make [toroidal black holes]," says Teukolsky. "We succeeded"—although the donut hole always closed up soon after the collapse.

Hot and cold black holes

Another group of theorists is using the weirdness of black holes as a clue to physics beyond Einstein's equations entirely. No one has yet merged quantum mechanics—which describes the small-scale graininess of matter and energy—and relativity to make a successful theory of "quantum gravity" that would extend this graininess to space and time. One possible route could lie in the esoteric mathematics known as string theory (*Science*, 15 September 1995, p. 1511). But striking parallels between the mechanics of black holes and classical concepts of temperature and entropy—a system's degree of randomness—could also end up showing the path to quantum gravity, says Robert Wald of the University of Chicago and the principal organizer of the Chandra symposium.

A century ago, he reminded his listeners, the second law of thermodynamics—the inevitable increase of entropy of a system such as gas in a piston's chamber—helped persuade physicists that all matter consists of atoms. By accounting for atomic motions, they found, they could actually prove the law. Lately, says Wald, theorists are finding resemblances between the textbook mechanisms and the workings of black holes that are "just too amazing, I think, to be some mathematical curiosity."

In this analogy, the area of the event horizon takes the place of entropy. Just as total entropy always increases when parcels of gas merge or get pushed around mechanically, the event horizon always expands when, say, two black holes interact or more matter is added to a black hole. Black holes have a temperature, too, as Hawking showed in 1974 when he found that black holes should radiate particles. This radiation is fed by the normally undetectable pairs of particles that, according to quantum mechanics, constantly pop in and out of existence throughout space: Near the event horizon, one member of a pair can get sucked into a black hole while the other flies away. And he and others have shown that this Hawking radiation should have a "thermal" spectrum of energies, shaped exactly like the spectrum of radiation from an object glowing at a particular temperature. The stronger a black hole's gravity at the event horizon, the higher its "temperature" would be.

Physicists hope that such correspondences will let them understand the rest of the story. Working backward from the black hole's entropy, says Rafael Sorkin of Syracuse University in New York and ICN-UNAM in Mexico City, shows that "it's just as if the black-hole horizon was made out of many pieces of about the Planck size"—what would be the smallest imaginable dimension in quantum gravity. Sorkin is still sorting out exactly how that graininess might arise. But he thinks that ultimately, black-hole entropy may "[lead] us to the atoms of space-time itself."

Physicists acknowledge, however, that the analogy comes with deep mysteries, such as how the horizon area could ever take the place of the entire volume, the natural setting for classical thermodynamics. Even more distressing to some traditionalists is a black hole's apparent disregard for "real" information such as the kind of material that falls into it, which can figure in the standard kind of entropy. The Hawking radiation allows black holes to slowly "evaporate" and disappear without yielding any information about what they had swallowed up. That's uncomfortable for some physicists who, Hawking says, "seem to have a strong emotional attachment to information."

Hawking's talk only deepened this discomfort by proposing that the process could be ubiquitous: Microscopic pairs of black holes could be forming and evaporating throughout space, consuming small-scale order like Pac-Mans. Such black holes might, for example, eat one kind of particle and emit another as they evaporate, violating some of the most hallowed conservation laws of particle physics.

But this mind-bending vision was also a fitting conclusion to the symposium, said Hugo Sonnenschein, president of the University of Chicago, where Chandra spent nearly 6 decades as a faculty member. "It's an amazing juxtaposition to call yourself a wanderer"—one of Chandra's favorite descriptions of himself—"and be in so many ways unsure, and yet feel that you can solve mysteries that are beyond imagination."

–James Glanz

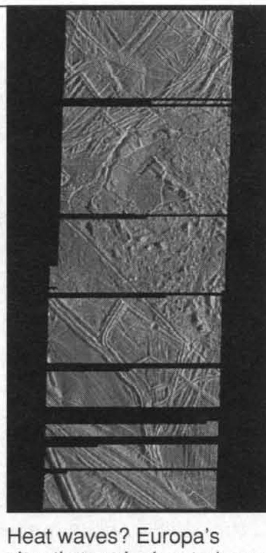
PLANETARY SCIENCE

An Icy World Looks Livelier

WASHINGTON, D.C.—The latest images of Jupiter's moon Europa, released here last week at a NASA press conference, reveal a landscape in turmoil. To team members poring over images returned by the Galileo spacecraft, the wild jumble of ridges, grooves, pits, ice flows, and chaotic terrain shows ever more signs that heat forged Europa's icy surface. Even to a nonscientist, it's clear that this moon's surface is—or was—mobile. Pope John Paul II, who was shown images of the satellite last week after a scientific meeting in Italy, said simply, "Wow!"

"These new images demonstrate that there was enough heat to drive [ice] flows on the surface," says Galileo imaging team member Ronald Greeley of Arizona State University. And where there's water and enough heat, there might once have been life, he says. "Europa thus has a high potential" as a place where life could have gotten started.

Space scientists had already raised the notion that Europa might at some time have been warm enough to support a water ocean, thanks to Voyager images taken in the 1980s and Galileo images from an earlier, more distant flyby (*Science*, 20 December 1996, p. 2015). Now, images showing details up to 20 times finer—as small as 36 meters—add weight to that possibility. Greeley points to several features in the accompanying image that he suspects depict various stages in the rising of plumes of warm ice or a wet, icy mush. The plume first bulges the surface and cracks it (middle of top block). Then, some unearthly geologic process takes over, and the broken terrain collapses into a chaotic jumble of ice blocks (right side of middle image blocks). Greeley speculates that sublimation of small amounts of ammonia or methane ice from the water ice weakens the terrain, and so it crumbles. In other images, rising water or icy mush appears to have burst through the surface like an ice volcano, flowing as 100-meter-thick lobes of ice for hundreds of kilometers.


JPL/NASA

Heat waves? Europa's chaotic terrain *(center)* may suggest a heat-driven plume from below.

Even these features don't prove that an ocean lurks beneath the surface. Icy volcanism could be driven by scattered hot spots in a solid layer of ice rather than an actual ocean. Or an ocean may have existed in the moon's youth and frozen solid since, squeezing out these few dribbles of ice with its last gasp. But it's also possible that there may still be a warm, liquid sea—perfect for life—hidden below the ice. Galileo's future close encounters with Europa may tell.

–Richard A. Kerr

For more images of Europa's surface, see the Jet Propulsion Laboratory's Web page at: http://www.jpl.nasa.gov:80/galileo/status970117.html