Titan's Soggy Enigma

Where Goes the Rain?

Donald F. Robertson

It is raining. A stream emerges from a wide canyon cut through low hills. It meanders across a fine-grained beach and runs gently down to a calm sea.

At first glance, the scene looks remarkably like Earth. Look closer, though, and this rain is fantastically strange. The raindrops are half again the size of drops on our planet. They fall with dreamlike slowness in the low gravity beneath a hazy, orange sky. This rain is not made of water: it's methane (CH_4).

This vision of Saturn's giant moon Titan is not pure fiction. Since the paired NASA Cassini spacecraft and ESA Huygens probe first arrived in the system in 2004 (*S&T*: January 2005, page 20), scientists have discovered indirect but strong evidence for rain on Titan. Cassini has observed temporary discoloration of desert sands in the wake of cumulus clouds, and radar images show canyons and dendritic channels, which imply drainage from precipitation.

Some of these channels may be active riverbeds emptying into dark areas near the poles. These areas can be the size of North American Great Lakes. Specular reflections — like sparkles on a lake at sunset — and other evidence imply that the dark features are liquid-filled seas. If so, they are mirror-flat. The moon's weak surface winds are typically predicted to blow below the threshold necessary to make waves, but they might kick up occasional ones up to a half meter (less than 2 feet) tall during summer, says planetary scientist Alex Hayes (Cornell University).

Flat, lake-like features, dendritic channels, river deltas, and discolored sands — it all adds up to strong, albeit circumstantial, evidence for rainfall.

If it does rain methane on Titan, the compound must return to the sky through evaporation so that it can fall as new rain. Scientists have had a hard time finding that return path and closing Titan's weather cycle. But recent studies have uncovered strong evidence of evaporation — and potentially from an unexpected source.

Mysterious Methane

Scientists think Titan's rain is methane because this compound is both abundant in the atmosphere (it accounts for 5% of the atmosphere at the surface, around the same amount as water vapor on Earth) and exists on Titan near its triple point. A triple point is the combination of pressure and temperature that allows a compound to be stable as a solid, liquid, or gas. On Earth, conditions match water's triple point, and water's rapid dance between states, absorbing and releasing solar energy at every step, drives the immense complexity of our weather.

In addition to methane, Titan has a second climate actor: ethane (C_2H_6), which is produced when methane interacts with sunlight. Ethane is not quite at its triple point, but it's not so far off that it lies frozen as an inactive solid. Cassini observations have identified ethane as one of the principal constituents in the lakes. Like a godfather figure pulling hidden strings behind the scenes, ethane is probably active just enough to be important in Titan's long-term climate cycle.

If all it did was rain on Titan, the clouds and methane would soon disappear from the atmosphere. The poles appear to receive annual rainfall, whereas some equatorial

Saturn's moon Titan has a mysterious weather cycle.

Illustration by Casey Reed

NASA / JPL-CALTECH / SPACE SCIENCE INST.

HAZY MOON Larger than the planet Mercury, Titan hides a fascinating landscape beneath its orange haze, visible here in a natural-color composite from NASA's Cassini spacecraft.

regions might wait 100 or even 1,000 years for a torrential storm — the morphology of streambeds suggest that clouds could dump tens of centimeters or even meters of rain. However rare, these storms and the polar rains should deplete the atmospheric methane much faster than typical geologic processes can restore it.

That brings up a second issue, one acting on a far longer timescale. Methane is unstable over geologic times, because solar radiation destroys atmospheric methane. Calculations suggest the moon must generate some 50 million tons of methane each year just to keep its atmosphere enriched to present-day levels. There must be some source of methane seeping out of Titan itself, but it remains unclear what that source is.

Although scientists still don't have the answer to the geologic side of Titan's methane mystery, they're much closer to understanding methane on the seasonal timescales relevant to weather.

Alien Fog

Titan's extraordinarily deep atmosphere prevents the Cassini orbiter from flying closer to the moon's surface than about 900 kilometers. Because of that great distance and the perpetual haze, Cassini's images have resolutions of hundreds of meters (compared with some orbital images of Mars, where we can distinguish person-size objects).

While Cassini has observed changes in south polar lakes using both its Imaging Science Subsystem (ISS) cameras and its radar — including the disappearance of some small lakes — the exact reasons behind the changes remain unclear, says Hayes. If the removal of liquid is to blame, the hydrocarbons could have either seeped into the ground or directly evaporated into the atmosphere. Last year, researchers discovered potential oases or mudflats near the desert-like equator, patches of sand that might be dampened by liquid only a few inches deep welling up from the ground (October issue, page 12). Careful study of Ontario Lacus, a large lake near the south pole, also suggests it might be a depression that drains and fills from below, implying some sort of "groundwater" (in this case, ground methane).

However, the river-like channels indicate that rain does fall and drain into lakes. And even if the lakes primarily fill from a subsurface reservoir instead of the atmosphere, evaporation must still play a role, Hayes explains. "The methane needs to return to the atmosphere somehow," he says. "The only difference is whether the liquid interacts with the subsurface (either by flowing in a porous medium or by wetting water-ice) before evaporating, or evaporates directly from the pooled liquid."

Earlier in the Cassini mission, Michael Brown (Caltech) and his colleagues found evidence for direct

FOG RISING Fog-like features appear in shots of Titan's surface (*near right*) and also in the lower troposphere (*center*), but are not as pronounced higher up.

MICHAEL E. BROWN ET AL. / *ASTROPHYSICAL JOURNAL*

evaporation, in the form of two different kinds of condensation. The first is lake-effect clouds near the large north polar seas. Lake-effect clouds form as colder air flows over a relatively warm lake, picking up vapor which then condenses over land. One terrestrial example is the heavy snowfall that blows off Lake Michigan and onto residents of Chicago. (But Titan is too warm for methane snow.)

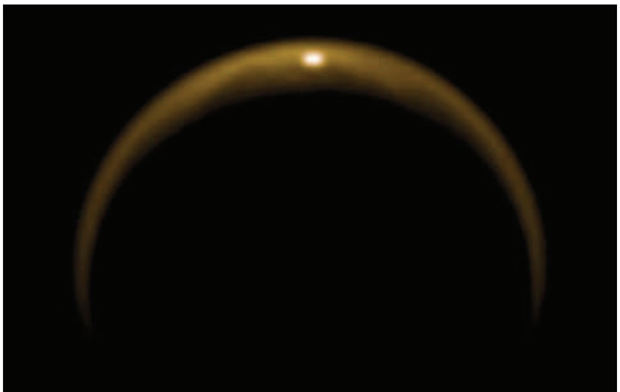
The second type of direct evaporation from the surface is fog. Any fog must lie close to the ground, a long way from prying orbital eyes. In a clever and elegant experiment, Brown's team used an artificial filter to split existing images from Cassini's Visible and Infrared Mapping Spectrometer (VIMS) into four wavelength ranges. Each range penetrated to a different altitude. The scientists looked for temporary features visible near the surface, but not visible higher in the atmosphere.

After carefully reviewing some 9,000 images by eye, the team found four low-lying wisps near Ontario Lacus. Their spectra were unlike that of any nearby surface, but they were similar to the spectra of methane clouds seen higher in the troposphere. The best fit to the data were clouds of vapor just 750 meters above the ground — fog.

Finding fog and lake-effect clouds does not explain how they got there. Fog generally forms when a compound (such as water on Earth) condenses from nearly saturated air. The only reasonable explanation for such high methane humidity on Titan is that the hydrocarbon evaporates from the moon's surface. Brown and his colleagues suggested that nearly pure evaporating liquid methane would be the best explanation for their results: the fog-like features were made of large particles, such as those found in methane clouds in the troposphere, meaning they probably formed from the condensation of an abundant compound. Methane is the only major surface constituent that could evaporate in the conditions present.

Fog also needs cooled air to persist. Terrestrial fog forms when air temperatures cool to within a couple of degrees of the dew point, the temperature at a given pressure where water condenses. Titan's atmosphere is too dense to cool much on short timescales, even during the world's Earth-day-long evenings. But pools of evaporating liquid methane could drain heat from overlying air, explaining how temperatures could drop to fog-sustaining conditions, the scientists concluded.

Although pure methane could evaporate on Titan, the compound would disappear far too quickly to explain the seas, which are stable on a seasonal timescale. Ethane lies at the other end of the scale. Ethane does not easily evaporate, and its presence in large concentrations actually inhibits the effective evaporation of methane. Scientists think that the lakes are primarily ethane with a bit of methane mixed in, which would make the lakes stable long enough to explain their growth in summer and waning in winter. Titan's year lasts 29½ Earth years, so that stability has to last several Earth years.



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ALIEN LAKE Cassini caught this flash of sunlight off a lake's surface in 2009. This glint, called a specular reflection, confirmed the presence of liquid in the moon's northern hemisphere.

SUBSURFACE OCEAN?

Deep below Titan's icy surface could lie a liquid water-ammonia ocean. Analyses of Cassini observations suggest that an ocean starts somewhere between 50 and 200 km below the crust and is possibly 300 km thick.

Still, the lakes cover only 20% or less of the polar regions during summer; overall, they make up a few percent of the moon's total surface. Whether direct evaporation from the lakes could close the methane cycle on its own is an open question.

By Land, Not by Sea

To understand Titan's meteorology, "one has to show up and observe," says F. Michael Flasar (NASA Goddard Space Flight Center). On January 14, 2005, researchers did just that when the Huygens probe became the first vessel to make landfall in the outer solar system (*S&T*: April 2005, page 34).

Huygens's equatorial landing site (10.2°S, 192.4°W) looks like a sandy flood plain, just off a rugged highland called Adiri. Recent analyses of Huygens's data show that the probe made a 12-centimeter-deep hole when it landed, then bounced out to slide along the moon's surface and wobble to a halt. The landing's dynamics suggest the probe fell on damp sand covered by a dry dust layer, possibly organic particles that drizzled out of the atmosphere. The sand, probably made of water ice or organic material like the dunes, supports pebbles that appear rounded in the same way silicate rocks are eroded in streams on Earth.

During the landing, the Gas Chromatograph Mass Spectrometer's warm inlet tube was shoved into the sand and saw a sudden increase in methane gas, as well as other hydrocarbons. Ralph Lorenz (Johns Hopkins University Applied Physics Lab) argues the GCMS's inlet appeared to be embedded in a surface that acted as an effective heat sink, most plausibly ground that's wet or damp with liquid methane. Erich Karkoschka and Martin Tomasko (both of the University of Arizona's Lunar and Planetary Lab) think the probe's camera might even have seen a methane dewdrop falling from a cold baffle on the descent imager.

The presence of moisture in the sand at the landing site was the clue scientists needed to look for another potential source for the fog. There's no standing methane near Huygens's landfall, but Hayes points out that lakes cover only a small fraction of Titan's surface. "You have a much larger surface area of potentially wet ground," he says. "So, if the liquid is at or very near the surface, the total volume of evaporated methane could be greater over the sand than over a lake surface with a similar composition."

If methane evaporates from the ground, moisture-laden air pulled from the land could pass over lake margins, where it would encounter lower air pressures and temperatures, says Tetsuya Tokano (University of

Descend with Huygens through Titan's haze and see more awesome Titan sights at skypub.com/TitanUnveiled.

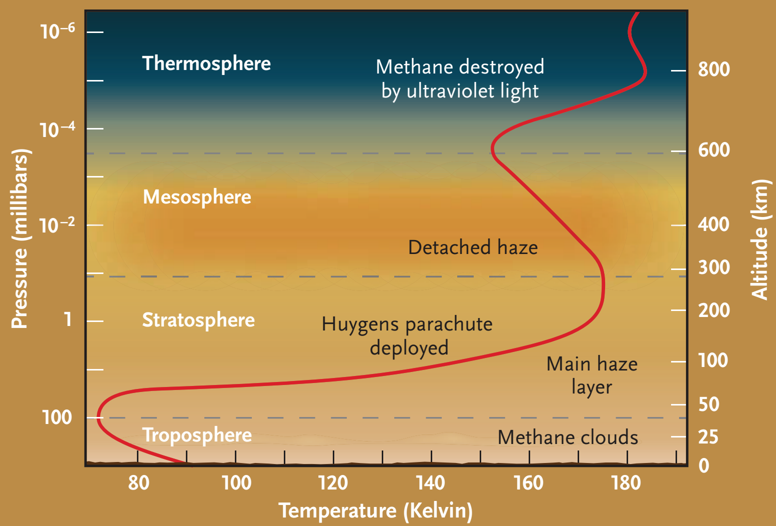
A Foreign Atmosphere

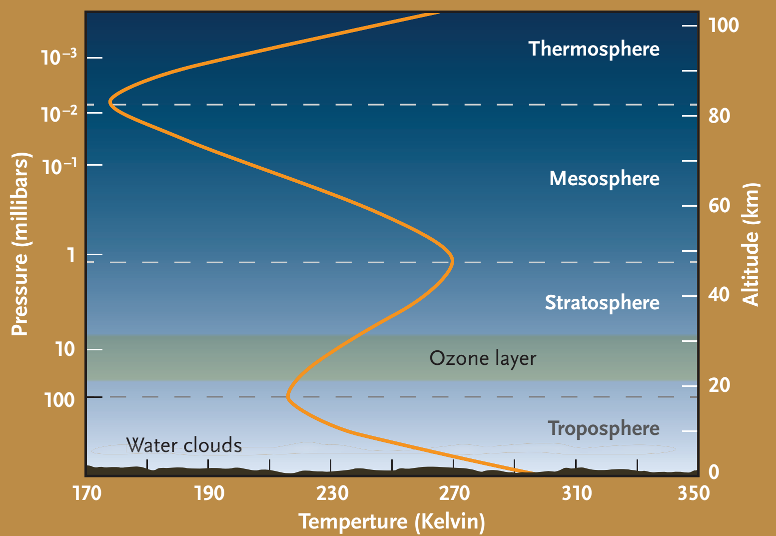
Saturn's moon Titan features many Earth-like landscapes: elevated terrains cut by what look like rain-fed streams and river canyons, the largest dune fields discovered in the solar system, and lakes that rival those on Earth. Even the atmosphere is often described as similar to Earth's.

It's not. Titan's atmosphere is predominately molecular nitrogen and supports cumulus clouds in the troposphere, like Earth, but that is where any resemblance ends. The second most abundant gas is not the chemically hyper-reactive oxygen, or even water vapor, but methane — with the addition of a lot of smog-like complex organic chemicals.

Relative to the planet's size, Earth's atmosphere is about as thin as an eggshell. Three-quarters of the gas lies within 11 kilometers of the surface, and "space" is defined as beginning at 100 kilometers.

Titan's atmosphere is deep: the atmosphere extends more than 600 kilometers, over one-fourth of the moon's radius. Most of Titan's rain clouds reside above 10 kilometers, many times higher than on Earth. The mass of all that gas on this small world, even in Titan's low gravity, results in a surface pressure 50% higher than Earth's.





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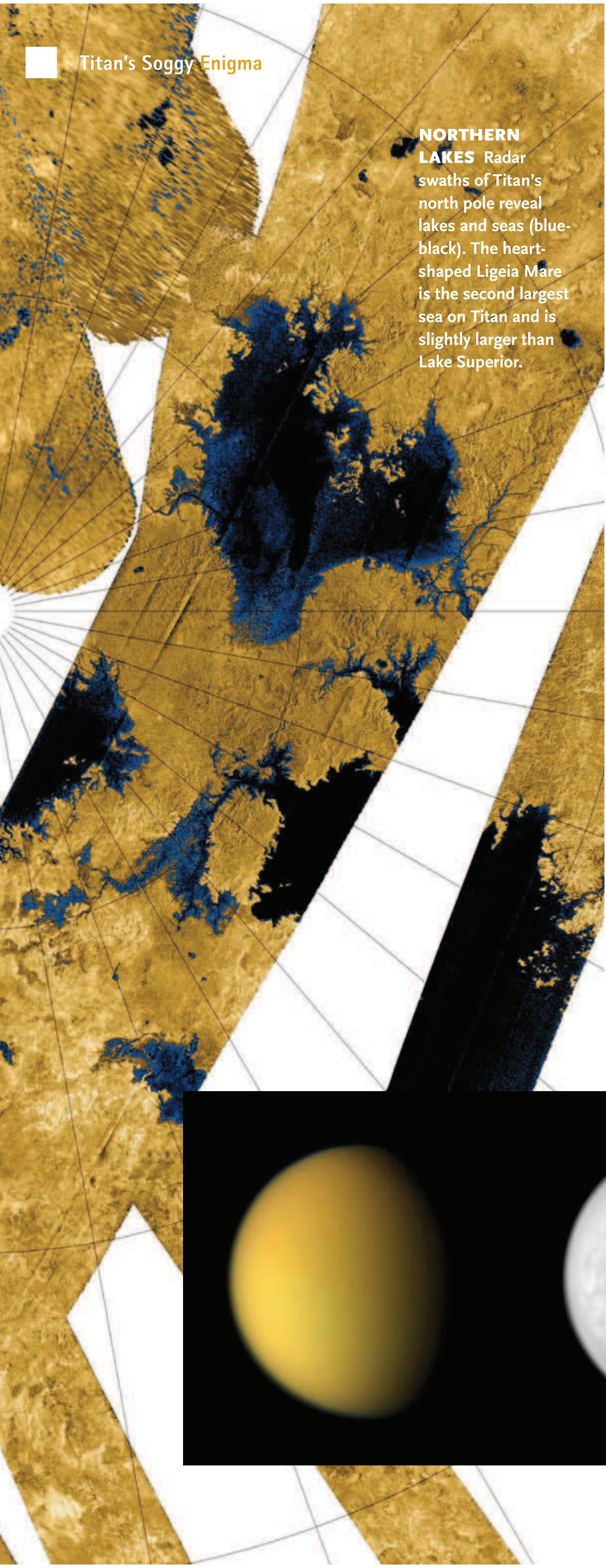
TWINS? NOT SO MUCH Titan's atmosphere *(top)* has similarities to Earth's *(bottom)*, but notice the altitudes: Titan's stratosphere reaches roughly six times higher than Earth's does.



NORTHERN LAKES Radar swaths of Titan's north pole reveal lakes and seas (blue-black). The heart-shaped Ligeia Mare is the second largest sea on Titan and is slightly larger than Lake Superior.

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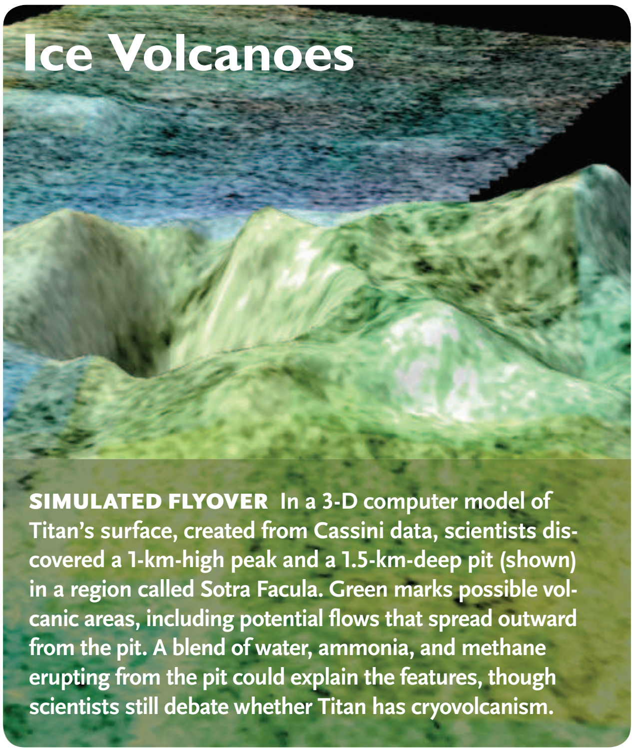
Ice Volcanoes



SIMULATED FLYOVER In a 3-D computer model of Titan's surface, created from Cassini data, scientists discovered a 1-km-high peak and a 1.5-km-deep pit (shown) in a region called Sotra Facula. Green marks possible volcanic areas, including potential flows that spread outward from the pit. A blend of water, ammonia, and methane erupting from the pit could explain the features, though scientists still debate whether Titan has cryovolcanism.

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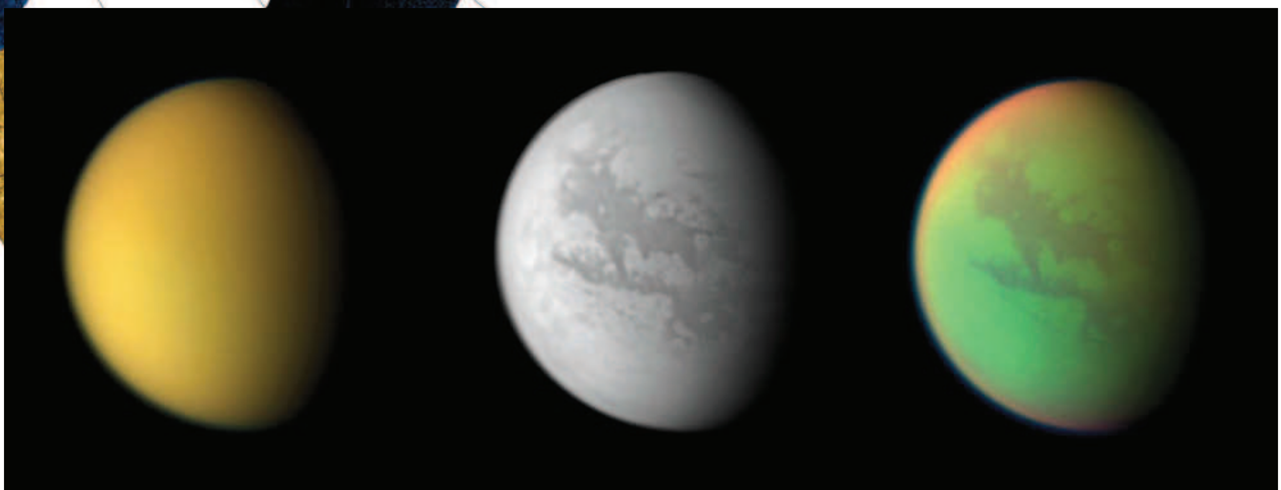
Cologne, Germany), who uses detailed climate models to study connections between Titan's lakes and atmosphere. These conditions would encourage methane to condense and rain back out — primarily over and near the sea. Surface darkening associated with cloud activity has indeed appeared near Ontario Lacus, suggesting that rain wet the ground shortly before the images were taken. Hayes thinks these particular features are too far from Ontario Lacus for the rain to have been generated by Tokano's mechanism, but

PEELING THE PEACH Titan's fuzzy orange glow is the only thing visible in a natural-color composite (left), but the surface appears in images taken in near-infrared light (middle) and in a composite of visual and infrared wavelengths (right).



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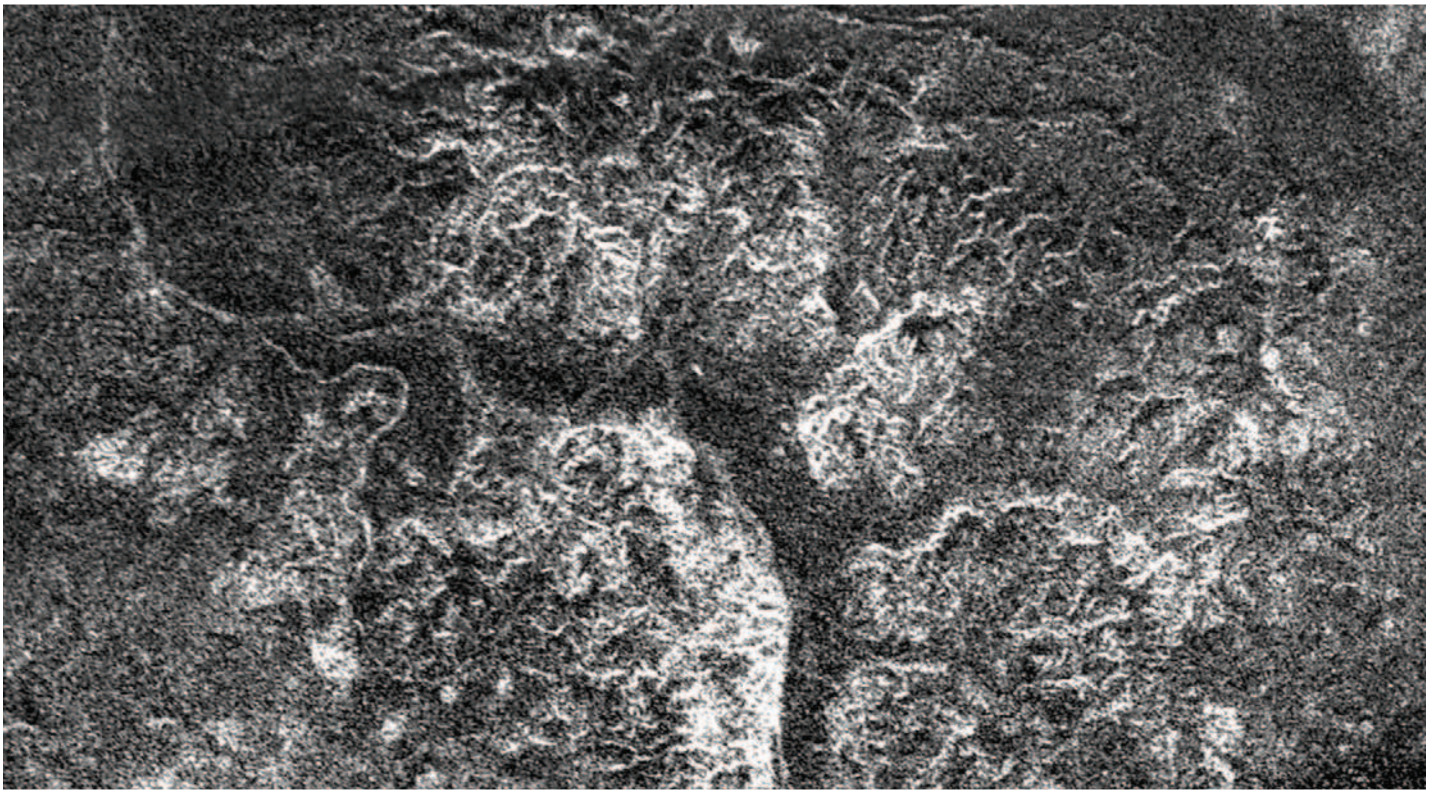

NASA / JPL

RAIN-FED RIVERS Cassini's radar revealed this canyon system on Titan in 2009. The channels flow from high plateaus to lowland areas, and their many tributaries suggest that rainfall erodes the surface.

the process could still work elsewhere.

Answers could come in the near future. Brown and his colleagues have used 3-D simulations to track Titan's weather cycle. They suggest that the methane accumulates in polar regions during summer, then somehow travels — either on or below the surface — to lower latitudes and evaporates. Their work not only predicts the rare, intense rainstorms observed in low latitudes, but also that clouds should form around the north pole in the next two years, as that hemisphere transitions to summer. With those clouds should come precipitation, raising northern lake levels over the next 15 years. These changes should be clearly observable by Cassini.

Determining the final answer to how Titan's weather cycle works might have to wait for another surface mission. NASA didn't select the proposed Titan Mare Explorer from its list of Discovery-class applicants, but European scientists are in the early stages of exploring a similar project to sail a Titan sea. Called the Titan Lake In-situ Sampling Propelled Explorer (TALISE), the mission would send a probe to float on Ligeia Mare, one of the moon's largest seas. Perhaps that mission's future discoveries, paired with Cassini's phenomenal work, will help solve the case of Titan's mysterious evaporation. ✦

Donald F. Robertson is a freelance writer based in San Francisco. See **www.donaldfrobertson.com** *for more of his work.*

Backyard Titan Observer

Amateur astronomers can help monitor Titan's weather, too, says Ralph Lorenz. At the moment Titan appears fainter than magnitude 9, and although it's above the horizon most of the night it's only 0.8 arcsecond wide, making it a challenging target to resolve. Short-exposure and video imaging can circumvent seeing problems, especially if you stack images. Under good skies a skilled backyard observer with a suitable telescope just might resolve Titan's disk, says Lorenz.

Amateur observations could bridge the gap between Cassini and whatever comes next. It looks increasingly like that gap will be large: no flagship-class mapping missions are on NASA's budgetary horizon. In the meantime, a 20-centimeter telescope with a commercial CCD can obtain useful spectra of seasonal changes in Titan's haze. Several years ago Antonin Bouchez (Caltech), then a grad student doing CCD photometry with a 35-cm telescope in Pasadena, successfully plotted Titan's light curve from night-to-night variations as the moon rotated, although he wasn't able to conclusively determine that the transient bright spots he saw were clouds. Atmospheric structure can also be measured during stellar occultations. You can find out more about observing Titan with amateur equipment on Lorenz's website: **www.lpl.arizona.edu/~rlorenz**.