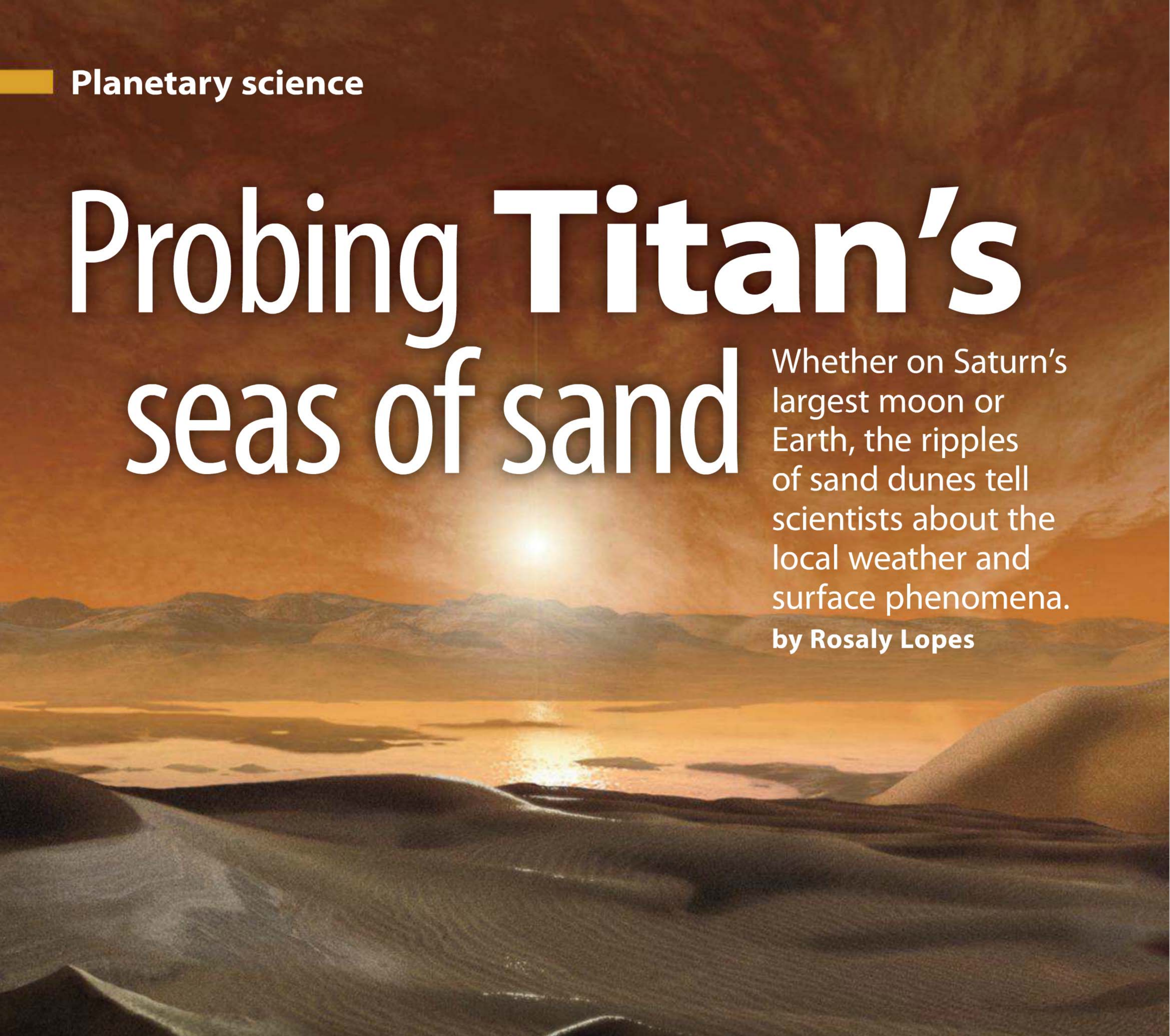


Probing Titan's seas of sand

Whether on Saturn's largest moon or Earth, the ripples of sand dunes tell scientists about the local weather and surface phenomena.

by Rosaly Lopes

Titan has long been an object of wonder in the solar system. First spotted in 1655 by Christiaan Huygens, Saturn's largest moon hid its surface behind a shroud of haze until the Cassini-Huygens mission arrived there three and a half centuries later.

When the Cassini orbiter began studying the moon in 2004 and the Huygens probe landed on it in 2005, we finally began to get a good picture of Titan's surface. Far from our Moon's old, cratered landscape, Titan proved to be a complex world, with interaction between its surface and atmosphere forming noticeable features — from seas of liquid methane near both poles to seas of sand near the equator. Fantastically, the more we learned, the more recognizable it became.

Almost familiar

Despite many differences, Titan has much in common with Earth. The moon's atmosphere, like ours, is mostly nitrogen, and its surface pressure is 1.5 bar (compared to 1 bar on Earth at sea level), but the air's density at the surface is four times Earth's. Both have precipitation and liquid lakes, but while Earth has a hydrological cycle based on water, methane drives Titan's equivalent cycle. Surface temperatures on the moon are so cold, about –288° Fahrenheit (–178° Celsius), that methane can exist as a liquid, solid, or gas.

Titan's surface boasts extensive river channels carved into icy bedrock, heavily eroded mountains, impact craters, pits, and flows that may be the results of ice volcanism, along with myriad lakes near the polar regions. We have observed changes likely due to evaporation in one of these lakes and have witnessed the darkening of an area probably due to methane rainfall soaking the ground. Methane clouds dot the atmosphere, joined by blowing winds.

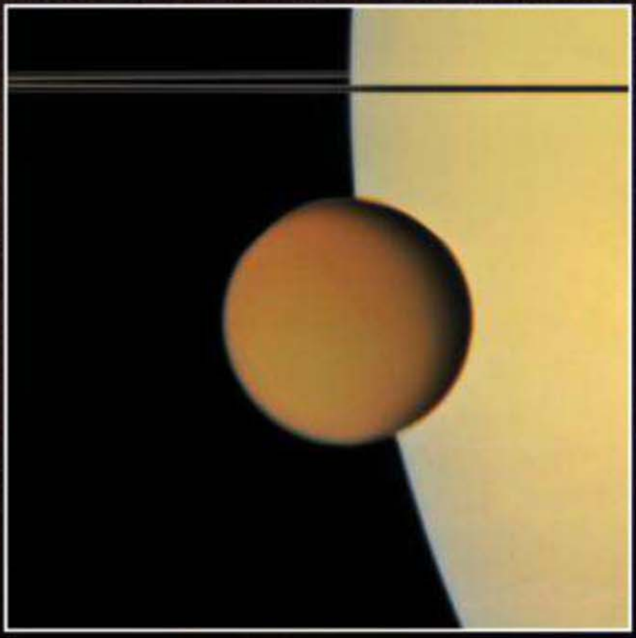
It turns out the moon also boasts another similarity to Earth. Large areas

Titan, the largest moon of Saturn, has turned out to be a strangely familiar place, full of lakes, clouds, and desert sand dunes. Michael Carroll for *Astronomy*

of Titan are covered with tens of thousands of sand dunes, much like those in many Earth deserts. Titan could have been the inspiration for the dusty, dry planet Arrakis in Frank Herbert's *Dune* — had that book not been written decades before Cassini first revealed the moon's hidden surface.

When the probe's first images revealed vast dark patches in the equatorial regions, it was unclear what they could be. Surface details show up best when Cassini's radar instrument uses its synthetic aperture radar (SAR) mode. However, we can only use SAR mode when Cassini flies close to Titan, so we can see only about 2 percent of the surface during each flyby.

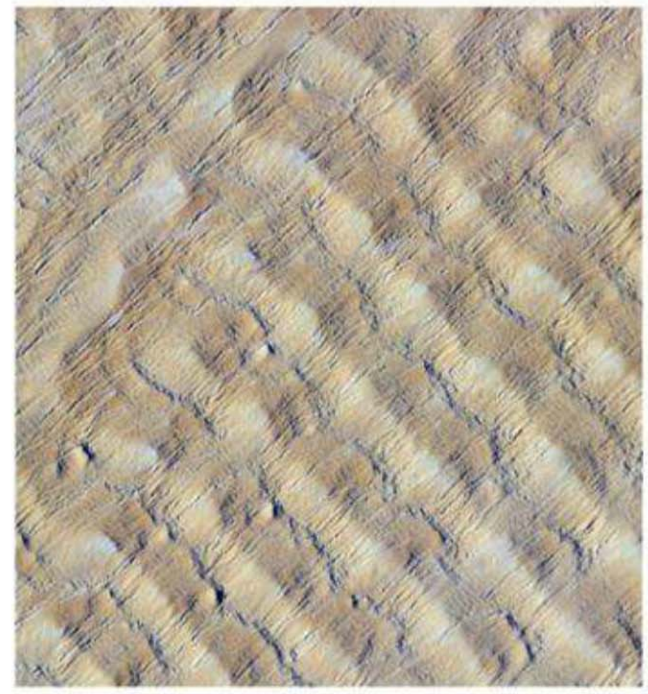
The first SAR pass missed much of the satellite's dunes because it surveyed high northern latitudes, far from the equatorial regions most filled with the dunes. It was during the second SAR flyby, in February 2005, that we first noticed patches of peculiar radar-dark parallel stripes against a radar-bright background. Geologists could not figure out what these land formations



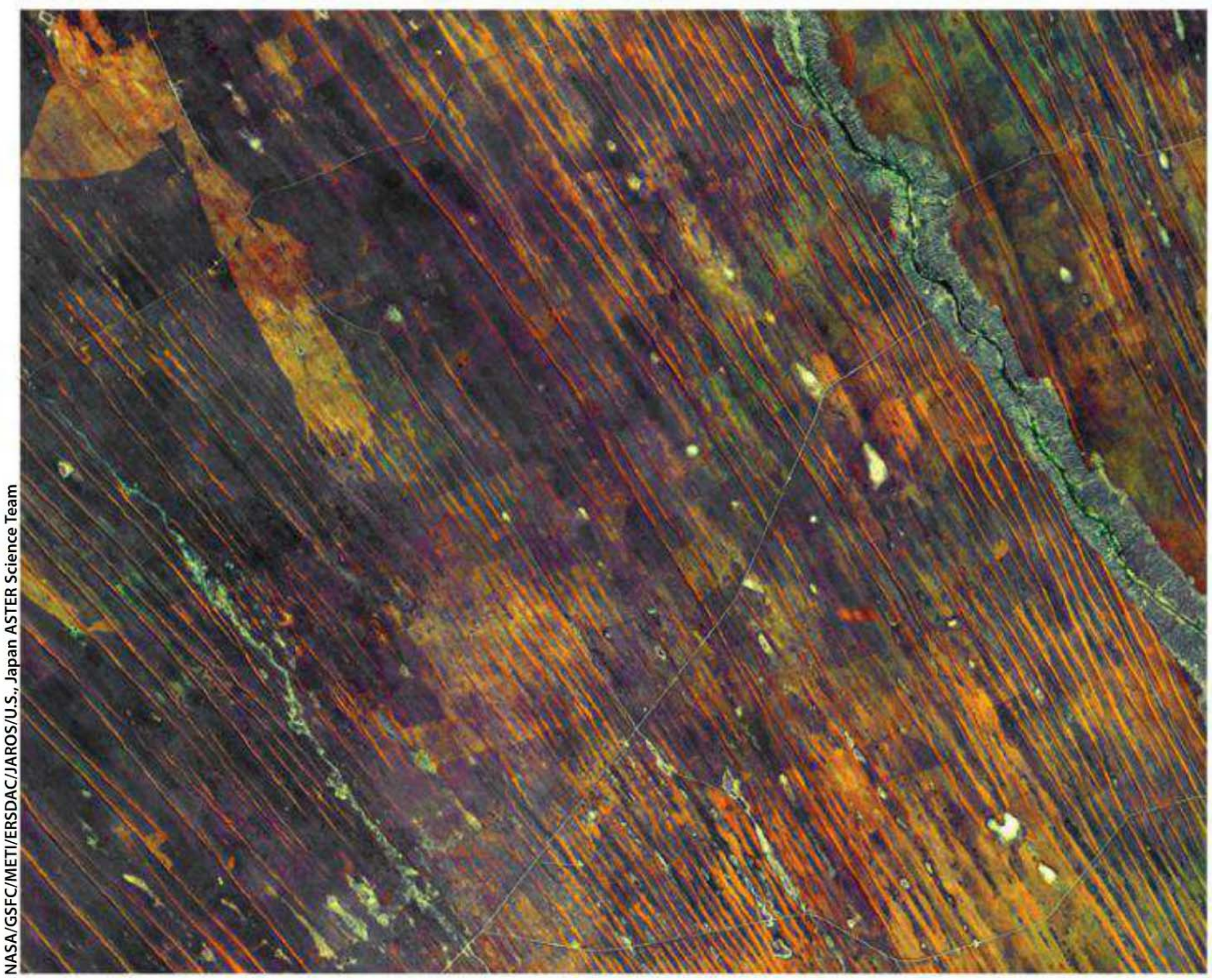
NASA/JPL/Space Science Institute

Titan's thick cloud and haze cover prevented scientists from learning any details of the moon's surface until recently.

Sand dunes come in three general classes. Barchans such as this one occur with loose collections of sand if the prevailing winds blow in a single direction. Daniel Mayer



Transverse dunes, like these in Niger, form under similar conditions as barchans, but require much more sand. (Look closely to spot a tiny set of linear dunes crossing them.) NASA/Expedition 22 crew



NASA/GSFC/METI/ERSDAC/JAROS/U.S., Japan ASTER Science Team

These linear or longitudinal dunes in Namibia, formed when winds blow from two directions, are some of the largest on Earth. Linear dunes make up the bulk of Titan's thousands of dunes.

were, and someone nicknamed them "cat scratches" based on their appearance.

The scratches stop abruptly at the edge of Titan's largest impact feature, Menrva. Clearly, the crater's topography created an obstacle for the scratches, and the possibility that they could be wind-formed dunes seemed the most reasonable option. Any doubts vanished when we obtained SAR images in October 2005 showing Titan's equatorial sand seas for the first time. The long, dark ridges of the dunes are close together, except where they encounter a topographic obstacle and divert around it in a teardrop pattern, something common to Earth's deserts. Indeed, it looks as if Titan's surface has been raked, like the sand in a Japanese garden.

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Although the SAR data convinced us that dunes are present on Titan, questions remained. What is the "sand" actually made of? And more perplexingly, how do these dunes form under Titan's conditions? Although the moon has a dense atmosphere capable of sustaining winds, it's so far from the Sun that such surface winds were thought too weak to allow dunes to form. Gradually, however, the answers became clear.

Sand and wind

So what is Titan's sand? The composition of materials on the moon's surface has been hard to determine because the same dense atmosphere that allows winds to blow also shields the surface from view. However, combining observations and models, the current preferred interpretation is that Titan's surface materials are complex hydrocarbons (molecules chained together by carbon atoms), nitriles (carbon molecules with a nitrogen atom attached), or perhaps both. The moon's lithosphere, or bedrock, is largely water ice.

Dune sands are dark in visible and infrared wavelengths, which is consistent with organic materials such as hydrocarbons. The radiometry mode of Cassini's radar instrument shows that the dune sands are probably fine-grained organic particles.

The source of the sand is likely the atmosphere itself: We know that organic "snow" composed of atmospheric haze particles constantly falls on Titan's surface, leading to vast deposits. These probably form sedimentary layers, which are later eroded by methane rainfall and flowing channels. Then, these channels, winds, or both carry the particles to sand sinks where they accumulate. Eventually, globe-encircling winds blow the sands into dunes.

The Cassini probe's radar instrument can use its synthetic aperture radar mode to best observe Titan's surface features. Here, long dunes and bright ridges show up on a relatively young crater-free surface. NASA/JPL

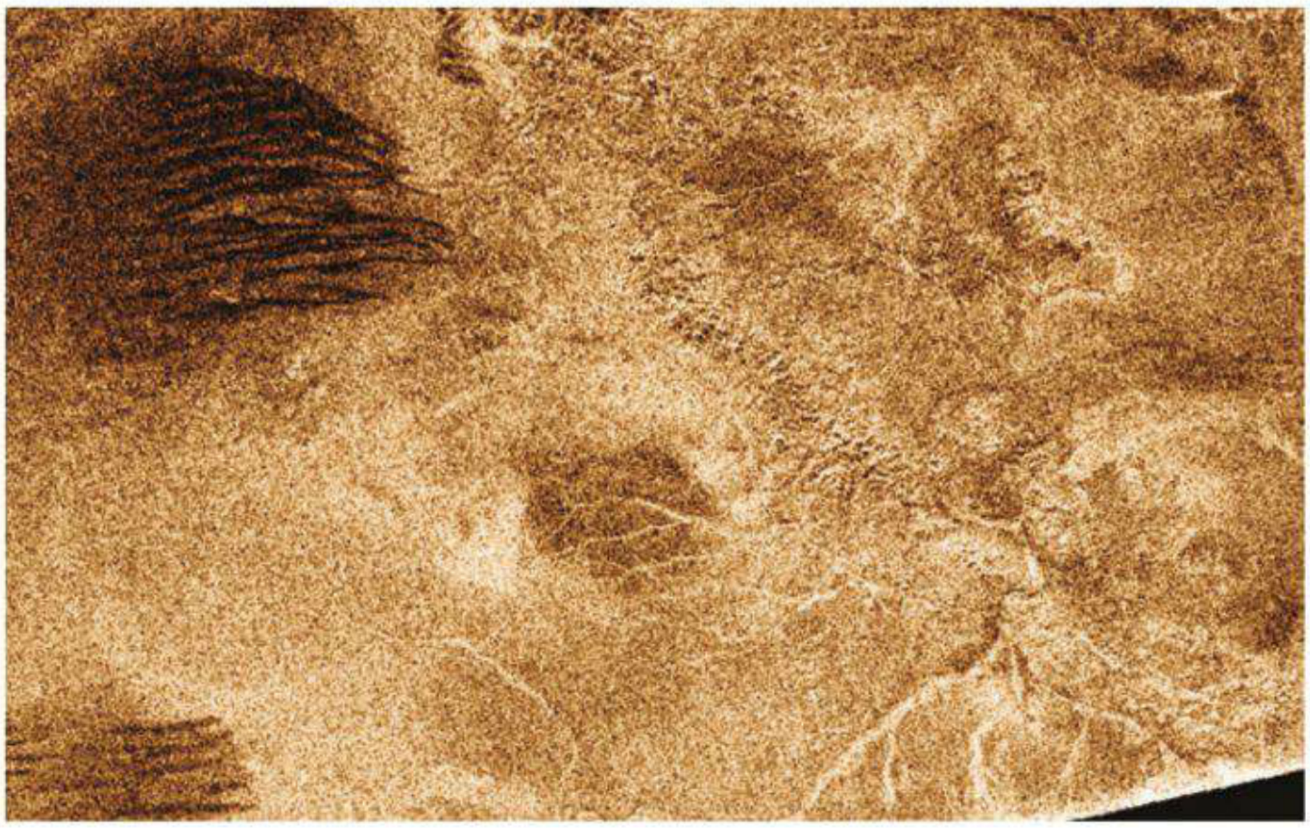
Dunes 101

Wherever in the solar system they may be, dunes form and move through the motion of individual sand grains that "jump" in a process called saltation. The process is a well-studied one on Earth, both in wind tunnels and out in the field. We know that the wind speed needs to be sufficiently high, and the sand dry, to send grains jumping forward. As each grain flies forward in the wind and hits the ground, it kicks up other grains from the surface. This process happens in a thin layer near the ground and can become self-sustaining. A dune may initially form where some small irregularity in ground topography traps a concentration of sand.

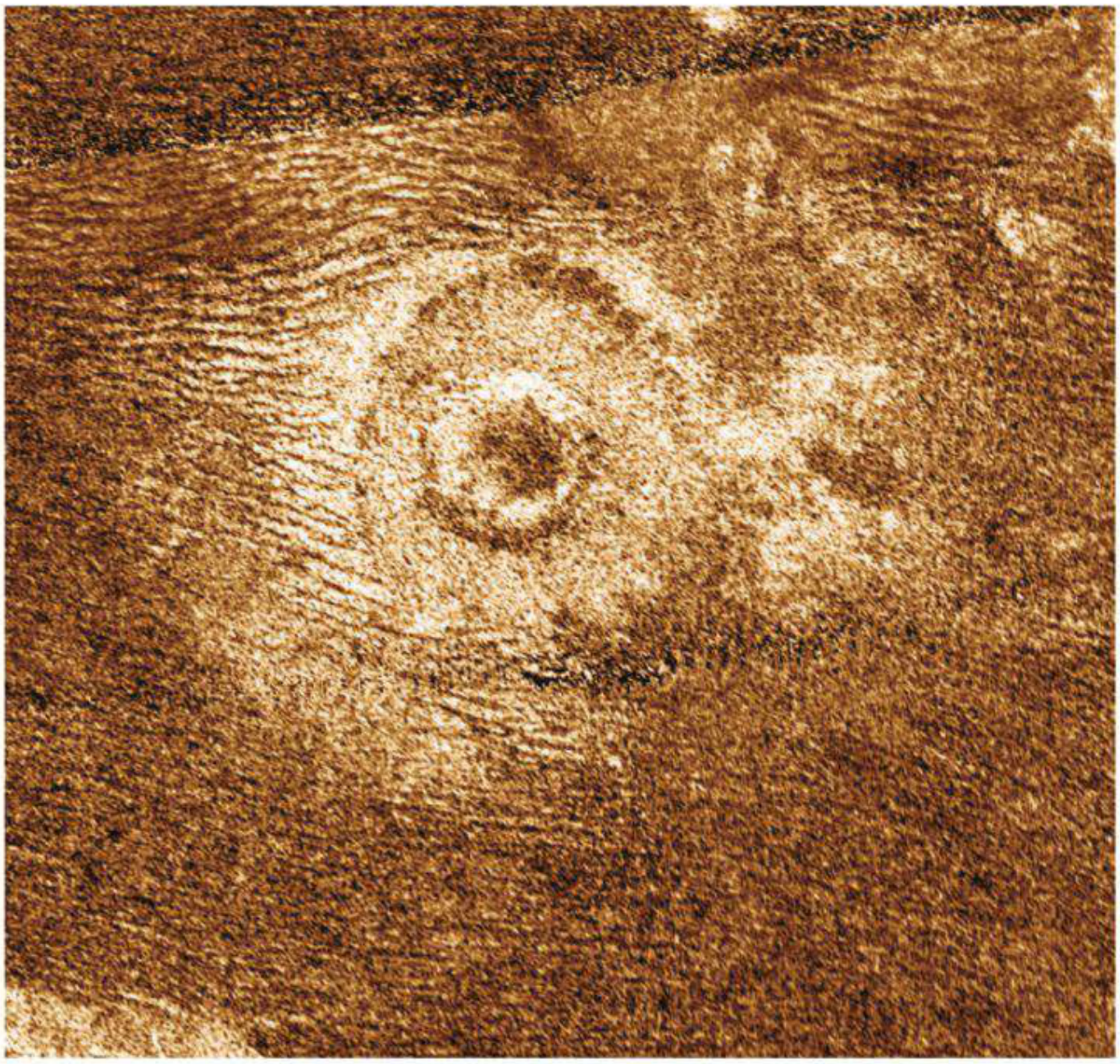
Once a dune exists, it often grows, sometimes over thousands of years. Depending on the wind's direction and constancy, dunes can take different forms. If the wind (and thus the sand transport) is in a single direction, it forms the most familiar pattern, called transverse dunes: long ripples perpendicular to the main wind direction.

However, if the sand supply is relatively low, the resulting dunes, known as barchans, will be isolated and crescent-shaped. In either case, the dune will have a steeper, well-packed side facing the wind direction called the stoss slope, and a loose, forward-moving downwind side called the slipface, or lee side. Desert peoples use this fact to their advantage, as they know it is much easier to walk on the stoss slope.

The largest dunes, the linear or longitudinal type, form when the wind comes predominantly from two directions, often due to seasonal changes. The net sand transport will occur roughly in the average direction of the strongest winds. About half the dunes on Earth are of this type, and they can stretch tens of miles, covering much of the Sahara, African, Australia's Simpson, and Arabian deserts. Some longitudinal dunes, especially those with a sinuous form, are also called seif dunes after the Arabic word for sword. Titan's thousands of dunes are of the longitudinal type.



The Cassini probe's synthetic aperture radar mode finally provided astronomers views of Titan's surface in 2005, and surprised them with the unusual "cat scratch" features seen here. NASA/JPL



Seeing that large craters and hills appeared to divert the "cat scratches," scientists figured out the odd features were likely wind-formed dunes similar to ones found in Earth's deserts. NASA/JPL-Caltech

Sand dunes on Earth and the dunes on Titan form remarkably similarly, with each revealing clues about its world's weather patterns and surface composition. The author took this photo during a trip to study the dunes of Namibia. Rosaly Lopes

TITAN BY THE NUMBERS

16 days
Length of orbit around Saturn

3,200 miles
(5,150 kilometers)
Diameter

1.5 bar
Surface air pressure

12 to 20 percent
Fraction of surface covered with sand dunes

16,000+
Dunes spotted by scientists

Dunes elsewhere

As Cassini acquired more data, we realized that dunes are common landforms on Titan, covering at least 12 percent of the surface, and maybe as much as 20 percent — or about 4 million square miles (10 million square kilometers). In comparison, dunes cover only 4 percent of Earth's surface. Mars and Venus also sport a number of dunes, but in small areas; on Mars, they cover only about 1 percent of the surface, and on Venus, it's even less.

Wind patterns in the thin martian atmosphere are fairly constant, forming transverse and barchans dunes. But although the Red Planet's surface is arid, dune fields are relatively rare, as wind speeds must be faster to move sand in air that's about 100 times less dense than air on Earth. The largest concentration of martian dunes forms a dark crescent surrounding the polar cap called the Northern Polar Erg. Other dune fields on Mars are small — in patches at the bottom of features such as Victoria Crater.

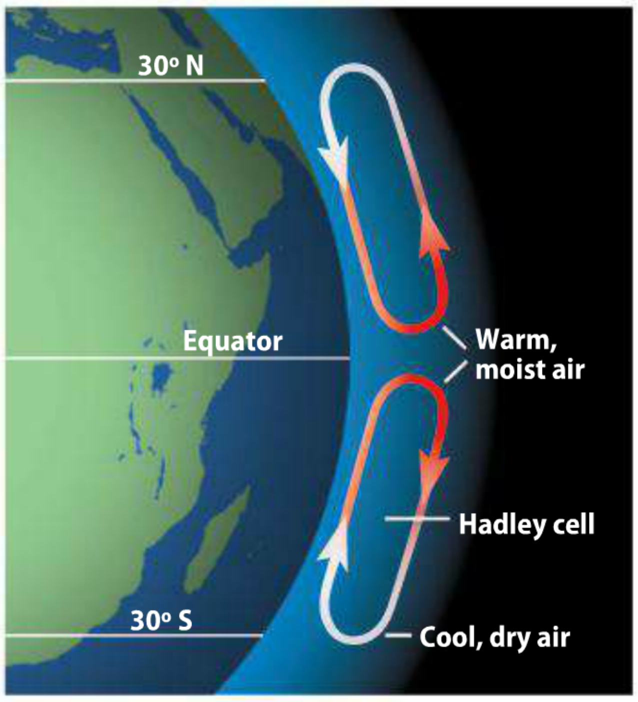
We have much higher-resolution images of Mars than we do of Titan, so it is likely that small dune fields on Titan exist as well, but have simply escaped detection. SAR imaging has covered only about half of Titan's surface, with a resolution of about 1,000 feet (300 meters) at best. We are a long way from knowing the surface of Titan as well as we know that of Mars.

The SAR images Cassini has acquired so far show more than 16,000 dunes on Titan. Most of these are within 30° of the equator, with a few isolated patches up to 55° away. The distribution implies that most of the sand supply, along with suitably dry conditions for dune formation, lies in the equatorial regions of Titan. On Earth, deserts are mostly located in two belts, about 20° to 30° north and south of the equator. Their location relates to air circulation in a meteorological model called the Hadley cell (see graphic on page 35). In simplified terms, the strong heat at the Earth's equator leads to an upwelling of moist air, forming large thunderstorms. The storms precipitate out the water from the rising air, so the downwelling side of the cell is therefore dry, leading to the arid belts on either side of the equator.

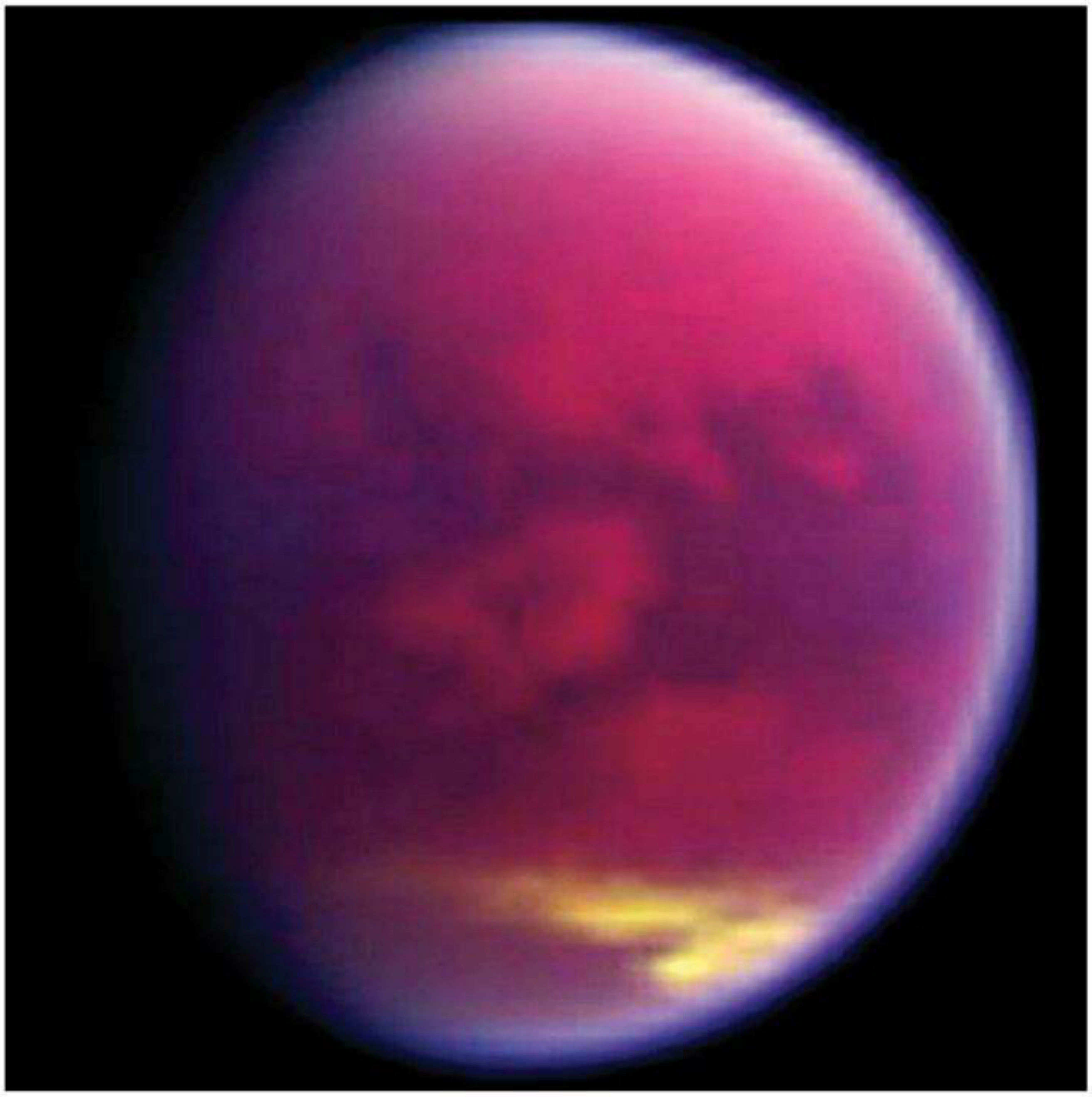
Dunes, therefore, can be indicators of climate. With that in mind, we plotted the distribution of Titan's dunes and made measurements of their sizes. Jani Radebaugh of Brigham Young University in Provo, Utah, and her students mapped thousands of Titan's dunes, measuring their lengths, widths, spacing, heights, and variations. In the equatorial sand seas, dunes are narrow, closely spaced, long, and straight, indicating abundant sand. At higher latitudes, near the edges of the sand seas, dunes have greater widths and spacing, and they tend to be shorter and more sinuous — these are the cat scratches we first spotted. By comparing these findings with studies of Earth's deserts, we can tell the higher latitudes must have a more limited supply of sand.

NASA/JPL-Caltech/University of Arizona/Cornell/Ohio State University

The Red Planet's conditions are also favorable for creating sand dunes, as seen in this Mars Reconnaissance Orbiter image of Victoria Crater.



A weather process modeled by the Hadley cell explains why desert regions occur about 20° to 30° away from Earth's equator. A similar process is at work on Titan, which helps distribute moisture. *Astronomy*: Roen Kelly



Continued studies of Titan throughout its various seasons will help scientists understand this mysterious world even better. In this false-color image of the moon, cloud cover appears yellow and its thick atmosphere appears magenta. NASA/JPL/University of Arizona/University of Nantes/University of Paris Diderot

The winds of Titan

As on Earth, the dunes of Titan offer clues about dominant winds, as the orientation and type of dunes indicate where the predominant breezes originate. Therefore, we initially concluded that winds on Titan blow from west to east. We geologists had no problem with this interpretation, but the atmospheric scientists didn't like it.

According to circulation models of Titan's atmosphere, winds should go the opposite way. Titan rotates in the same direction as Earth does, and the surface of these bodies transfers its angular momentum to the lower atmosphere, effectively pulling the atmosphere along. Titan's winds should blow from east to west, atmospheric scientists argued, like our familiar terrestrial trade winds. This "wind blowing backward" was quite a puzzle, and one of the atmospheric scientists even wondered if we had our images flipped around.

We had direct measurements of Titan's winds from the Huygens probe's descent, but not enough to solve the puzzle. As it landed near the equator, the probe's instruments indicated that winds blew toward the south-southwest. We knew that because Titan's dunes are longitudinal, they would likely be the result of bimodal winds — that is, two strong winds blowing from widely separated directions (more than 90°). The dunes align with the average sum of the winds, weighed by their strength.

Eventually, new atmospheric models for Titan were developed by Tetsuya Tokano from the University of Cologne in Germany and Ralph Lorenz from the Johns Hopkins University Applied Physics Lab in Laurel, Maryland. They took into consideration Titan's wind history throughout a solar orbit, which lasts 30 years, to come up with an answer. The scientists concluded that east-to-west winds, as predicted by the circulation models, generally blow on the moon, but that strong west-to-east winds occur briefly at the equinoxes. Although these winds are rare, they are strong at Titan's surface and better able to reach the velocities needed for particles to saltate — about 3 to 7 feet (1 to 2m) per second. This is what really answered the riddle.

As is often the case in science, it proved useful to have scientists from different fields working together. The models of atmospheric circulation on Titan also help explain why the dune fields are concentrated near the equator, as they predict that Hadley circulation transports humidity away from the equator and toward the polar regions. In order for sand to saltate and form dunes, the grains must be dry. And indeed, Titan's polar regions are home to the moon's giant methane lakes and seas.

Still mysterious

Despite all we've learned, Titan remains enigmatic. One exciting aspect of the Cassini mission is that we are observing something without precedent: the changing of seasons on another world.

When Cassini arrived at the saturnian system, it was winter in the north of the planet and its moons. Titan's northern polar regions were in darkness and its spectacular lakes and seas visible only to the radar. After equinox, in August 2009, the northern regions have come into light, and the local climate has begun changing. The Cassini probe should keep sending data until 2017, giving us time to observe even more behaviors on this new and strange world.

Test your skills telling Earth landscapes apart from alien ones at www.Astronomy.com/toc.