and the local peaks in the electrostatic potential not accounted for by those atoms: Yellow blotches represent large potential peaks, and gray blotches represent smaller ones. With a less accurate method, there would have been no correlation between the largest potential peaks and the expected H locations—the H signal would have been overwhelmed by noise. Here, though, the yellow peaks agree well with the known H positions in paracetamol and the expected H positions in cobalt aluminophosphate.

The new results show that when x-ray diffraction fails due to crystal size, electron diffraction has the potential to stand in for it. But Palatinus and Boullay don't expect x-ray diffraction to give up its position as the favored technique for structural analysis anytime soon. The lower risk of radiation damage to the sample makes x-ray diffraction far less technically challenging. And although the dynamical scattering theory calculations can be performed on an ordinary desktop computer, they can take up to several hours to complete; computing structures from x-ray diffraction data is 100 to 1000 times faster.

Johanna Miller

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Circuitry made robust enough for Venus

Silicon carbide devices lasted more than three weeks in a laboratory simulation of the corrosive conditions that prevail on the planet's surface.

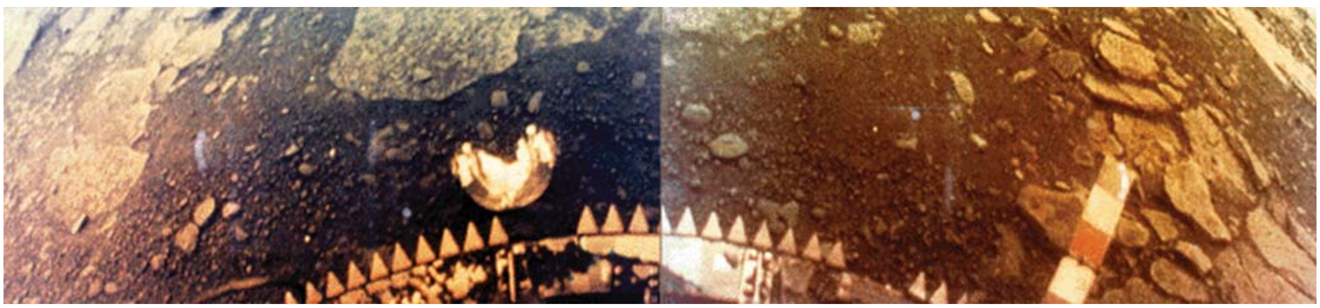

FIGURE 1. THE SURFACE OF VENUS, as captured in true color by the *Venera 13* lander during the 127 minutes its instruments remained functional on the planet's surface. The base of the spacecraft appears surrounded by flat rock slabs and soil, and the entire scene appears orange because the planet's thick atmosphere efficiently filters blue light from incident solar radiation. (Adapted from ref. 7.)

Day or night, the temperature on Venus varies little from its mean of about 460 °C. That's hot enough to melt lead and an extreme demonstration of the runaway greenhouse effect of carbon dioxide, which makes up most of the planet's thick atmosphere. With the planet's crushing surface pressure of 9.4 MPa—93 times that on Earth—the gas exists in a supercritical state and behaves as a solvent. (On Earth, supercritical CO_2 is used to decaffeinate coffee beans.) Overhead, sulfuric acid clouds tens of kilometers thick are blown around the planet by hurricane-force winds.

Of the 26 spacecraft sent to Venus since 1961, only a handful have even attempted to land on its harsh surface. In 1982 the Soviet *Venera 13* lander sent the image shown in figure 1 before its instruments stopped working after a mere two hours on the surface, despite being housed in a protective pressurized vessel filled with heat-absorbing lithium salt. The quick demise is unsurprising: Silicon electronics start to fail at temperatures above 250 °C because too many electrons are thermally excited across the bandgap.

In the ensuing decades, silicon carbide technology has matured enough to make the semiconductor a more suitable choice for high-temperature applications.[1] Its strong, short Si–C bonds help protect the material from radiation damage by protons and gamma rays, and its wide bandgap allows for transistor action even at temperatures as high as 1000 °C. For the past several years, a team of engineers and materials scientists led by Philip Neudeck of NASA's Glenn Research Center in Cleveland, Ohio, has pursued the goal of developing durable SiC electronics sophisticated enough to reliably monitor the combustion conditions inside an aircraft engine, say, or the stability of an industrial drill bit deep underground.

To that end, the researchers have steadily toughened the various pieces of a SiC-based integrated circuit (IC). Those pieces include the metallic interconnects that run between field-effect transistors; the insulating dielectric layers that protect everything from oxidation, which can be particularly insidious in hot environments; the gold-capped contacts that help link the IC chip to an external circuit board; and the board's gold- and platinum-embedded glass traces that connect the IC to other circuits. The effort has involved, among other things, choosing pure and relatively inert electronic materials that are stable at high temperature and whose thermal expansion coefficients are well matched to each other.[2]

Now Neudeck and colleagues have demonstrated that the robust ICs can

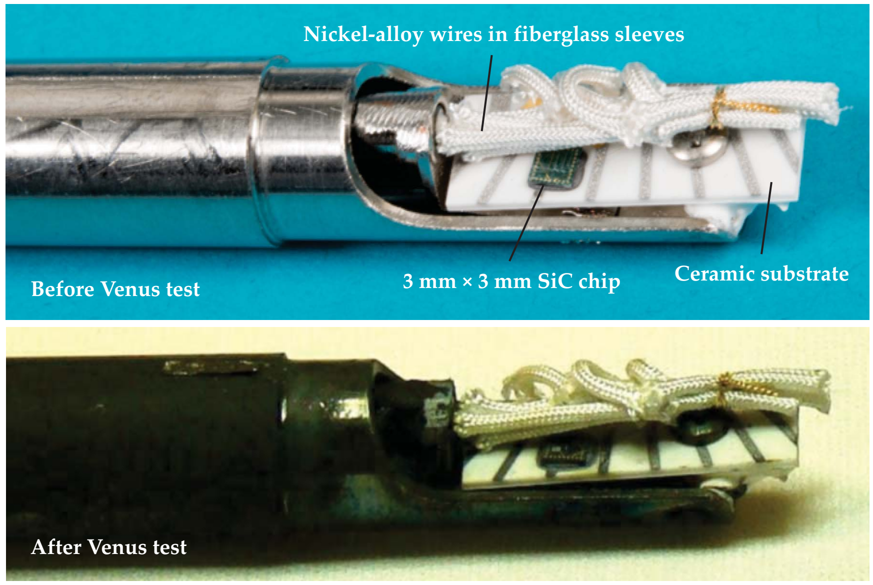

FIGURE 2. BEFORE AND AFTER PHOTOGRAPHS of a silicon carbide integrated circuit (IC) that was exposed to a simulated Venus surface environment for 21.7 days in NASA's Glenn Extreme Environments Rig. The IC, designed to output a constant-frequency signal, was connected to four leads on a ceramic substrate and to a fiberglass-insulated bundle of nickel-alloy wires that led to instruments outside the chamber. Although the feed-through wires short-circuited during the experiment and soot and other chemical debris discolored the steel housing, diagnostics performed after the experiment showed that the chip itself never failed. (Adapted from ref. 3.)

operate successfully for several hundred hours in a simulated Venus atmosphere.[3] The team placed two ICs in an 800-liter pressure chamber—NASA's Glenn Extreme Environments Rig (GEER)—and exposed them for nearly 22 days to the same temperature, pressure, and oxidizing chemical environment that a Venus lander would endure. The ICs were ring oscillators—a common logic technology demonstration circuit—each composed of dozens of transistors and resistors. Figure 2 shows one IC test chip before and after exposure. Instruments outside monitored each oscillator's constant-frequency signal. Although a feed-through cable short-circuited at the seal connecting one of the packages' circuit board to the outside instruments, neither chip failed.

The degree of success was a "big surprise to me," says Neudeck, who admitted that the test was the first Venus simulation his team had made on a working circuit. Besides the threat of material degradation and the diffusion of soot, he had worried that the dense gases would be electrically conductive enough to short-circuit the chips' power-supply leads, which were held at a constant 50 V. "A bunch of things could have gone wrong but didn't," he added. "The only reason we ended the experiment was that our scheduled time with GEER ran out."

According to Colin Wilson, a planetary physicist at Oxford University, the achievement is encouraging because it proves the durability of SiC electronics in harsh conditions beyond just high heat. "The demonstration paves the way for light, compact, more affordable missions to Venus," he says.

Indeed, in November 2016 Wilson, Carl-Mikael Zetterling (KTH Royal Institute of Technology in Sweden), and Thomas Pike (Imperial College London) pitched to the European Space Agency the idea of a Venus lander mission that would measure, for a period of months, the planet's seismicity.[4] Although they have not reported 460–500 °C operating times comparable to Neudeck's team, Zetterling's research group and others are also developing an all-SiC collection of electronic circuits for a lander: CPUs, memory, analog–digital converters, environmental sensors, and a telecommunications system. The only additional piece they propose is a radioisotope thermoelectric generator to power the electronics. (Because of Venus's thick cloud deck, little light reaches the surface.) For a similar mission planned by NASA, see reference 5.

Known unknowns

Despite its wildly different climate, Venus is sometimes known as Earth's twin. The two are similar in size, mass, bulk composition, and proximity to the Sun. And although radar maps have revealed Venus to be covered in volcanic and tectonic features, no one knows whether volcanism and tectonic activity continue today. Establishing the current geological state would help scientists address a fundamental question about Venus that they are still struggling to answer about Mars—whether the planet ever had a habitable environment with liquid-water oceans. (See the article by Ashwin Vasavada on page 34 of this issue.)

Unlike Mars's surface, whose study has benefited enormously from a succession of rovers crawling around the planet for the past decade, the surface of Venus remains almost completely unexplored. If roving on Venus's rugged terrain turns out to be too challenging or otherwise impractical, the high atmospheric density near its surface—50 times that on Earth—enables another possible way to get around: using metal Chinese-lantern-like balloons whose bellows can expand or contract to control buoyancy.[6]

The concept of planetary ballooning is less outlandish than one might think. Back in 1985 the Soviet Union successfully deployed two balloons in the clouds of Venus, 55 km above the surface. Too high up to image the ground, the balloons and their payloads were carried more than 10 000 km by fast winds and enjoyed balmy temperatures around 20 °C. Today's research into robust SiC circuitry could lead to high-temperature balloon missions that travel far closer to the ground—even touching down in spots—so that instruments can photograph passing terrain or sample its broiling soil and rock.

Mark Wilson

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PHYSICS UPDATE

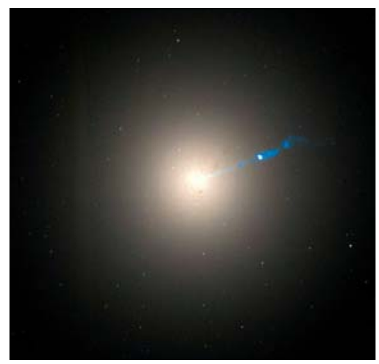
These items, with supplementary material, first appeared at www.physicstoday.org.

TESTING THEORIES OF MODIFIED GRAVITY

The accelerated expansion of the universe is usually attributed to a mysterious dark energy, but there's another conceivable explanation: modified gravity. Unmodified gravity—that is, Einstein's general relativity—satisfactorily accounts for the dynamics of the solar system, where precision measurements can be made without the confounding influence of dark matter. Nor have any violations been detected in one of general relativity's principal ingredients, the strong equivalence principle, which posits that inertial mass and gravitational mass are identical.

But those observational constraints are not ineluctable. In particular, a class of gravitational theories called Galileon models can also pass them. In 2012 Lam Hui and Alberto Nicolis of Columbia University devised a cosmic test that could refute or confirm the models. Their test hinges on the models' central feature: an additional scalar field that couples to mass. The coupling can be characterized by a charge-like parameter, Q. For most cosmic objects, Q has the same value as the inertial mass. But for a black hole, whose mass arises entirely from its gravitational binding energy, Q is zero; the strong equivalence principle is violated.

Galaxies fall through space away from low concentrations of mass and toward high concentrations. The supermassive black holes at the centers of some galaxies are carried along with the flow. But if gravity has a Galileon component, the black hole feels less of a tug than do the galaxy's stars, interstellar medium, and dark-matter particles. The upshot, Hui and Nicolis realized, is that the black hole will lag the rest of the galaxy and slip away from its center. The displacement is arrested when the black hole reaches the point where the lag is offset by the presence of more of the galaxy's gravitational mass on one side of the black hole than on the other. Given the right circumstances, the displacement can be measured.



Hui and Nicolis's proposal has now itself been put to the test. Asha Asvathaman and Jeremy Heyl of the University of British Columbia, together with Hui, have applied it to two galaxies: M32, which is being pulled toward its larger neighbor, the Andromeda galaxy, and M87 (shown here), which is being pulled through the Virgo cluster of galaxies. Both M32 and M87 are elliptical galaxies. Because of their simple shapes, their centroids can be determined from optical observations. The locations of their respective black holes can be determined from radio observations. Although the limit on Galileon gravity that Asvathaman, Heyl, and Hui derived was too loose to refute or confirm the theory, they nevertheless validated the test itself. More precise astrometric observations could make it decisive. (A. Asvathaman, J. S. Heyl, L. Hui, *Mon. Not. R. Astron. Soc.* **465**, 3261, 2017.)

—CD

WATCHING PEROVSKITE PHOTOEXCITATIONS, ATOM BY ATOM

Certain members of the class of crystalline materials known as perovskites have recently shown great promise for optoelectronic applications. Perovskites have the chemical formula ABX_3, where A and B are cations and X is an anion, arranged as shown on page 22. Crystals that combine an organic cation, lead as the