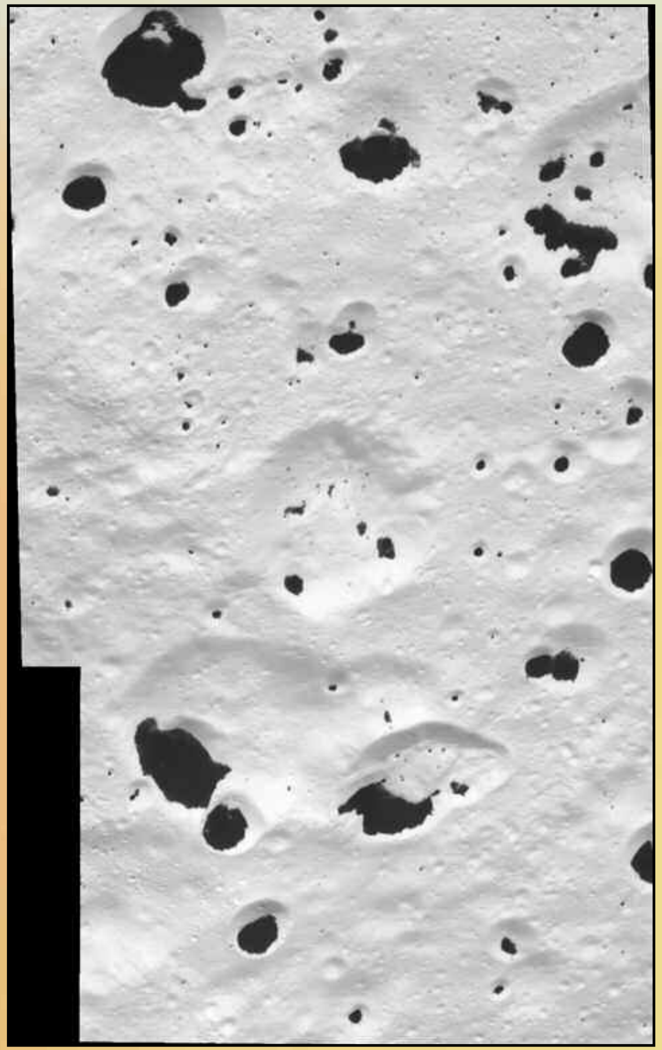
Nevertheless, our plans still did not include any imaging during the time the spacecraft neared Iapetus immediately before and also during closest approach. In an attempt to find a solution, I brought the issue to the attention of the ISS team in early 2006 and received their support for renewing our discussions with the *Cassini* navigation team regarding this problem. Perhaps, I wondered, with only modest deviations of the flyby trajectory, could a different star be found that would be occulted by Iapetus maybe 30 minutes or more before *Cassini*'s closest approach?

In summer 2006, Fred Pelletier from the *Cassini* navigation team contacted me on this issue. Fred looked at possible deviations of the flyby time, the minimum altitude, and the B-plane angle (if the spacecraft passes the moon to the left, to the right, above, or below), and the effects of all of these on fuel consumption, or "Delta-V" (velocity change of the spacecraft due to a maneuver). His conclusions did not sound promising at first. It seemed that all but the smallest deviations from the originally selected flight path would cost the spacecraft dearly in terms of precious fuel to correct. Nevertheless, Fred sent me a list of possible minor trajectory changes that looked acceptable for the navigation team. To my great surprise and enormous pleasure, the list contained one deviation that had Iapetus occulting the star Sigma Sagittarii more than one hour before closest approach! Since that moment, I was eager to push the development of this alternative trajectory in a way that would satisfy all the teams.



On September 9, 2007, as Cassini *sped toward its rendezvous with Iapetus, it swung around and took this panoramic view of Saturn and six of its satellites.*

Moons visible in this image are Dione at center left, Enceladus near the left side ansa (or ring edge), Mimas as a speck against the ring shadows on Saturn's western limb, Rhea against the bluish backdrop of the Northern Hemisphere, Tethys (1,071 kilometers, or 665 miles across) near the right ansa, and Titan (5,150 kilometers, or 3,200 miles across) near lower right. Image: NASA/JPL/Space Science Institute



In some places, the spotty black-on-white of Iapetus' transition zone looks like the coat of a dalmation. The bright material on the moon's frozen surface is water ice, and the dark material, preferentially found at the bottoms of craters, probably is carbonaceous in composition. This view, taken by Cassini*'s narrow-angle camera, is from the hemisphere that faces away from Saturn. T he image scale is about 32 meters per pixel.* Image: NASA/JPL/Space Science Institute

Everybody Wins

It worked! After going through a more detailed analysis with Fred, I brought the new trajectory before the SOST group, which endorsed it enthusiastically. Soon *Cassini*'s project scientist was convinced, and eventually the *Cassini* project manager was as well. In January 2007 he gave the navigation team the go-ahead to incorporate the trajectory tweak into the spacecraft's official plans.

It's rare to have a situation in life in which everybody wins, but in this case almost every instrument on board the spacecraft benefited from the change: the ORS instruments could now perform their high-resolution surface studies continuously, starting 45 minutes before closest approach. The Voyager Mountains could now be observed rising over the horizon, and the dark terrain ridge would now be covered partly by high-resolution imaging. This additional observation time would also enable the spacecraft to make a major roll, allowing the fields-and-particles instruments to sample data of high quality—a major gain, because the spacecraft attitude in the original trajectory had been very bad for them, but now a better trajectory could be selected for the period around closest approach, before the roll.

Even the UVIS star occultation was better now. The improved data collected by *Cassini* on Iapetus' orbit showed that the moon would not in fact occult the original star, Zeta Ophiuchi, but only graze it. With the tweaked trajectory, the new occulting star, Sigma Sagittarii, would indeed disappear behind the moon and would do so at a slower pace, allowing more time for the UVIS instrument to gather data. Last but not least, as a ripple effect, the new trajectory also allowed for a stellar occultation by a volcanic plume from the moon Enceladus during a later orbit.

Final Preparations

In early 2007, we began work on the final pointing and shutter commands. In addition to coordinating the various ISS observations, my colleague in Berlin, Thomas Roatsch, and I had the task of planning precisely where the spacecraft should point during the period 55 minutes before to 3 hours after closest approach. This task required not only balancing the demands of the VIMS and ISS instruments but also implementing specific requirements of the CIRS spectrometer and the fields-and-particles instruments.

We had to fit a total of 11 different image mosaics, along with 65 surface pointings ("footprints") and 252 shutter actions into this time frame. Our planning activities for the camera were hampered by the fact that we had not yet seen large parts of the trailing side of Iapetus at sufficient resolution to determine the proper exposure times. There were strong indications that these areas are among the brightest on Iapetus—but how bright, exactly? Fortunately, *Cassini*'s 12-bit cameras are robust against such uncertainties, and I was relatively confident that my guesses would be adequate. However, it was only after we received low-resolution data in early July confirming that the exposures had been set right that I was truly able to sleep well at night.

It was also in July that the final commands that would guide the spacecraft through its Iapetus flyby were set in stone. The only remaining uncertainty now was the 70-meter Deep Space Network dish in Madrid, which would receive large parts of the data transmissions from the spacecraft. The Iapetus flyby was to take place near the end of a maintenance period, and it was unclear until very late in our planning if the giant dish would be back online in time.

Approaching the Mystery Moon

We took the first images showing Iapetus as a thin crescent on September 3 at a resolution of nine kilometers (about six miles) per pixel, and they looked much as we expected. However, subsequent observations on September 5–7 included some blank images. Fortunately, I managed to figure out the cause and realized that the same mishap would not occur for the top-priority data. Early on September 9, *Cassini* produced a mosaic of Saturn and its biggest moons "as seen from Iapetus," showing how Saturn would look to a future Iapetus astronaut.

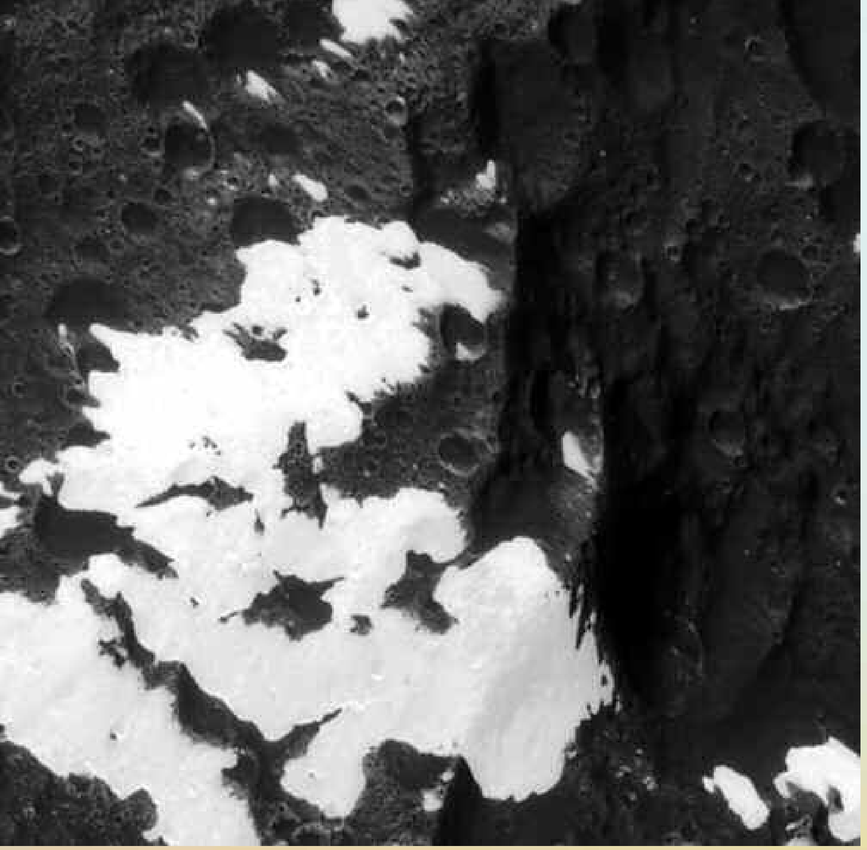
At this point, *Cassini* was so close to Iapetus that the moon no longer fit within the field of view of the spacecraft's narrow-angle camera. Because of problems with NASA's Deep Space Network, only one of two ISS mosaics of Iapetus's growing crescent—taken about half a day before closest approach—made it back to Earth. Fortunately, the one we got was the higher-quality mosaic. The CIRS instrument was less lucky: it lost a very important polarization observation.

Our highest priority now was to record data beginning 5 hours and 25 minutes before closest approach at an altitude of 45,000 kilometers (28,000 miles) above the moon's surface. On Monday morning, September 10 (European time), two of the most important events of the year were taking place at the same time: *Cassini* had its closest encounter with Iapetus, and my son had his first day in a new school. The school's inauguration ceremony exactly coincided with the most important activities at Iapetus. As I enjoyed the ceremony, I followed in my mind what the spacecraft was doing each moment.

Getting the Data—A Bittersweet Story

Initial data from the closest approach began arriving in the middle of the night in Europe, and by the following morning, we had two new images. The timing was selected so that the Deep Space Network stations at Goldstone and Canberra could track *Cassini* at the same time, providing a bit of insurance that no data would be lost. This strategy worked—besides imaging and other data, the most important radar data made it back to Earth with the downlink.

The bulk of the data were expected to arrive in mid-



A close look at the "Voyager" mountains was a major quest for the Cassini *team. The scientists first discovered the mountains in 1999 while looking through* Voyager 2 *data. The mountains turned out to be mainly dark, with bright patches seemingly draped over them. This image was taken at a distance of 9,240 kilometers (5,740 miles) from the surface. The scale is 55 meters per pixel.* Image: NASA/JPL/Space Science Institute

morning, and indeed, a few images of the ridge appeared on the screens. For many hours after that, however, no data followed. At first, I thought that the real-time data stream from the JPL computers to the imaging team servers in Boulder, Colorado, had been interrupted, but after several hours of silence I became nervous. Finally, in the late afternoon European time—morning in California—I received a phone call from JPL. It seems a cosmic ray hit triggered a switch in *Cassini*'s transmitter, and the spacecraft responded by stopping all activities, including data transmission. It was the first time in more than four years that the spacecraft had gone into safe mode.

This "cosmic" bad luck was disappointing because it became clear immediately that the observations planned for the subsequent days as the spacecraft was moving away from Iapetus would not take place. The losses included not only a global multi-colored mosaic of the trailing side and other observations of Iapetus but also some important and unique observations of Saturn. The spacecraft, in fact, would not be operating any of its science instruments for several days.

Fortunately, the spacecraft navigational systems could be returned to operation within hours. This was very important, because the crucial maneuver designed to bring *Cassini* back to its original trajectory, using 11 kilograms of propellant, was to take place only three days after the flyby. If this maneuver had been missed, *Cassini* would have needed to expend a huge amount of fuel to be put back on track.

The other lucky fact was that the entry into safe mode occurred at the beginning of the downlink, after *Cassini* had acquired all the Iapetus flyby data. If the spacecraft had entered safe mode one day earlier, all the data from the flyby would have been lost.

A Quest Completed

Later that night, the DSN station in Goldstone, California picked up the data stream once more, and a large number of images began flowing in. The Voyager Mountains turned out to be bright patches on mainly dark mountains; the dark/bright boundary appeared very complex; and, strangely, the terrain was either dark or bright but almost never gray—much like a Dalmatian dog's coat.

All the dark crater walls were facing the equator, whereas the bright walls were facing the poles at the moon's low and mid latitudes. The ridge appeared continuous to a certain point, then turned into separate isolated ridges that continued up to the location of the first, easternmost of the *Voyager* Mountains. The images of this mountain, seen rising over the horizon, arrived near midnight. I could finally see what I had been hoping to see for more than seven years.

Surprisingly, the mountains looked very similar to what I had expected, yet they were somewhat different. I expected their pyramidal shape, but I did not anticipate their level of brightness. The visible eastern flank is actually covered by dark, not bright, material. (This turned out to be a lucky break, because the exposure time had been set slightly too long, and this mountain would have been overexposed if its bright patches would extend to its eastern flank.)

We discovered another feature in the images that we had hoped to find: small, bright craters in the dark terrain. We hadn't detected any during the B/C flyby, and we had some doubts as to whether the craters actually were there. With the detection of these small craters—mostly smaller than a football stadium—we can now roughly estimate the thickness of the dark material and the length of time it takes a fresh, bright crater to turn as dark as its surroundings.

In retrospect, the Iapetus flyby was one of the most challenging as well as one of the most exciting satellite flybys of the *Cassini* mission. Unfortunately, some of the data collected from the moon were lost irretrievably, mostly because the spacecraft entered safe mode at a crucial time. Fortunately, however, we received nearly all the top-priority data we had hoped for, and only less important images were lost. This means that the possibly only Iapetus flyby to take place during the lifetime of most of us can be considered a big success. All the data, not just the images, are wonderful, stunning, strange—and alien.

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