**COMET CRUMBS:**
A New Meteor Shower?
PAGE 34

**SEEING RED:**
Catch May's Total Lunar Eclipse
PAGE 48

**RARE CATCH:**
Mercury's Sodium Tail
PAGE 52


# SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

MAY 2022


## Comet Leonard SURPRISES

Page 58

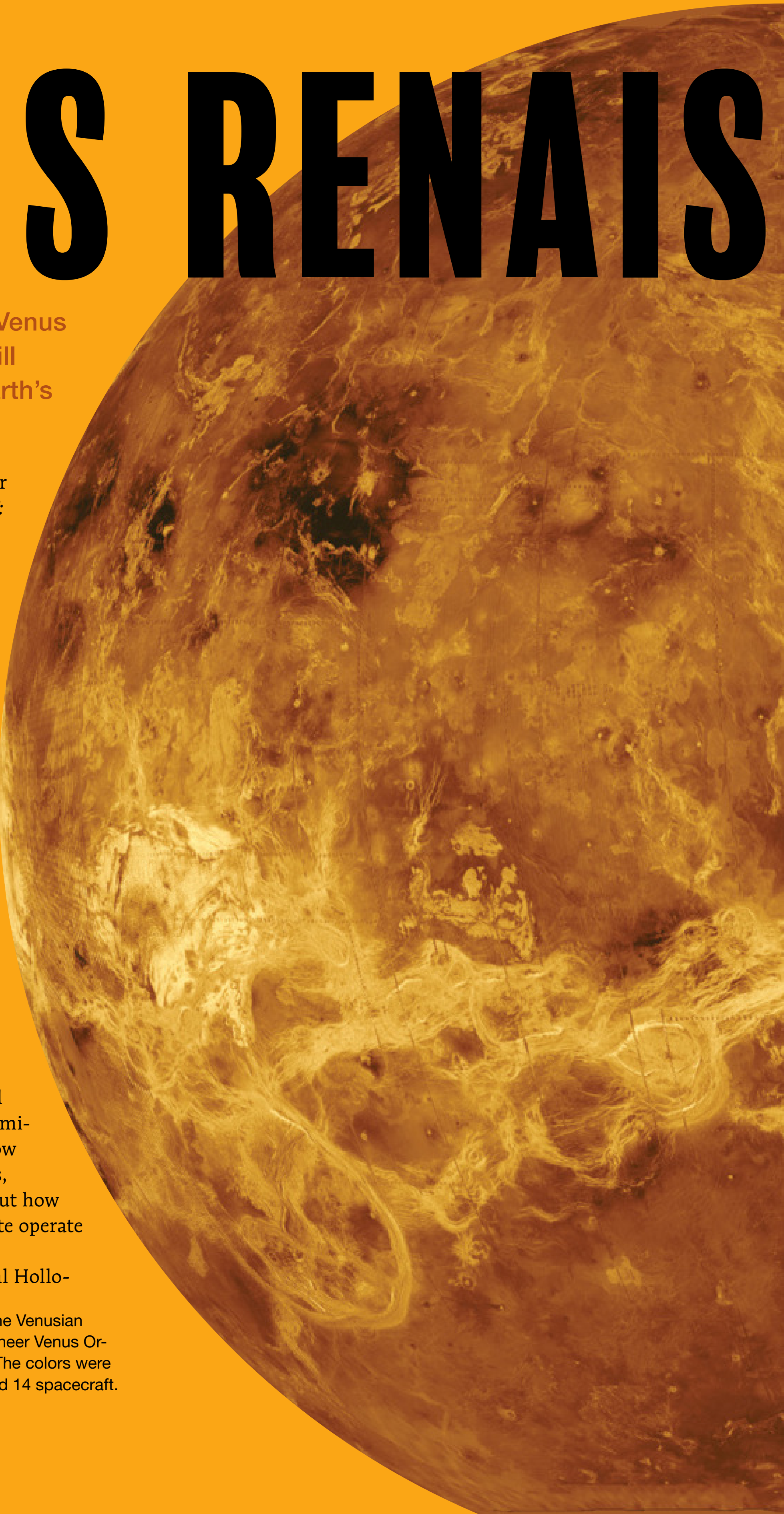
skyandtelescope.org

$7.99US $8.99CAN
05
0 71896 02207 0

**Scientists Set Their Sights on Venus**
Page 12

**A Telescope Made of Solid Glass**
Page 74

# VENUS RENAIS



**Only two spacecraft have orbited Venus since 1994. Three new missions will transform our understanding of Earth's evil twin in the 2030s.**

This is the dawn of a new Age of Venus. After a dry spell lasting more than 25 years (*S&T:* Sep 2018, p. 14), NASA has finally selected not one but two missions to our neighboring planet: the VERITAS orbiter, launching as soon as 2027, and the DAVINCI flyby and atmospheric probe, launching in 2029. The European Space Agency will follow with the EnVision orbiter in the early 2030s.

What broke the drought? "To some degree, it had just been so long that it was becoming kind of an embarrassment," says David Grinspoon (Planetary Science Institute), a co-investigator on DAVINCI. Just as important, however, was that exoplanet researchers had started advocating for Venus missions. "They're already starting to find exo-Venuses. What hope do we have of figuring things out that many light-years away if we haven't really looked at Venus?"

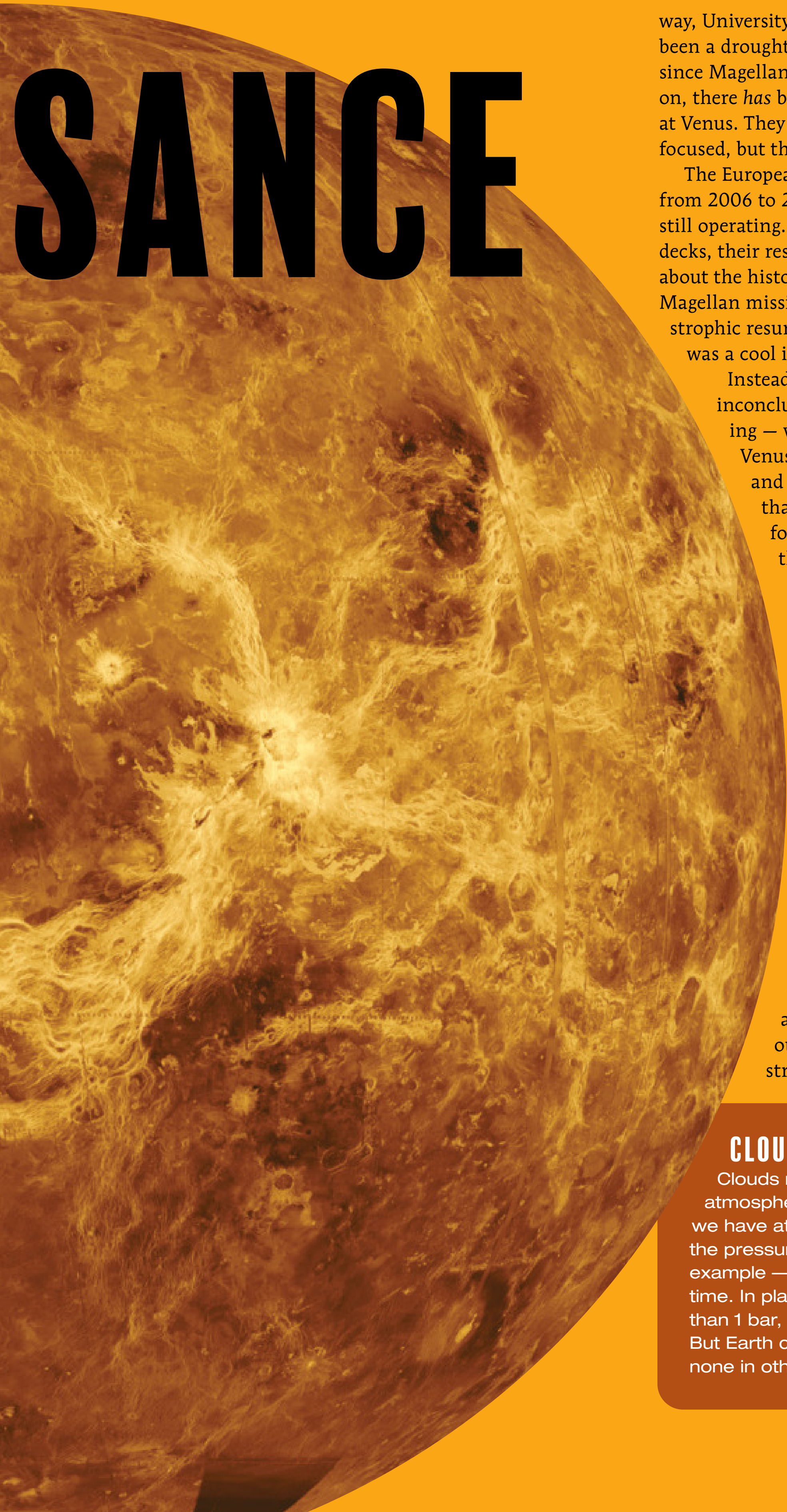
Suzanne Smrekar (Jet Propulsion Laboratory), principal investigator on VERITAS, gives additional credit to Earth scientists. "There are a lot of open questions about plate tectonics," she explains — questions that are best answered by comparing our planet with another one of similar size, age, and composition. But we don't know enough about Venus to understand its tectonics, much less to use that understanding to figure out how Earth's dynamic tectonism, weather, and climate operate in the present, past, and future.

If you talk to EnVision's Richard Ghail (Royal Hollo-

▶ **VENUS AS WE KNOW IT** This simulated mosaic of the Venusian surface combines radar data from the Magellan and Pioneer Venus Orbiter spacecraft colorized to enhance surface features. The colors were inspired by images recorded by the Soviet Venera 13 and 14 spacecraft. The hemisphere is centered at 180° east longitude.

NASA / JPL

# SANCE



way, University of London), though, there hasn't actually been a drought. "The attitude is: 'We haven't had a mission since Magellan, nothing's happened,'" he says. "Like, hang on, there *has* been Venus Express, there *has* been Akatsuki at Venus. They were atmosphere-focused and not surface-focused, but they have been doing surface science."

The European Space Agency's Venus Express studied Venus from 2006 to 2014; Japan's Akatsuki arrived in 2015 and is still operating. Despite being devoted to the planet's cloud decks, their results have overturned prevailing attitudes about the history of Venus's barren landscape. "Out of the Magellan mission came this paradigm that Venus had catastrophic resurfacing and then quiescence," says Smrekar. "It was a cool idea, but I think it's wrong."

Instead, Venus Express produced abundant (though inconclusive) evidence for recent — and even continuing — volcanism. Both it and Akatsuki have shown Venus's atmosphere to be much more dynamic, and much more connected to the rocky surface, than we realized. Those discoveries have laid the foundation for thrilling new Venus missions in the 2030s.

## Hot Wind, Acid Clouds

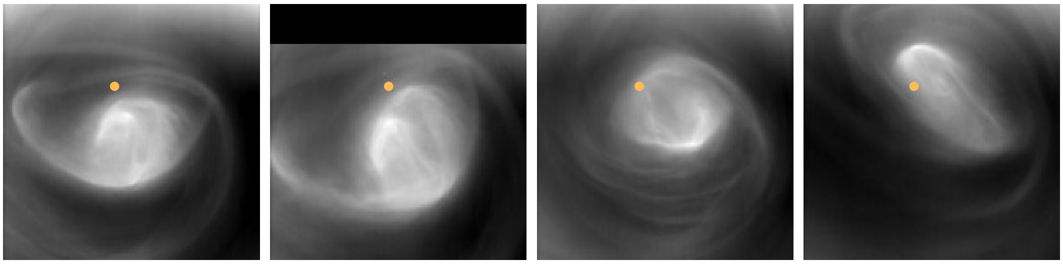
We've known the fundamental facts about Venus's atmosphere since Mariner 2 performed the first-ever planetary flyby in 1962; probes, balloons, and landers from the Soviet and American space agencies filled in much of the rest. Very nearly the same size as Earth and only a little closer to the Sun, Venus rotates backwards, but slowly. The retrograde rotation counteracts its orbital motion, so its sidereal days (243 Earth days long) are longer than its years (225 Earth days).

Venus's surface is shrouded by an utterly opaque layer of clouds, more than 20 kilometers thick. The clouds are 75% pure sulfuric acid droplets, but they also contain a mysterious "ultraviolet absorber" that creates dark streaks in ultraviolet-filter images. Fortuitously,

### CLOUDS

Clouds most commonly form at or above an atmospheric pressure of around 1 bar, or what we have at sea level on Earth. On worlds where the pressure is much higher than that — Venus, for example — clouds cover the entire planet, all the time. In places where the pressure is much lower than 1 bar, such as Mars, clouds are rare and thin. But Earth can have thick clouds in some places and none in other places.

CLOUD ICONS: KUSDARTI / THE NOUN PROJECT



**EYE OF THE STORM** Venus Express caught rapid changes in the vortex over the planet's southern pole (yellow dot). From left to right, the infrared images show changes over the course of two days. The vortex hovers about 60 km above the Venusian surface.

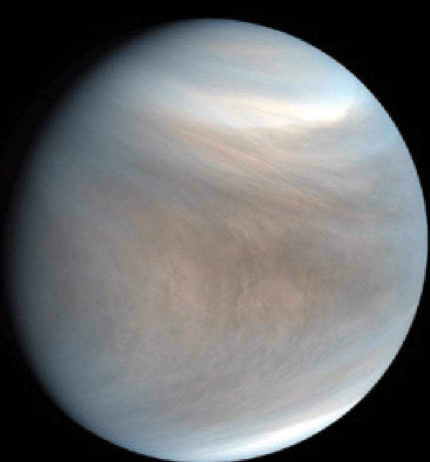
those dark streaks enable scientists to track cloud motions and measure wind speeds.

The temperature and altitude of the top of the troposphere are constant almost everywhere on the planet, except near the poles. Wind speed is oddly constant, too. Except near the poles, the entire atmosphere moves westward at 100 meters per second (more than 200 mph), traveling completely around the planet once every four days. There's nothing quite like this atmospheric "super-rotation" anywhere else in the solar system.

Probes showed that the winds weaken closer to the surface, but the speed never drops to zero; the lowermost 10 kilometers of Venus's atmosphere always experience a breeze of 1 to 3 meters per second.

The surface roasts at a temperature of 740K (470°C, 870°F) and bears a crushing atmospheric pressure 92 times that of Earth's. The air is almost all carbon dioxide. In fact, it appears that Venus has about the same proportion of carbon that Earth does, but whereas Earth's carbon is mostly locked into rocks like limestone and marble as carbonate minerals, Venus's carbon is all in the air.

There's also a high proportion of heavy hydrogen relative to regular hydrogen in Venus's atmosphere, which has led scientists to hypothesize that Venus has lost most of its primordial water. Without much water, geologists reasoned, Venus's rocky interior would be much less mobile than Earth's, making Earth-style plate tectonics impossible.



**VENUS IN UV** This synthesized image combines Akatsuki observations at two different ultraviolet wavelengths to show mesmerizing detail in Venus's atmosphere. Dark blue streaks mark the presence of an unidentified chemical substance.

## Europe Goes to Venus

The Soviet Union and the United States initiated the first phase of Venus exploration at the same time that they were rushing to land on the Moon and bring home lunar rocks. Scientifically speaking, Soviet and American planetary science therefore grew out of geology. At Venus, both countries focused on penetrating Venus's clouds to see the rocky surface for comparison with Earth, the Moon, and Mars.

Europe's planetary science community, on the other hand, has stronger roots in a different aspect of Earth science: "We accepted climate change long before the United States did," Ghail says. Trying to explain Venus's hellish climate had inspired the idea of a runaway greenhouse. But what triggered the runaway greenhouse, and could the same thing happen on our rapidly warming Earth? ESA's Venus Express mission sought to better understand climate change on both Venus and Earth. Similar goals motivated Akatsuki.

Venus Express immediately gave us improved views of weird features at both of Venus's poles. The poles are surrounded by a *cold collar*, where both the temperature and altitude of the top of the troposphere drop, and with them the top of the visible clouds, by about 5 kilometers.

With longer-wavelength infrared imaging, Venus Express could easily see down to the middle cloud layer (approximately 55 km above the surface), where gigantic vortices of relatively warm air spin and wobble drunkenly around both poles once every two to three days. They most commonly look like wispy figures of eight, described as a double vortex, but are sometimes oval and sometimes triple. They never looked quite the same from one Venus Express orbit to the next. How these persistent storms connect to the upper or lower polar atmosphere, or to the global rotation of the rest of the atmosphere, remains a mystery.

A long mission followed these early discoveries, and the longevity generated unique science, Grinspoon explains. "What was great about Venus Express, and is great about Akatsuki, is the sustained presence of these orbiters with first-rate instrumentation, because there's a lot of complexity and variability."

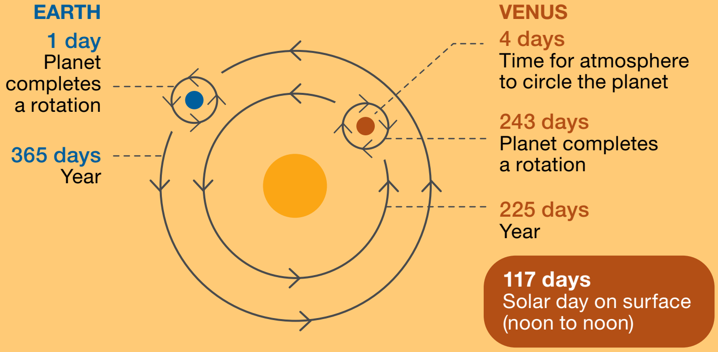
Wind speeds changed and cloud brightness varied from one Venus Express orbit to the next. As Venus Express watched between 2006 and 2010, the superrotational wind sped up from 100 to 120 meters per second. At much smaller scales, both Venus Express and Akatsuki have seen turbulent, bubbly motions in the lower clouds.

POLAR VORTEX IMAGES: ESA / VIRTIS / INAF-IASF / OBS. DE PARIS-LESIA / UNIV. OF OXFORD; VENUS IN UV: PLANET-C (AKATSUKI) PROJECT TEAM

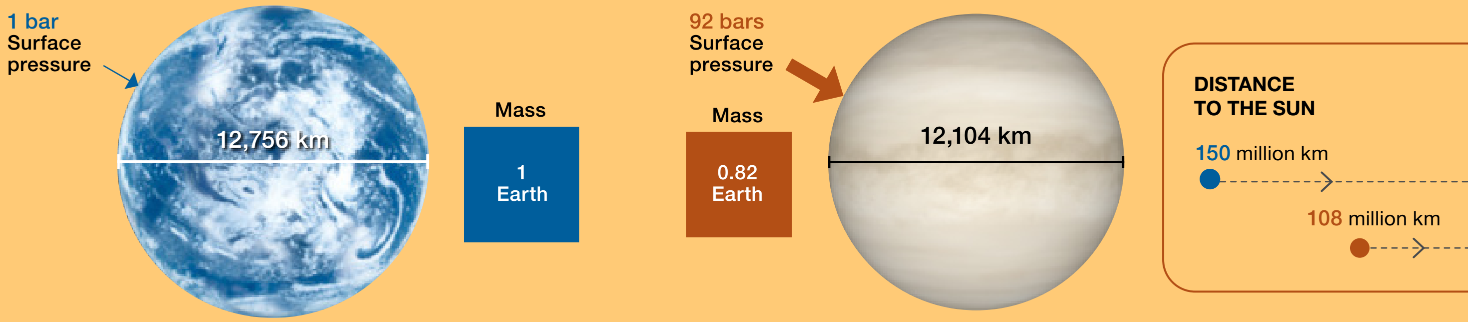
## VENUS VS. EARTH

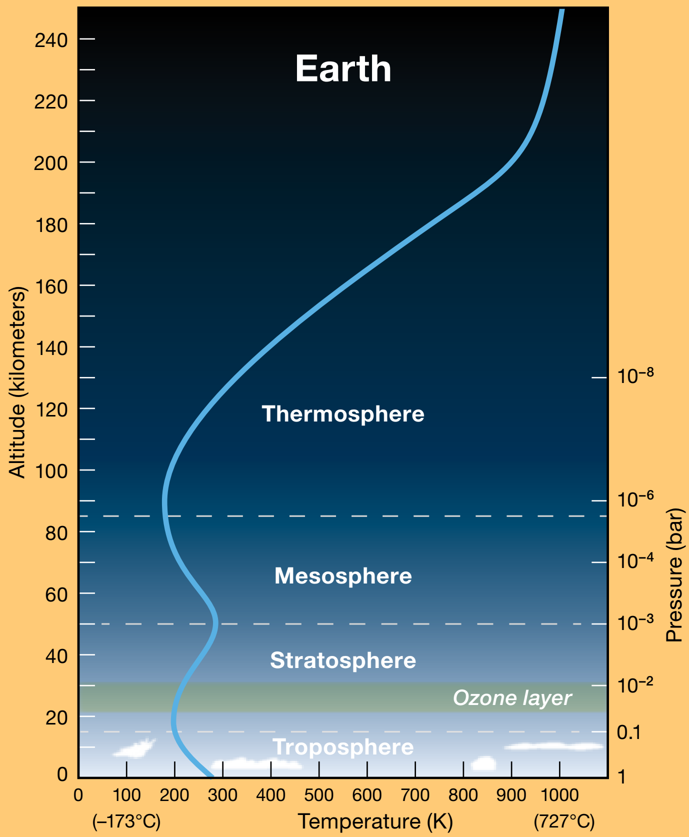
**Venus and Earth share similar sizes, masses, densities, and even distances from the Sun. But Venus's atmosphere and rotation make it dramatically different from our planet.**

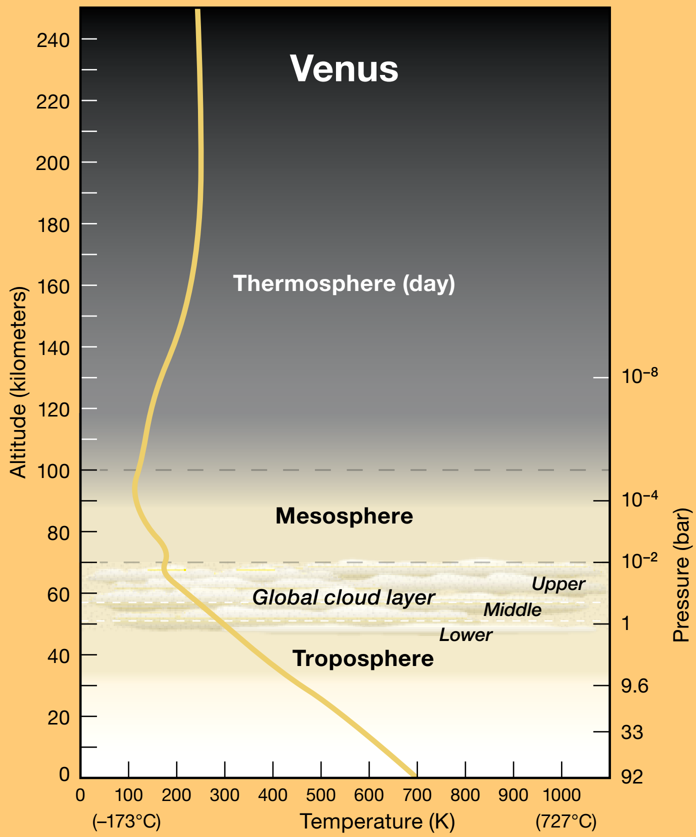
▶ Venus rotates slowly clockwise (unlike Earth), but it orbits the Sun counterclockwise (as all the planets do). So although it takes 243 Earth days to rotate once about its axis — called its *sidereal* day — it takes 117 Earth days for the Sun to travel from noon to noon at Venus's equator (its solar day). Complicating matters, Venus's cloud deck circles the planet in about four Earth days, for reasons unknown. *(Not to scale)*




**SIMILAR, BUT DIFFERENT**

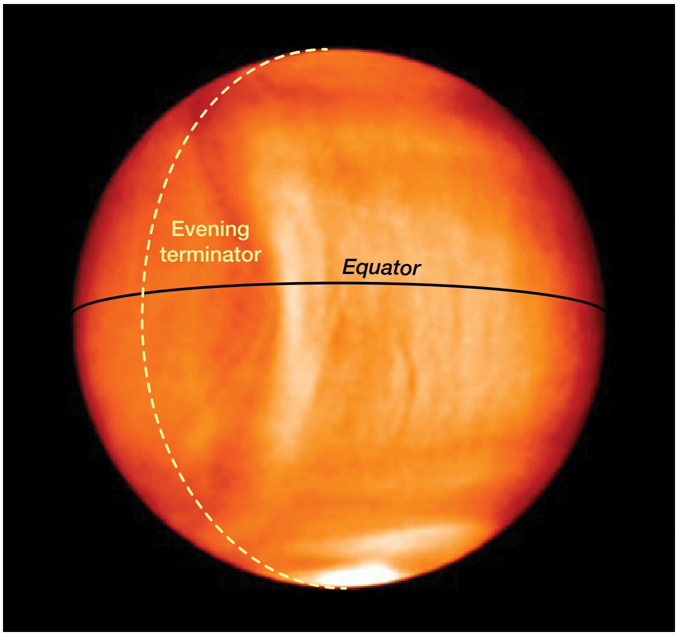



▲ **ATMOSPHERES AT A GLANCE** Atmospheric pressure, ground heating, solar heating, and chemistry combine to create unique conditions on Venus and Earth. The troposphere is where weather happens: Molecules that exist as gases near the warm ground cool and condense to cloud-forming droplets as they rise in altitude. Clouds rarely go above the troposphere, because above it, temperature increases and pressure decreases, and a cloud's molecules change to gas again. Conditions don't permit Venusian clouds to form until roughly 50 km up — about three times higher than Earth's clouds ever reach. At this altitude on Venus, temperature and pressure are Earth-like.

INFOGRAPHIC: TERRI DUBÉ / *S&T*; VENUS: NASA / GSFC SCIENTIFIC VISUALIZATION STUDIO; EARTH: *S&T* ILLUSTRATION; ATMOSPHERES OF VENUS AND EARTH: GREGG DINDERMAN / *S&T*




▲ **PLANET-SIZE CLOUD** Upon arrival at Venus in 2015, the Akatsuki spacecraft spotted this persistent, bow-shaped feature in the planet's clouds. It sits above Aphrodite Terra, the largest continent-like highland region. Image is a false-color infrared view.

The composition of the atmosphere is variable, too. For example, Venus Express found sulfur dioxide above the clouds to be "random" and "patchy," with huge variations from one place to another and from one orbit to another. One way to puff sulfur oxides high into the atmosphere in patchy and random ways is to spew it out of volcanoes.

## Akatsuki: Surface to Air Connections

Earth's variable weather is driven by interactions between the air and ground — think of rain shadows behind mountain ranges — but scientists thought Venus's atmosphere was too thick to "feel" the ground below it. However, right after arrival, Akatsuki's cameras spotted a planet-spanning, stationary, bow-shaped cloud. This enormous atmospheric feature permanently sits directly over some of the highest-elevation crust of Venus, Aphrodite Terra.

"I think the most striking result from Akatsuki is this weird connection between the surface topography and massive structures in the clouds," Grinspoon says.

Venus Express scientists found local changes in atmospheric composition in the same location. Climatologists now believe the cloud feature to be a *gravity wave*, a vertical displacement that's the result of the interaction of the moving, buoyant atmosphere and the high topography.

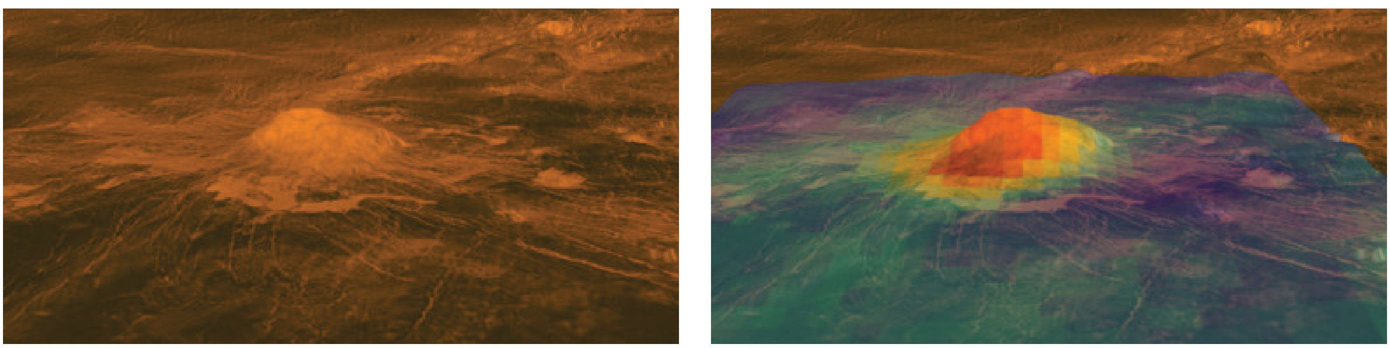
"The atmosphere is much more dynamic than anybody had expected," Ghail says. "And those dynamics must be driven by something."

There are two ways to put energy into an atmosphere: The Sun delivers heat from the top down, and a planet's internal heat puts in energy from the bottom up. Geologic activity — particularly surface volcanism — can shunt a lot of heat into an atmosphere. Venus has lots of volcanoes, but are they active today? Neither orbiter could see the surface clearly enough to tell us for sure what might be happening there, though Venus Express provided enticing glimpses.

For instance, some of Venus's volcanic flows might be fresh. Venus Express saw hints of the heat signature from fresh lava flows that bloomed and then vanished. Volcanism might also explain the short-lived sulfur dioxide clouds the spacecraft detected. The extra heat and volcanic gases could cause rapid chemical weathering on Venus's surface. On Earth, water attacks fresh lava to alter its minerals, but on Venus, sulfur compounds probably connect the chemistry of air and rocks, and sulfur oxides might be the ones to react with minerals.

Any one of these bits of evidence isn't enough to say that Venus is presently volcanically active, but taken together, they at least "demand further investigation," Ghail says. "That's what really justified going back. To understand all those really big surprises in Venus Express data, we need to understand the geology, because Venus Express said: 'Venus isn't anything like you think it is from Magellan. It's active, it's dynamic, it's got things going on.'"

▼ **ACTIVE VOLCANISM?** *Left:* The volcanic peak Idunn Mons lies in the southern Imdr Regio and rises about 2.5 km above the surrounding volcanic plains (vertical extent is exaggerated 30 times in this image, simulated from Magellan data). Bright areas in the radar data indicate rough or steep terrain; dark areas are smooth. *Right:* Heat patterns (colors, red-orange is warmest) observed by Venus Express indicate the summit is warmer than the surrounding terrain, perhaps due to recent lava flows.



GRAVITY WAVE IN VENUS'S ATMOSPHERE: PLANET-C PROJECT TEAM; HOT SPOT ON VENUS: ESA / NASA / JPL-CALTECH

## Exoplanet Next Door

What Venus Express and Akatsuki have taught us about Venus's climate has reinforced the idea that the planet may have looked quite Earth-like — watery and temperate — for much of its history (*S&T:* Oct 2021, p. 12). Other missions, like Rosetta, have demonstrated that Earth's water didn't come from comets but may have been part of the planet from the start (*S&T:* May 2017, p. 14).

Smrekar points out that as far back as Magellan, argon isotopic data suggested that if Earth and Venus started out with the same amount of water and other lighter constituents, today's Venus may actually retain more water, deeply buried in mantle rocks, than Earth does.

"We've seen all these low-density planets squashed right up against their suns," Smrekar says. "The idea that your position in the solar system determines how much volatiles you got dealt is wrong. We can't just say, 'Oh, Venus is close to the Sun, so it doesn't have much water.'"

Clearly, to understand exoplanets, it would help if we understood our nearer neighbors better. In a way, exoplanet science has merged with Venus science to produce the current list of highest-priority questions for future missions.

A NASA science advisory body called the Venus Exploration Analysis Group (inevitably abbreviated VEXAG) provides opportunities for Venus scientists to discuss and agree on the most important goals for future Venus exploration. VEXAG members presented the latest version of their consensus at a meeting in November 2021. There are three overarching goals.

The first goal is to figure out what Venus looked like early on and whether it was habitable, in order to better understand the evolution of Venus-size exoplanets. Was Venus once watery like Earth? Is its present state representative of the way that Venus-size planets evolve, or is it unusual?

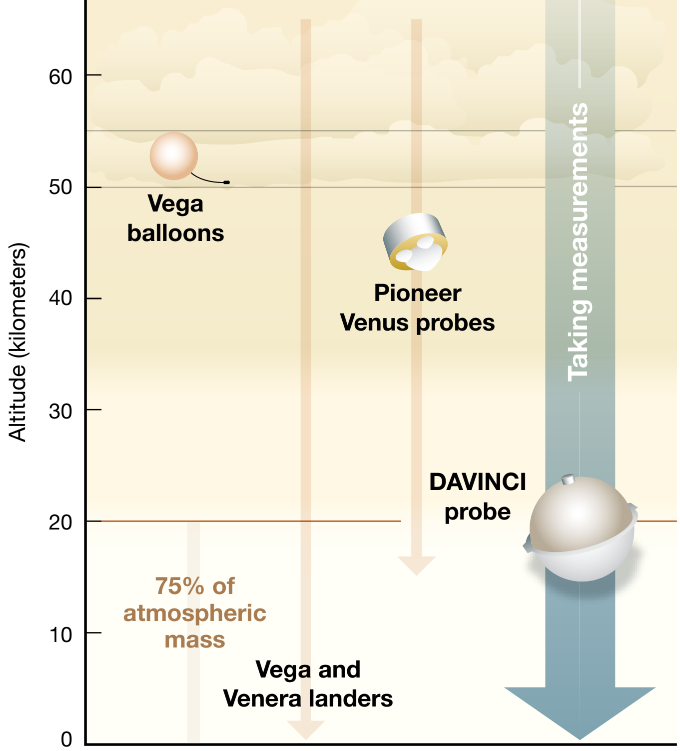
The second is to understand the composition and motions of the atmosphere. What drives all that variable behavior? How are the different parts of the atmosphere connected to one another? What the heck is that ultraviolet absorber?

The third goal is to understand the surface's geologic history and how the surface and atmosphere interact today. What stories are preserved in Venus's rocks? What can we learn from their composition and the landforms they build? What processes shape and modify the surface today? What is the structure of the interior? How do the atmosphere and surface interact chemically?

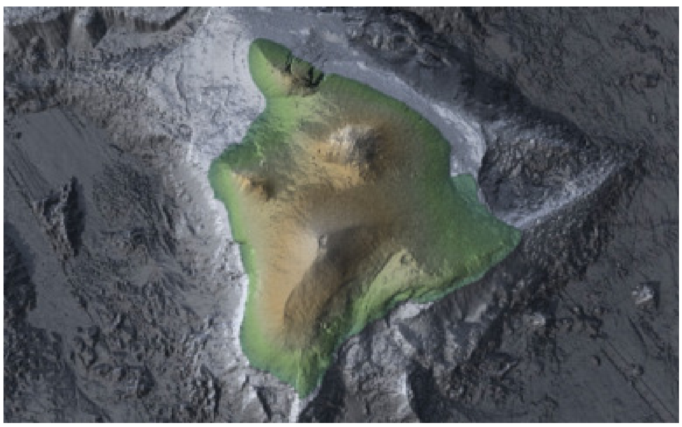
The three missions that will explore Venus in the 2030s will address all of the VEXAG goals. And they will do it cooperatively, building on one another to produce a body of scientific data that is much more than the sum of its parts.

## The New Venus Fleet

The study of Venus's geology now is in a similar state to Martian science at the turn of the millennium. (Thanks to Venus Express and Akatsuki, Venusian climate science is more advanced than that.) Following the end of the Mariner and




▲ **A UNIQUE VIEW** Previous missions gave us limited information about the structure of Venus's atmosphere (thin arrows), but DAVINCI will take a wide range of measurements throughout its descent to the surface.



▲ **EYE-OPENING** VERITAS's radar instrument, VISAR, will deliver topographic measurements roughly 100 times sharper than Magellan did. Based on U.S. Geological Survey data, these images show how the island of Hawai'i would look to Magellan *(top)* and to VERITAS *(bottom)*.

DAVINCI'S DESCENT: GREGG DINDERMAN / *S&T*; RESOLUTION COMPARISON: VERITAS TEAM

### WHICH WAY IS SUNRISE?

If you could see the Sun from Venus's surface, it would rise in the west and set in the east.

Viking missions to Mars in the 1970s, geologists lacked new data for the Red Planet until the 1990s. Venus has likewise experienced a long hiatus: The Pioneer Venus, Venera, VeGa, and Magellan missions produced global data sets on surface geology and near-surface atmospheric chemistry, but the only dedicated visitors Venus has had since 1994 are Venus Express and Akatsuki.

VERITAS, DAVINCI, and EnVision stand to kick off a renaissance at Venus like the one that happened on Mars after Pathfinder landed in 1997 and was followed within a decade by four orbiters and two rovers, bringing Mars science into the digital age.

The Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) orbiter will launch first, late in 2027. It has a narrow but extremely important focus: establishing a foundational, global data set of Venusian topography and radar images using 21st-century technology. It's directly analogous to the Mars Global Surveyor mission, whose laser altimeter MOLA produced the first good topographic map of Mars. Topographic maps are good for science on their own, but their lasting value is as a geodetic base map, which will tie all other past and future data sets to a single model of the planet's geometric shape, enabling data-rich connections among missions. Its first global maps should be available in mid-2031.

VERITAS will also produce a global radar map at a resolution of 30 meters per pixel, similar to early Earth maps from the Landsat satellites or to one of the best current global Mars maps, the one from Mars Odyssey's thermal imager. As with VERITAS's topography data, there will be exciting science revealed in the radar map, but its lasting contribution will be as a geographic reference that will unite all other data.

Finally, VERITAS carries an infrared imaging system that will peer through narrow "windows" in the atmosphere where carbon dioxide is moderately transparent. The resulting maps will be a little fuzzy, because the thick atmosphere scatters light, limiting the resolving power to a pretty low 10 kilometers per pixel.

The images will likely not provide conclusive answers about how Venus's rock composition varies from place to place, but they should provide clear evidence for anomalous spots worth further investigation. And they could even spot telltale emissions from an active eruption, Smrekar hopes. "I would be thrilled if we actually see water coming out of a volcano," she says. "That would be the best day ever."

Following VERITAS is the Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging (DAVINCI) mission. Nearly 50 years after the last time we obtained in-situ data from Venus's deep atmosphere, DAVINCI's probe will descend through the clouds to make direct measurements of atmospheric temperature, pressure, and composition.

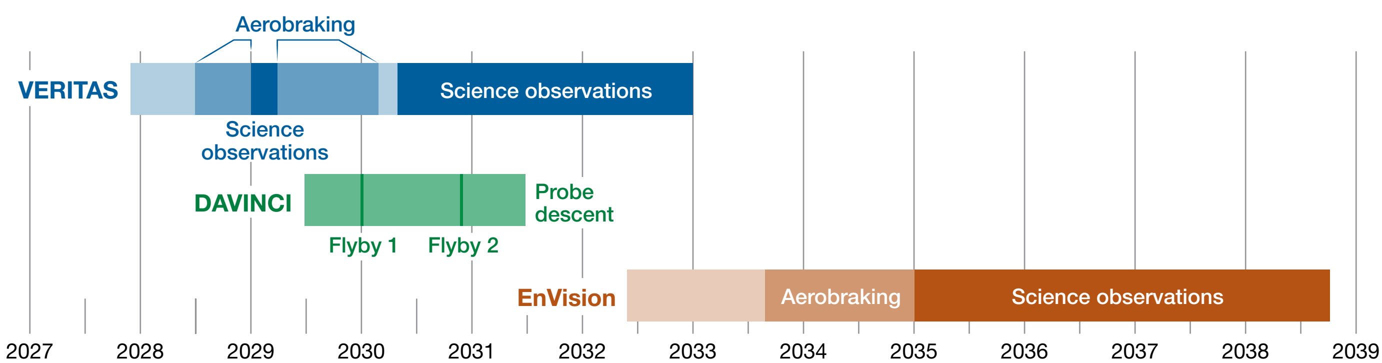
"DAVINCI can measure things that we can't measure from orbit," Grinspoon says. "The rare gases and isotopes have never been decently measured on Venus. And they're just so key to formation and evolution theories." It'll be a "reprint the textbooks" moment when the data come in.

The DAVINCI probe's science payload is heavily based on the miniaturized analytical laboratory instruments in the Curiosity rover that are currently sampling Mars's atmosphere. The probe's descent will take about an hour; for about half of that time, it will be below the bottom of the cloud deck. Unlike any previous Venus descent probe, DAVINCI will shoot images on the way down, like both Curiosity and Perseverance did on Mars, using a similar camera. DAVINCI will serve the same role for Venus as the Huygens probe did for Titan science, connecting Cassini's orbital measurements through Titan's haze to directly measured properties of the atmosphere and surface.

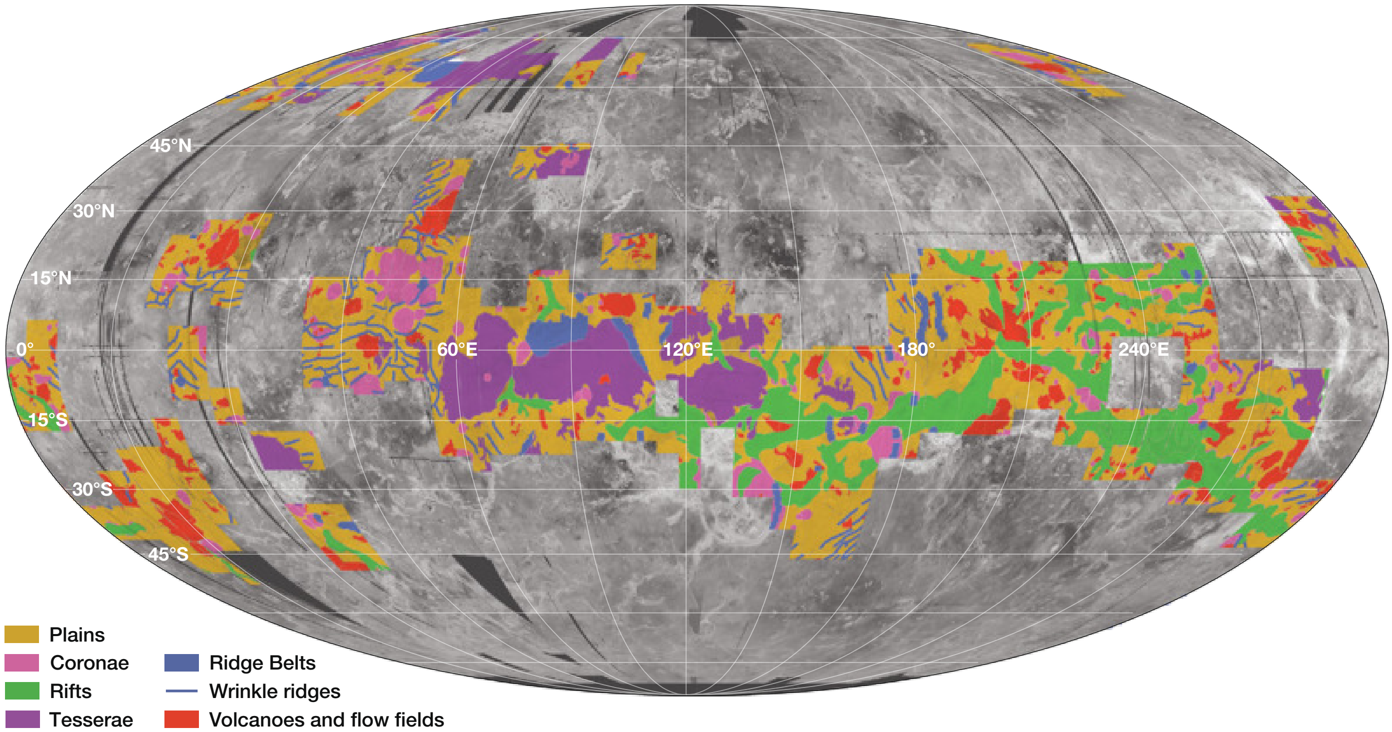
For the best photos, DAVINCI needs to land with the Sun as high overhead as possible. Setting that up requires two flybys, and DAVINCI's carrier spacecraft will make use of those flybys to record long series of images watching the roiling motions of clouds at different levels in the atmosphere.

Both of the NASA missions may be over before the European Space Agency's EnVision arrives at Venus, though we can

**TENTATIVE MISSION TIMELINES**




SUN ICON: YELENA POLYAKOV / THE NOUN PROJECT; TIMELINE: GREGG DINDERMAN / S&T




▲ **WHAT ENVISION MIGHT SEE** EnVision's radar will penetrate Venus's clouds, mapping key geological features such as volcanoes and continent-like tesserae at a resolution of about 10 km. This map shows one example of the targets the mission could study.

hope that VERITAS will last longer than its primary planned mission, and that DAVINCI can continue performing flybys. In fact, according to DAVINCI principal investigator Jim Garvin (NASA Goddard Space Flight Center), DAVINCI could go into Venus orbit on its next flyby after dropping the probe.

With VERITAS's global maps and DAVINCI's in-situ measurements already available, EnVision will be able to reach its full potential. If NASA had not selected its two missions for development, EnVision would have had many more mapping responsibilities, Ghail explains. "VERITAS is a global geophysics mission. It's about getting topography and gravity globally, at high resolution. And it's very good at that, better than EnVision would be."

EnVision's radar mapper won't get VERITAS's global coverage, but it will see parts of the surface at higher resolution, focusing on especially compelling geologic features to elucidate the present and past of Venus. EnVision will therefore be able to function like ESA's Sentinel Earth orbiters or the HiRISE camera on NASA's Mars Reconnaissance Orbiter, monitoring Venus's atmosphere and surface for changes over time. EnVision's radar sounder will also draw profiles of the subsurface structure across Venus craters, cracks, volcanoes, and crumpled mountains, just as Mars Express and Mars Reconnaissance Orbiter have done, helping to tell the story of Venus's geologic history.

Finally, EnVision carries a suite of spectrometers that will see to many levels of the atmosphere as well as to the surface. In fact, one of EnVision's spectrometers will be a near-duplicate of the one on VERITAS. Flying a nearly identical instrument twice is not something that happens often in planetary science, but it's very common on Earth orbiters, and it will enable scientists to establish a continuous record of weather and surface changes from VERITAS through EnVision, spanning a decade and possibly more.

## The Decade of Venus

To say that Venus scientists are thrilled about the selection of three new missions is understating things. But there are reasons to be happy besides the new data. "It's been a big tension between all the [proposed] missions," Smrekar says. "It's been very fracturing to be so competitive all the time. It's really a pleasure to be cooperating instead of competing."

Grinspoon agrees. "There was this wonderful moment after the selection when we realized, 'Oh, now we can all be friends again,' because until then we'd been so in competition against each other."

Europe and the United States aren't the only ones planning new missions to Venus. The next decade could also see missions launched by India and even from a private company, Rocket Lab, based in New Zealand. A spacecraft from the United Arab Emirates will also swing by Venus en route to the asteroid belt. Underappreciated and poorly understood for so long, Venus will finally enjoy the kind of scientific boom that Mars has experienced for 25 years. May that boom last at least as long as the Age of Mars has.

■ Contributing Editor **EMILY LAKDAWALLA** is a freelance space writer and artist. Her second book, *Curiosity and Its Science Mission: A Mars Rover Goes to Work*, is forthcoming from Springer-Praxis in 2023.