The Moon That Would Be a Planet

Titan, Saturn's largest natural satellite, scarcely deserves to be a called a mere moon. It has an atmosphere thicker than Earth's and a surface that is almost as varied

By Ralph Lorenz and Christophe Sotin

KEY CONCEPTS

- Before the Cassini/Huygens mission, Titan was a cipher—the largest expanse of unglimpsed terrain left in the solar system, larger than the planet Mercury.
- Having penetrated the haze with infrared images, radar and a descent probe, the mission has discovered a dynamic landscape of rivers, lakes, dunes, mountains and possibly volcanoes. It is a frigid version of Earth, where methane substitutes for water, water substitutes for rock, and weather cycles last centuries.
- Studying Titan is already elucidating the geologic processes of our own planet, such as dune formation and climate change.

—The Editors

If we had not known the images were coming back from Titan, we might have guessed they were new pictures of Mars or Earth. Some people in the control room saw the California coast, some saw the French Riviera, and one person even said that Saturn's biggest moon looked like his backyard in Tucson. For three weeks, the Huygens probe had coasted, dormant, after detaching from the Cassini spacecraft and being sent on its way to Titan. Those of us watching anxiously felt a deep personal connection with the probe. Not only had we worked on the mission for a large part of our careers, but we had developed its systems and instrumentation by putting our minds in its place, to think through how it would function on an alien and largely unknown world. We imagined Titan might be like the comparably large moons of the outer solar system, such as Jupiter's cratered Callisto or grooved Ganymede.

And so on the morning of January 14, 2005, at the European Space Operations Center in Darmstadt, Germany, the pictures caused jubilation and puzzlement in equal measure. None of us expected the landscape to look so Earth-like. As Huygens parachuted down, its aerial pictures showed branching river channels cut by rain-fed streams. It landed on the damp, pebble-covered site of a recent flash flood. What was alien about Titan was its eerie familiarity.

Now, five years on, we have had time to digest the probe's findings and put them in the bigger picture that Cassini, having flown past Titan more than 60 times in its looping orbit around Saturn, has gradually pieced together. In size (bigger than Mercury), dynamism (more active than Mars) and atmosphere (thicker than Earth's), Titan is a planet by any other name. A wide variety of geologic processes shape its surface. Methane plays the role that water does on Earth. It evaporates from lakes, forms clouds, precipitates out, carves valleys and flows back

RON MILLER

IT WAS a dark and stormy night on Titan. It often is. Smoggy haze all but obscures the sun and Saturn. In the distance, the rain falls in torrents.

into lakes. If only the atmosphere had some oxygen and the temperature were not –180 degrees Celsius, you would feel at home on Titan.

Seas of Sand, Seas of Methane

Before Cassini, our perspective on Titan was very one-dimensional. When the Voyager spacecraft flew by in 1980 and 1981, it saw only a haze-shrouded, orangish billiard ball, and the best that observatories in the mid-1990s could manage was a crude infrared map showing vaguely dark and bright areas [see "Saturn at Last!" by Jonathan I. Lunine; Scientific American, June 2004]. Scientists talked in terms of Titan's surface or its atmosphere, as if a single measured quantity or descriptive phrase could capture an entire world. These generalizations have withered under the barrage of new data. We now have to refer to the low-latitude sand seas, or the atmosphere above the north pole in summer, or a cloudy day in the southern lake district.

Titan's low latitudes are a mix of rugged, bright hills, most notably the vast area named Xanadu, and dark sand seas, once thought to be liquid seas. (Astronomers are always tempted to call dark areas "seas," the lunar mares being the most obvious example.) Sand dunes 100 meters high, like the largest dunes found on Earth, stretch for tens to hundreds of kilometers. The dark sand on Titan is not made of silicate minerals such as quartz, as on Earth, but of hydrocarbons, looking rather like heaps of coffee grounds.

Around the poles, we find liquid hydrocarbons: small lakes in steep pits a few tens of kilometers across; shallow playa such as Ontario Lacus, slightly larger than its namesake of Lake Ontario; and seas such as Kraken Mare, as big as the Caspian. The surface level of these lakes appears to have changed with time. Wedged in between the desertlike tropics and the wet polar regions are the strangely inscrutable midlatitudes, with heavily eroded landscapes and evidence of flowing liquid.

Planetary scientists recognized after the Voyager encounters that Titan might have a methane cycle with clouds, rain and seas analogous to the hydrologic cycle on Earth. This speculation was based in part on a single data point: the surface temperature of Titan was close to the triple point of methane, just as the Earth's is close to that of water. At this temperature, gas, solid and liquid can coexist. Did it mean that transitions among these three phases of matter regulated Titan's temperature, or was it coinci-

ESA/NASA/JPL/UNIVERSITY OF ARIZONA (*landing site*); NASA/JPL/SPACE SCIENCE INSTITUTE (*Titan* and *sand dunes in Belet region*); SOURCE: USGS NATIONAL CENTER FOR EROS AND NASA LANDSAT PROJECT OFFICE (*Namibia dunes*); NASA/JPL/USGS (*large north polar region*); NASA/JPL/UNIVERSITY OF ARIZONA/DLR (*Kraken Mare glinting*); NASA/JPL (*close-up of Kraken Mare*); NASA/JPL/ESA/UNIVERSITY OF ARIZONA (*close-up of river channels*)

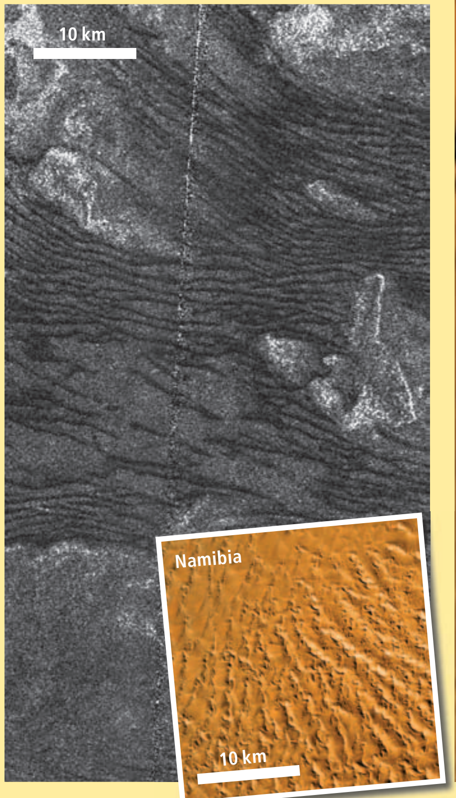
[SURFACE]

A Tour of Titan

The Cassini orbiter and Huygens descent probe have given humanity its first real view of Titan's surface, one of the most varied in the solar system.

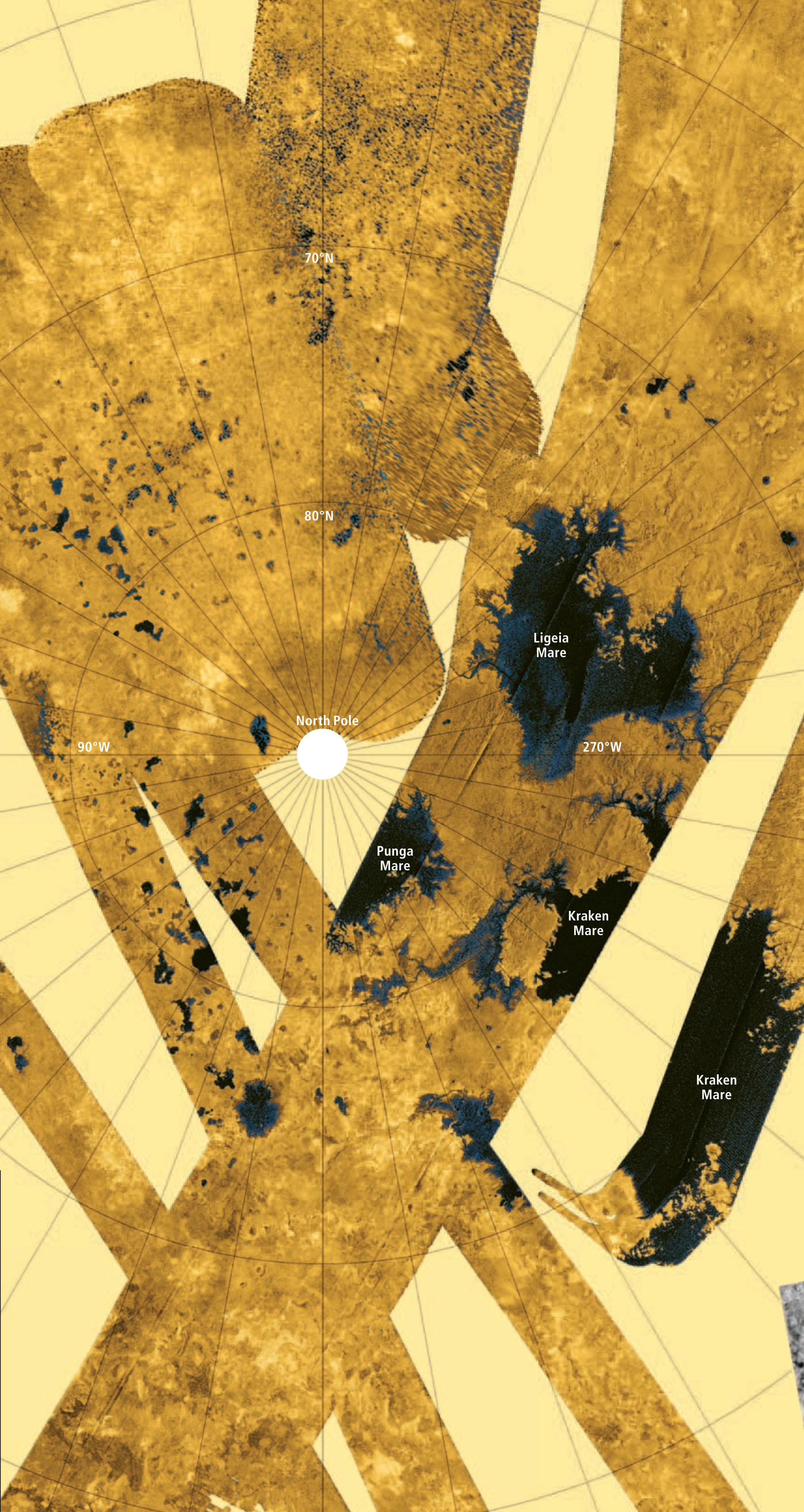
▶ Huygens saw a landscape of fist-size chunks of ice strewn on moist sand. Their rounded shapes suggest they were eroded by flowing liquid, presumably methane.

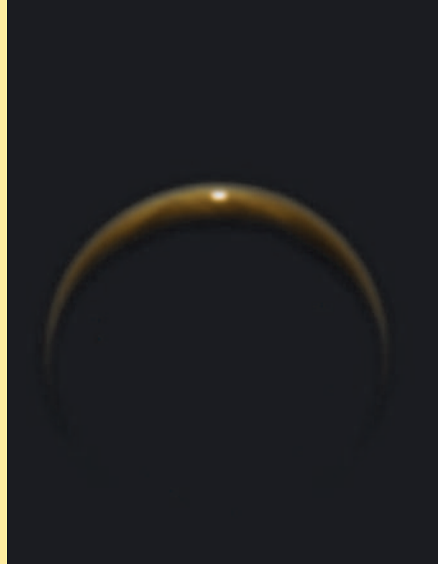
▼ Sand dunes in the Belet region show up as dark streaks on a radar image. Tens to hundreds of kilometers long, they run parallel to the average wind direction and break around bright mounds. The sand is thought to be made of hydrocarbon molecules, like coagulated smog. Despite this exotic composition, the dunes have the same spacing and height as the largest on Earth, such as those in the Namib Desert (*inset*)—perhaps because the atmospheric boundary layer, the turbulent lowest layer of air, is the same thickness on both worlds.



◀ **TITAN ON THE EVE OF CASSINI**

In 1980 Voyager 1 mission scientists had to decide between making a close flyby of Titan and aiming for an eventual rendezvous with Pluto. They chose Titan. And all they saw was a featureless haze—a "fuzzy, seamless tennis ball," in the words of team member Tobias Owen [see "Titan," by Tobias Owen; Scientific American, February 1982]. The Voyager 2 team decided to skip Titan. Although the images were disappointing, Voyager 1's ultraviolet, infrared and radio instruments discovered that the atmosphere is mostly nitrogen and that conditions allow for methane clouds, rain and even oceans. Clearly, something interesting lurked under the haze.

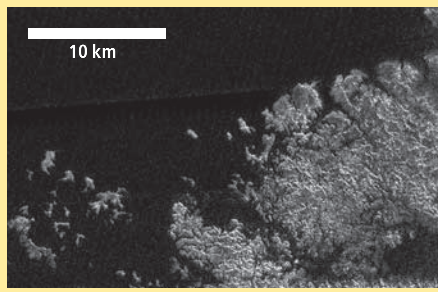




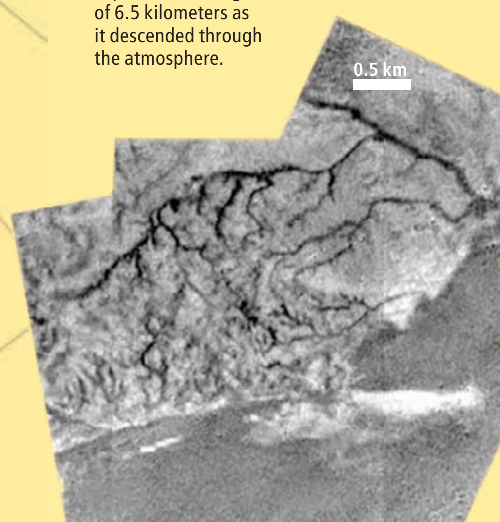
▲ Sunlight glints off Kraken Mare, as seen last July by Cassini's infrared imager. The lake had been in winter darkness for 15 years and passed into spring in August.

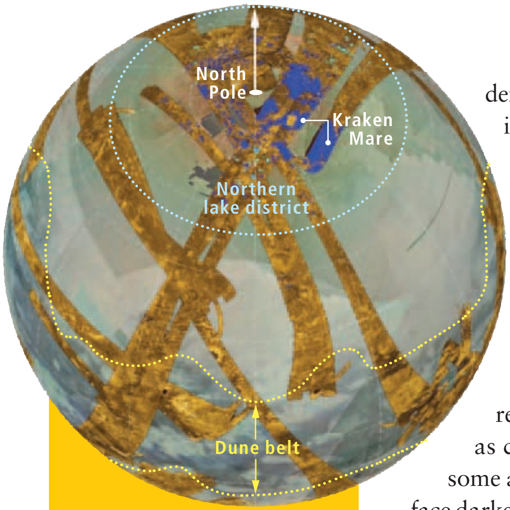
◀ Cassini radar images of Titan's north polar region show dark areas that are presumably lakes of methane and ethane, including Titan's three largest (*labeled*). Liquid appears dark for the same reason that a wet road looks dark when you are driving at night: the smooth surface reflects the radar or headlight beams away from your eye. Dry, rough terrain looks bright (*gold*).

▼ A close-up of Kraken Mare shows islands, cays and other features evocative of Earthly seas.



▼ River channels may have been carved by liquid methane flowing from a series of ridges (about 200 meters high) down to a lakebed (now dry). The pattern of tributaries suggests that the methane rained down on the surface. Huygens captured this image from an altitude of 6.5 kilometers as it descended through the atmosphere.





GLOBAL MAP of Titan has been gradually assembled by Cassini's main camera, observing in near-infrared light, supplemented by partial radar coverage (*gold, above*). It reveals the general variation of terrain with latitude, as well as a paucity of impact craters (*orange, below*)—a sign that the surface is geologically young.

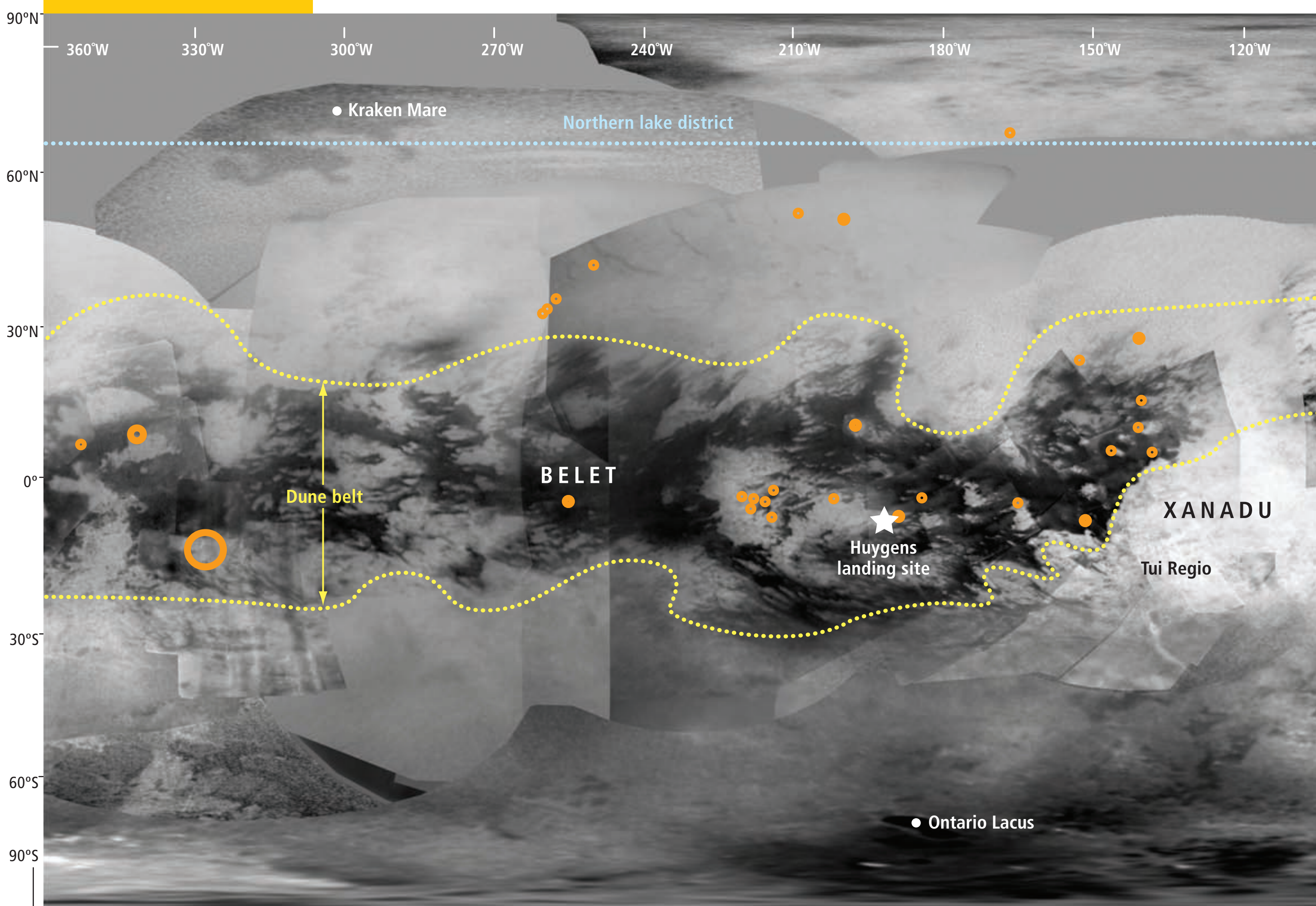
dence? The first good evidence that the idea held water, so to speak, was the detection by ground-based telescopes in the late 1990s of transient clouds at the altitudes at which methane would be expected to condense. Better telescopic observations, and then Cassini, were able to see these clouds in action, puffing upward just like terrestrial cumulus and then dissipating as cloud droplets turned into rain. In some areas, Cassini has observed the surface darken after clouds have passed over, perhaps indicating that rain fell there.

Cassini has not directly observed precipitation, but the Huygens aerial photographs leave no doubt that at least parts of Titan's landscape have been shaped by rainfall and the rapid flow of liquid across the surface. The probe's landing site was about 10 degrees south of the equator, at the edge of some bright, icy hills in the midst of a vast sand sea. The imagery shows a couple of long dunes in the distance, but the immediate area around the landing site is more like a streambed, littered with rounded cobbles on top of sand. A penetrometer designed and built by one of us—Lorenz, as a graduate student some 12 years before the hardware got to its destination—poked into the ground and measured its mechanical properties, showing it was somewhat soft but cohesive, much like wet sand or clay.

Thermometers indicated that heat was wicked away from the probe so quickly that the ground must have been damp—just as a finger stuck into moist sand at the beach feels colder than one in dry sand. Recent work suggests that methane vapor may have also condensed on the cold baffle of the Huygens camera, and one image shows the distinctive pattern of light reflected by a dewdrop as it falls across the camera's field of view—the first close-up shot of liquid on an extraterrestrial world.

Planet Gone Wild

Titan is to the hydrologic cycle what Venus is to the greenhouse effect : a terrestrial process taken to extremes. On Earth, solar energy is enough to evaporate about one meter of water per year. The atmosphere can hold only a couple of centimeters' worth of moisture before clouds and rain form, so terrestrial weather is broadly char-



acterized by showers dropping a few centimeters of rain every week or two.

On Titan, the feeble sunlight allows only about one centimeter of evaporation per year. But the atmosphere can hold the equivalent of about 10 meters of liquid. So Titan's weather should feature torrential downpours, causing flash floods, interspersed by centuries of drought. The Huygens landing site was probably the scene of a flash flood, which could have happened a month before the landing—or a millennium before. Titan's boom-bust weather cycle is an extreme version of what may be happening on Earth because of global warming. As our lower atmosphere, or troposphere, warms, it holds more moisture, and both rainstorms and droughts become more intense.

On Earth, the tropics are dominated by the Hadley circulation. Warm air rises at the equator and, as it flows toward the poles, is sheared by the planet's rotation. At about 30 degrees latitude, air descends toward the surface. Because the down-welling air is dry, most terrestrial deserts are found at this latitude. But Titan rotates very slowly, only once every 15 days, so the corresponding circulation pattern extends from the summer midlatitudes all the way to the winter pole, with the overall result that the entire equatorial region gets dried out—hence the extensive sand seas centered on the equator.

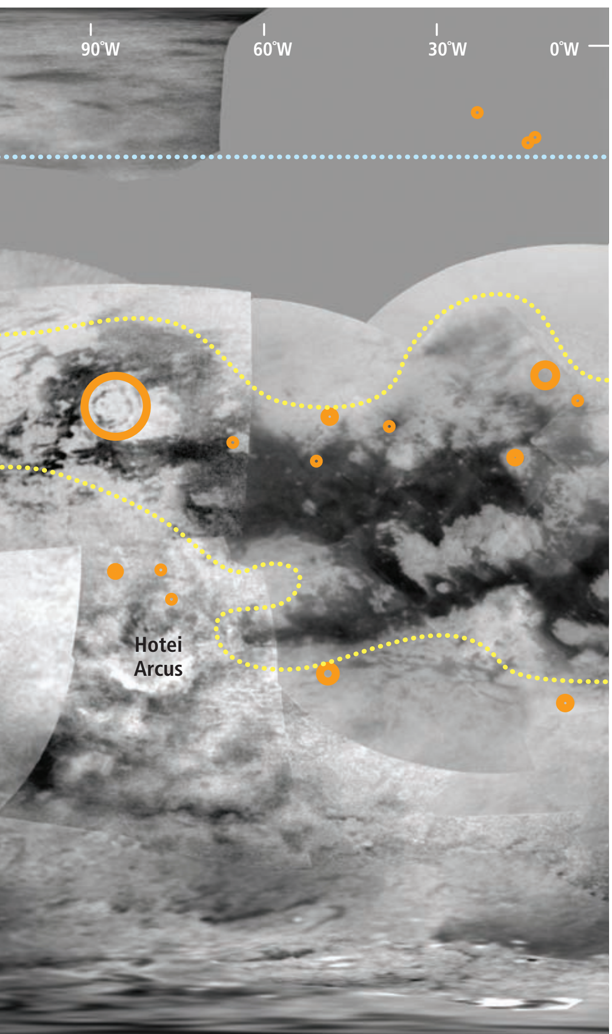
Though much colder, Titan's atmosphere has a temperature profile similar to Earth's. The troposphere is warmed by a greenhouse effect, and temperatures fall with height. Above it is the stratosphere, which is warmed by the absorption of solar radiation. On Earth, the absorber is ozone, whereas on Titan it is the opaque haze that envelops the world—underscoring the recurring theme of Titan science, familiar physics with unfamiliar substances.

To analyze the haze, Cassini has sampled the upper atmosphere at an altitude of around 1,000 kilometers as it sweeps past Titan. Before Cassini, we expected the haze to consist of a comparatively light hydrocarbon molecule such as ethane, with an atomic weight of 30. Yet Cassini has detected a dramatic and unexpected abundance of heavy organic molecules, including benzene, anthracene and macromolecules with atomic weights of 2,000 or more. This material has formed by the action of sunlight on atmospheric methane. Presumably the material eventually coagulates into larger grains and settles to the surface to create the seas of sand, but how that happens is not at all understood.

A Global Apocalypse?

Along with the short-term water cycle driven by solar energy, Earth has a long-term cycle driven by plate tectonics. It involves the exchange of water between the interior and surface. Over hundreds of millions of years water is released from the interior at volcanic hotspots and mid-ocean ridges and recycled into the interior at subduction zones, the areas where crustal plates collide and sink. Were it not for this cycle, water would have built up in the atmosphere and ultimately escaped to space.

What about Titan? The sun-powered photochemical reactions in the upper atmosphere produce heavier organics at such a rate that they would use up all the methane in the atmosphere and on the surface within a few million years unless it were replenished [see "The Mystery of Methane on Mars and Titan," by Sushil K. Atreya; Scientific American, May 2007]. Therefore, Titan must have underground reservoirs of methane that feed the



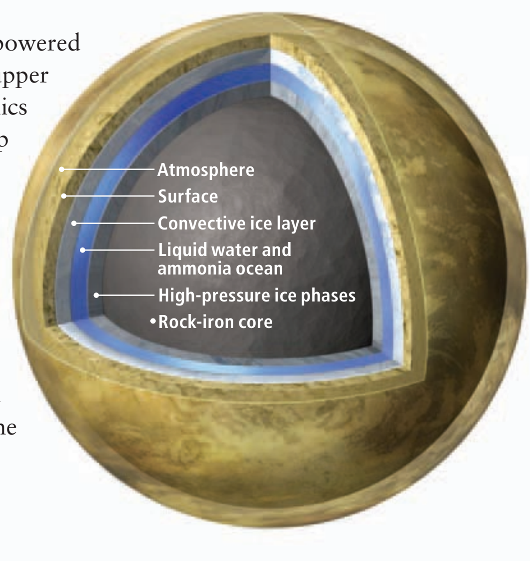
NASA/JPL/SPACE SCIENCE INSTITUTE (*surface mosaic*); NASA/JPL/CALTECH/UNIVERSITY OF ARIZONA/CASSINI IMAGING TEAM (*global map*); KEVIN HAND (*cutaway view*); COURTESY OF RALPH LORENZ (*Lorenz*); COURTESY OF BRIGITTE SOTIN (*Sotin*)

[THE AUTHORS]

Ralph Lorenz helped to design and build the Huygens probe, made the first maps of Titan with the Hubble Space Telescope and led the team that planned Cassini's radar observations of Titan. He is now at the Johns Hopkins University Applied Physics Laboratory. Among his many books is *Spinning Flight,* for which he instrumented frisbees to study their aerodynamics. Christophe Sotin has been involved in making and analyzing observations of Titan's surface with Cassini's Visual and Infrared Mapping Spectrometer. He is now at the Jet Propulsion Laboratory of the California Institute of Technology. He remembers, as a 10-year-old, camping in a remote area of Brittany and listening to the radio as Neil Armstrong stepped out onto the moon.

GOOEY ON THE INSIDE

Titan's density indicates the moon is half rock (the core) and half water (the mantle and crust), with a veneer of hydrocarbons. Models predict that the upper 50 kilometers of ice is warm and pliable enough to undergo slow convection. Underneath it may be an ocean of liquid water mixed with ammonia. The ocean could be hundreds of kilometers thick and may once have been even thicker. Some scientists have speculated that the ocean could support life.



gas into the atmosphere—a rough analogue of Earth's long-term water cycle.

Cassini has seen no volcanic hotspots or plate tectonic features, but it has discovered at least two areas that look like frozen volcanic flows, Hotei Arcus and Tui Regio. They are brighter in near-infrared light than any other area on Titan, showing that they are compositionally distinct. Some have suggested that the bright material is a coating of carbon dioxide or ammonia frost from an eruption, but its composition and origin remain a mystery. Another sign of geologic activity is the almost complete lack of impact craters, a sign that volcanism or similar processes pave them over. Given the expected impact rate, the surface is between 200 million and one billion years old.

Because Titan appears to lack plate tectonics, its interior cycling may not occur continuously, as on Earth, but in fits and starts. In one proposed reconstruction of Titan's history, the interior released methane into the atmosphere during three periods: the formation of Titan 4.5 billion years ago; the onset of convection in the core 2.5 billion years ago; and the onset of convection in the ice crust within the past billion years. The most recent episode would have unleashed a global volcanic apocalypse that repaved the entire surface, much like the cataclysm that befell Venus a billion years ago or so [see "Global Climate Change on Venus," by Mark A. Bullock and David H. Grinspoon; Scientific American, March 1999]. Immediately after the injection of methane, the surface may have been even wetter than it is today. In between these intense episodes, Titan was tectonically quiet, and the flow of methane from the interior was a dribble at best. Such a model explains not only the low crater density but also the detailed isotopic composition of the atmosphere.

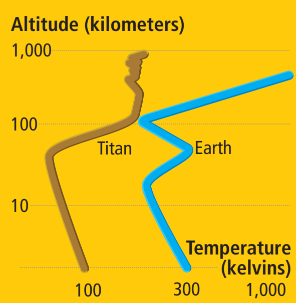
As well as deep reserves of methane, Titan may also have an underground ocean of liquid water, as mathematical models describing its interior evolution predict. Electrical measurements made by Huygens hinted at an electrically conductive layer of material about 45 kilometers below the surface, and water is the prime candidate. Cassini radar measurements suggested that the crust rotates faster than the core, as though a liquid layer acted as a giant bearing that allowed the two to spin at different rates; a recent reanalysis questions this conclusion, however.

Unfortunately, Titan's atmosphere prevents Cassini from approaching the surface more closely to look for the secondary magnetic field that Saturn would induce in an ocean. Such fields were crucial to the case for oceans on the Jovian satellites [see "The Hidden Ocean of Europa," by Robert T. Pappalardo, James W. Head and Ronald Greeley; Scientific American, October 1999]. As scientists debate whether the secondary field might still be detectable, they have drawn up plans to search for the magnetic signal, as well as telltale distortions of Titan's gravitational field, in the coming decade.

[ATMOSPHERE]

LIKE EARTH, ONLY COLDER

Titan's atmosphere, like Earth's, has a troposphere (a lower, dynamic layer where weather takes place) and a stratosphere (a stable layer heated by solar ultraviolet radiation). These and other layers are defined by the change of temperature with height (*right*). Titan's atmosphere is more than 200 degrees colder and, because of the satellite's weaker gravity, vertically stretched. Multiple layers of haze, consisting of hydrocarbon particulates akin to smog, play the same role as Earth's ozone layer.



LUCY READING-IKKANDA (*top*); KEVIN HAND (*bottom*)

Titan's Ice Ages

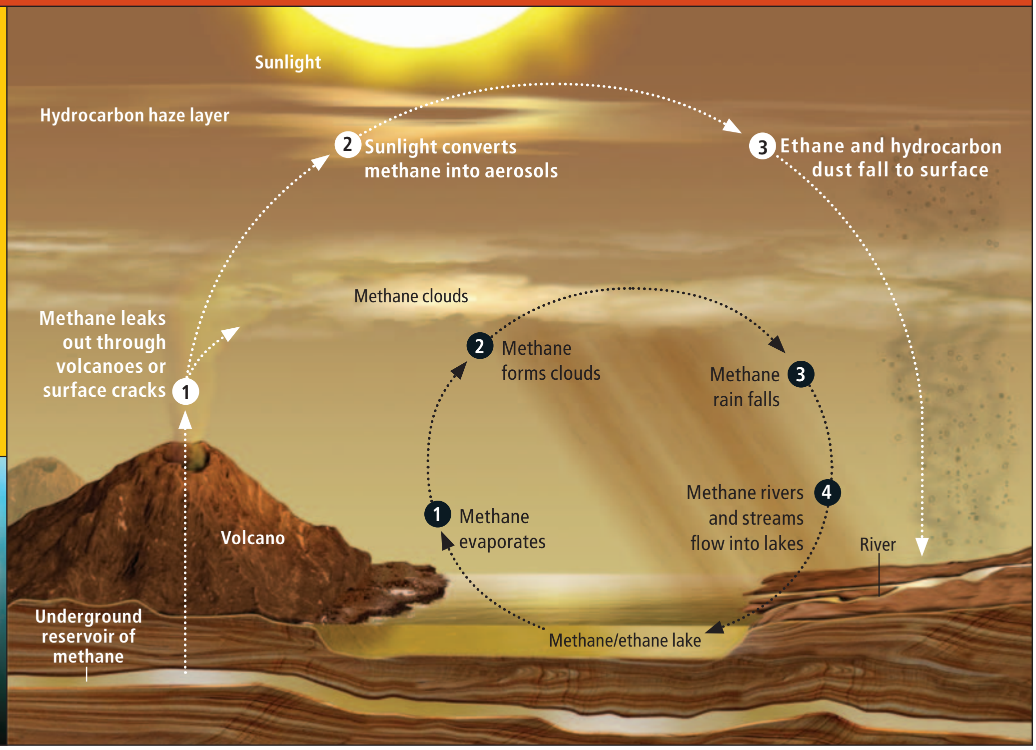
In addition to weather patterns occurring on a seasonal cycle and atmospheric replenishment occurring over geologic time, both Titan and Earth undergo climate change over intermediate periods of tens of thousands to millions of years. As first realized by 19th-century Scottish

[THE METHANOLOGICAL CYCLE]

FORECAST: A DELUGE OF METHANE

Methane undergoes a short-term cycle (*black*) much like the water cycle on Earth. Over geologic time there is an episodic one-way flow (*white*) of methane from interior reservoirs to the upper atmosphere, where solar radiation converts it to ethane and heavier hydrocarbon—forming the haze. The particulates settle onto the surface as what Carl Sagan called "manna from heaven."

Methane clouds over south polar region



NASA/JPL/UNIVERSITY OF ARIZONA/UNIVERSITY OF NANTES (*methane clouds*); KEVIN HAND (*methane cycle*)

scientist James Croll and later refined by Serbian geophysicist Milutin Milanković in the early 20th century, gravitational forces exerted by the other planets slowly shift Earth's tilt and orbit, altering the intensity of solar heating and giving rise to the cycle of ice ages.

On Titan, the southern summer is shorter but more intense than it is in the north, because Saturn (and therefore Titan) has an elliptical orbit around the sun. It is about 10 percent closer to the sun during southern midsummer. These asymmetric seasons may pump volatile compounds such as methane and ethane from the south to the north, which now has far more lakes and seas. Over time, however, the relative alignment of Titan's pole and Saturn's elliptical orbit shifts. In 30,000 years the northern summer will be the more intense one. Lakes will dry up in the north, and new ones will form in the south. It is yet another way that Titan is more like a terrestrial planet than an icy moon.

Cassini's findings of an exotic yet familiar landscape are prompting scientists to look at Earth in a new way. For example, Titan's fields of linear sand dunes resemble those in the Namib or Saharan deserts, where the dunes line up along the average of two dominant wind directions. Yet atmospheric simulations for Titan have trouble reproducing the dune orientations. The discrepancy may be a sign that scientists do not fully understand the formation of such dunes or that Titan's winds are controlled by effects not yet included in the simulations.

Moreover, observations of Titan's lakes so far show them to be dead flat, with no waves on the surface, even though the lower gravity and thicker air should, if anything, increase the wave strength. What does this stillness mean for our understanding of wind-wave generation? Titan's rotation rate may vary slightly with the seasons as the atmosphere and surface spin each other up and down like giant flywheels—an effect that is also seen, albeit much weaker, on Earth.

Thus, as is often the case in planetary exploration, Cassini's findings are prompting deeper questions. The rich range of scientific problems posed by Titan and the complex surface-atmosphere interactions will ultimately require a series of missions—just like NASA's Mars program—including landers, rovers, even balloons. Meanwhile Cassini continues to fly by Titan every few weeks. Last August marked the northern spring equinox on Titan, and as the sun progressively moves north, the atmospheric circulation and cloud patterns will change before our eyes. As the northern polar regions, which have been in cold, stagnant darkness, warm up, the one thing we can expect is the unexpected. ■

➥ MORE TO EXPLORE

Episodic Outgassing as the Origin of Atmospheric Methane on Titan. Gabriel Tobie, Jonathan I. Lunine and Christophe Sotin in *Nature,* Vol. 440, pages 61–64; March 2, 2006.

Titan Unveiled: Saturn's Mysterious Moon Explored. Ralph Lorenz and Jacqueline Mitton. Princeton University Press, 2008.

Titan: Exploring an Earthlike World. Athena Coustenis and Fredric W. Taylor. World Scientific, 2008.

Rivers, Lakes, Dunes, and Rain: Crustal Processes in Titan's Methane Cycle. Jonathan I. Lunine and Ralph D. Lorenz in *Annual Review of Earth and Planetary Sciences,* Vol. 37, pages 299–320; May 2009.

Titan from Cassini-Huygens. Edited by Robert H. Brown, Jean-Pierre Lebreton and J. Hunter Waite. Springer, 2009.