Physicists and cosmologists are teaming up to plan visionary projects that would glean fundamental physics from relics of the big bang and from energetic corners of today's universe

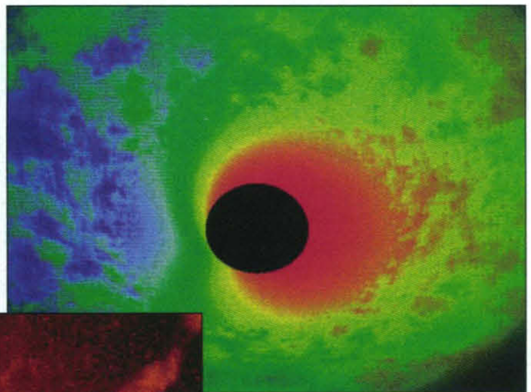
Space Becomes a Physics Lab

ROHNERT PARK, CALIFORNIA—In his vision of the future of x-ray astronomy, Nicholas White hovers above the boundary of a black hole at the center of a distant, turbulent galaxy. He sees the fabric of space-time contort weirdly around the giant hole, traced by bright gashes of x-rays as hot gas plunges from sight. His vantage point gives him a clear view of the mechanism that blasts powerful jets of matter into space from just outside the black hole. Occasional wormholes or other exotic portals may pop into view.

White's dream is not to inject himself directly into this relativistic mayhem but to study its details from afar, with a fleet of x-ray telescopes staring in unison from their orbit around the sun. Just as widely separated radio telescopes on Earth can act as a single outsized telescope to image fine detail in distant objects, an orbiting x-ray interferometer could probe the innermost workings of the most energetic bodies in the cosmos. "We've proved that black holes exist," says White, an astronomer at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "Ultimately, we want to know how they work, and this is the best way to do that."

The x-ray fleet, dubbed MAXIM for MicroArcsecond X-ray Imaging Mission, might not fly for 20 to 25 years, White acknowledges. That made it a perfect topic to broach at "Cosmic Genesis and Fundamental Physics," an unusual workshop held here this fall at Sonoma State University.* About 150 leading astronomers, cosmologists, and physicists convened to gaze into the crystal balls of their fields in the early 21st century, looking for areas of common focus. Their eyes settled upon the origin of the universe, when the basic laws of physics were set, and violent corners of the universe today, which host energetic physics beyond the reach of particle accelerators. At the workshop, they described dozens of bold experiments that might glean new physics from the cosmos.

For now, most of the projects have no funding or timetables, but the meeting organizers hoped the discussions would catalyze the planning needed for some missions to take wing in the next few decades. Traditionally, particle physicists and astrophysicists have blazed separate trails, with little communication and few interdisciplinary experiments. Two current exceptions, planned for launch by 2005, are the Gamma-Ray Large Area Space Telescope (GLAST), which will study supernova remnants, gamma ray bursts, and other cosmic particle accelerators, and the Alpha Magnetic Spectrometer, which will search for antimatter particles from a perch on the international space station. And NASA Administrator Daniel Goldin, for one, wants to see many more such collaborations in the new millennium.



Dark heart. A jet spews from the heart of galaxy M87, thought to host a supermassive black hole, in a Hubble Space Telescope image *(left)*. An orbiting array of x-ray telescopes might one day image the boundary of the black hole itself (simulation above).

At a meeting earlier this year at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, Goldin urged physicists to look to the cosmos for insights about ultrahigh-energy particles and processes (*Science*, 4 June, p. 1597). He renewed that theme on 6 November in Irvine, California, at an address to the Board on Physics and Astronomy of the National Academy of Sciences. "If we are to make grand breakthroughs in fundamental physics, we need to pay more attention to this overlap of physics and astrophysics," Goldin said. He envisions a new "Cosmic Journeys" program at NASA to support some of these projects and hopes other agencies—notably the National Science Foundation (NSF) and the Department of Energy (DOE)—will join in.

Goldin's Fermilab address, and the prospect of a new crosscutting funding initiative, motivated cosmologist Rocky Kolb of Fermilab and physicists Elliott Bloom of Stanford University and Jim Siegrist of Lawrence Berkeley National Laboratory in Berkeley, California, to organize the Sonoma State meeting. Speakers were encouraged to proffer blue-sky ideas that look a decade or a quarter-century into the future, perhaps drawing upon technologies that are mere twinkles in their eyes today. "I didn't have very high expectations, but we're in wild agreement about the need to approach these problems on many different fronts simultaneously," Siegrist said when the meeting ended. "This really could go somewhere"—if he and his colleagues can cross disciplinary barriers and make a unified case for the most promising efforts.

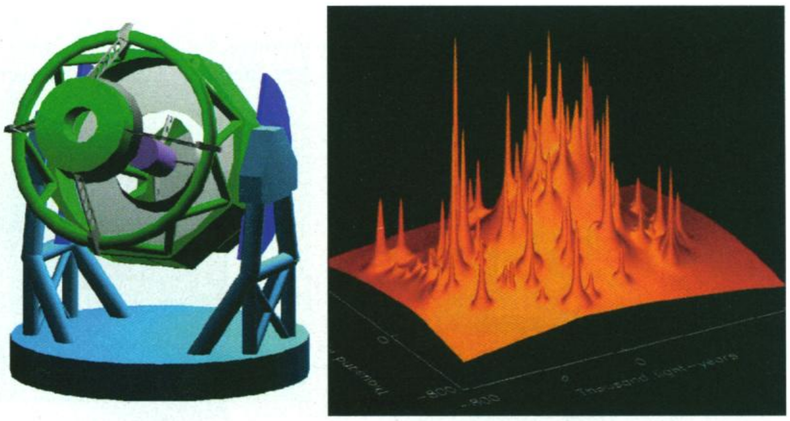
Ripples in space-time

Gravity in its many manifestations emerged as a favorite pursuit. Physicist Peter Bender of the University of Colorado, Boulder, described the Laser Interferometer Space Antenna, or LISA: three spacecraft arrayed in a triangle 5 million kilometers on a side. Laser beams would measure the position of a free-floating metal cube within each spacecraft to an accuracy of a tenth of an angstrom, relative to both other cubes. That's enough to resolve passing gravitational waves—ripples in space-time with waveforms and structures that, according to theory, are dictated by the relativistic physics near violent cosmic events. Whereas the gravitational-wave observatories about to start observing from the ground may see signs of powerful bursts, such as the collapse and explosion of massive stars, LISA's immense scale will make it sensitive to gravitational ripples with far longer wavelengths. Such stretched-out waves should emanate from phenomena that last hours to months—most notably, pairs of black holes locked in ever-tightening death spirals.

* www-afrd.lbl.gov/cosmicgenesis

CREDITS: (LEFT TO RIGHT) NASA/SPACE TELESCOPE SCIENCE INSTITUTE; BEN BROMLEY, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

If all goes well, LISA could fly within 10 years. Farther in the future, an improved array of satellites called LISA 2 might be sensitive enough to detect the gravitational-wave background of the universe itself—a buzz of gravity waves equivalent to the faint cosmic microwave background "glow" that pervades the sky. "That's incredibly exciting, because it would reveal the first instant of the universe's transparency to gravity waves," says Bloom. That moment occurred when gravity decoupled from the rest of nature's fundamental forces, perhaps just 10^{-38} seconds after the big bang. The relics of that moment may reveal how gravity influenced the primordial quantum fluctuations that etched a template for the large-scale structure we see in the universe today.



Spying the invisible. The proposed Dark Matter Telescope *(left)* would image patches of the sky six times wider than the full moon, searching for distortions that reveal the invisible mass (orange spikes in graph, right) binding large clusters of galaxies.

CREDITS: (LEFT TO RIGHT) ROGER ANGEL *ET AL.*, UNIVERSITY OF ARIZONA; ANTHONY TYSON, LUCENT TECHNOLOGIES

Those first gravitational waves also should have left subtle imprints on the cosmic microwave background itself, says cosmologist Marc Kamionkowski of the California Institute of Technology in Pasadena. Just as a lake polarizes light that reflects off the water, gravitational waves would have polarized the photons of the early universe at the moment that space cooled enough for them to escape the hot gas. The European Space Agency's Planck satellite may see hints of this shadowy polarization after its launch in 2007, but Kamionkowski advocates a dedicated post-Planck mission to scrutinize the polarization in detail. He notes that different scenarios for inflation, the wild burst of growth the infant universe is thought to have experienced, predict varying patterns of polarization in the cosmic microwave background. A satellite sensitive enough to discriminate among those patterns could settle the inflation debate and steer physicists closer toward understanding how the basic laws of nature operated in the first incandescent moments of the universe.

Cosmic particle factories

Other cosmic messengers are less subtle. Rare, ultrahigh-energy cosmic rays reach Earth carrying vastly more energy than terrestrial accelerators can generate: the punch of a brick dropped from a table, packed into a single particle. Physicists speculate that these wanderers may stream from the cores of active galaxies, gamma ray bursts, or spinning black holes, but no convincing theory exists about the astrophysical mechanisms that could boost particles to such extreme speeds. Ground detectors watching for the sprays of lower energy particles that an ultraenergetic cosmic ray excites as it slams into the upper atmosphere have spied only about 20 events so far, because the detectors monitor limited patches of the sky. Ultraviolet imagers in orbit could cover 10,000 times more area by watching the atmosphere from above, allowing Earth itself to serve as a kind of cosmic-ray display screen, says physicist Robert Streitmatter of NASA Goddard (*Science*, 5 December 1997, p. 1708). A pair of satellites, dubbed OWL for Orbiting Wide-Angle Light Collector, could trace the paths of the most energetic cosmic rays through the atmosphere, thereby pinpointing their sources and perhaps disclosing the nature of the objects that produce them.

Detailed surveys of the universe in visible light also have much to offer in the next few decades, says astronomer Roger Angel of the University of Arizona, Tucson, including the prospect of mapping something that doesn't shine at all: dark matter. Invisible concentrations of matter bind together large clusters of galaxies and surround individual galaxies like our Milky Way with vast cocoons. Although the motions of galaxies and stars reveal the gravitational pull of this dark matter, no one knows what it is made of—perhaps dim clumps of ordinary matter or exotic particles that physicists have not yet been able to detect on Earth. A detailed sky map of the dark matter might offer clues to its composition, as well as nailing down the total matter content of the universe.

Angel and his colleagues, including astrophysicist Anthony Tyson of Lucent Technologies in Murray Hill, New Jersey, have proposed a new telescope that they believe could chart dark matter in exquisite detail. The design of their "Dark Matter Telescope" takes advantage of the way these invisible mass concentrations warp our view of distant galaxies by acting as "gravitational lenses," dimpling the fabric of space-time. The telescope would use an 8.4-meter mirror and two 4-meter mirrors in a radical configuration to map these subtle distortions across gigantic patches of the sky, six times wider than the full moon.

The most mind-bending proposal for a dark-matter search may have come from Nobel laureate Martin Perl, a physicist at the Stanford Linear Accelerator Center (SLAC). Perl proposed scouring asteroids for massive particles that accelerators will never produce on Earth. These stable but ultraheavy particles, spawned in the big bang, might survive today in ancient material, such as asteroids or comets, as well as scattered between the stars. As a low-cost initial search, Perl's team plans to create tiny drops from meteorite fragments and measure the rates at which they fall in the laboratory. Although the drops, only about 10 micrometers across, will be too small to weigh easily, they will fall through air with different terminal velocities depending on their masses, perhaps revealing ultraheavy particles bound to ordinary matter within the meteorite material. But the best chance to spot them, Perl says, is to send a robot to an asteroid, where it could sift through the pristine soil and scan the terminal velocities of particles within the asteroid's minuscule gravitational field.

Some of the proposals discussed at the meeting are in the preliminary funding pipeline at NASA or one of the other agencies. Others would require substantial new funding. And which to pursue first was a common hallway question. "Everyone has a program, and everyone's program is interesting," says SLAC physicist Helen Quinn. "But how do you set priorities and decide which ones to do?"

The astronomy and particle physics communities both have mechanisms for doing so, but their approaches are different. Astronomers convene a "decadal review" panel that ranks the importance of new projects over a 10-year period; the next report is due in the spring. Particle physicists have a High-Energy Physics Advisory Panel, which advises the Department of Energy—the field's main funder—four times a year. For interdisciplinary proposals like the ones discussed at the Sonoma State meeting, it might be wise to set up a new advisory committee that reports formally to NASA, NSF, and DOE, says Peter Rosen, DOE's associate director for high-energy and nuclear physics—perhaps along the lines of SAGENAP (Scientific Assessment Group for Experiments in Non-Accelerator Physics), nine physicists who have advised DOE and NSF on projects such as GLAST.

But setting priorities is just a start. To attract funding for a major new initiative, astronomers and physicists will need to get savvy about marketing their plans, says Alan Bunner, science program director for the structure and evolution of the universe at NASA. "The added momentum of two or three agencies advocating the same initiative is hard to stop," Bunner says. "But the American people have to be engaged. Intellectual interest is not enough." He urged his audience at Sonoma State to distill the most exciting aspects of their proposed initiative and push them aggressively, both within the funding agencies and in their own communities.

Siegrist and his colleagues have charted the next few steps along this path. In February, theorists will gather in Aspen, Colorado, to discuss which future experiments have the most potential to solve fundamental mysteries in physics and cosmology. Two months later, the organizers will meet in Washington, D.C., to prepare a white paper for the directors of DOE, NSF, and NASA. If the prospects in Congress look good for a new physics-astrophysics budget initiative, the group will plan the last of its initial meetings, probably a Snowmass, Colorado, conference in the summer of 2001.

Another uncertainty may loom at that point: How well would astronomers and physicists collaborate when they face the nitty-gritty details of joint projects? "We have developed different traditions," says Rosen. "We don't have a tradition in high-energy or nuclear physics to make data widely available to anyone," because most complex detectors yield results only after painstaking analysis by the teams who built them. Astronomers, on the other hand, tend to build community instruments and quickly share what they find.

The organizers of this budding movement think these disparate fields will find a way to cooperate, because the opportunities are irresistible. "Don't be afraid to take a big step if one is indicated," Fermilab's Kolb urged his colleagues in a rousing final address at Sonoma State. "John Muir said that when one tugs at a simple thing in nature, he finds it hitched to the rest of the universe. Our laboratory for fundamental physics is now the universe itself." —**ROBERT IRION**

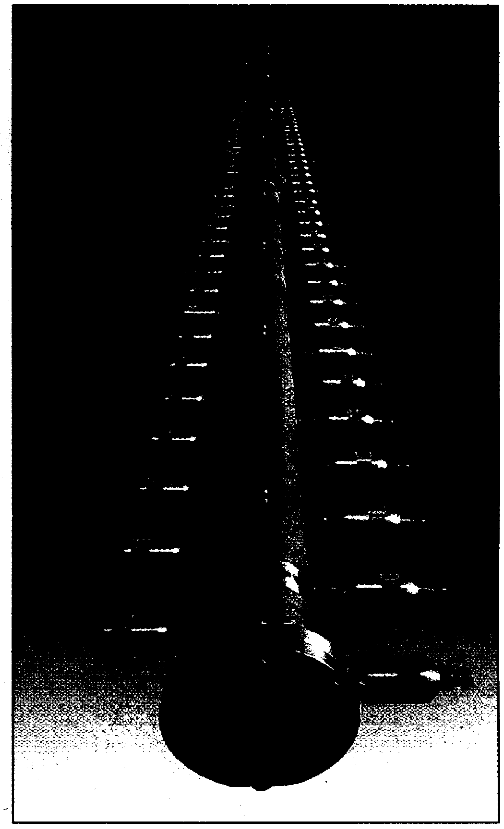
PHYSICS

Conjuring a Solitary Sound Wave

Spotted 150 years ago on the water of a canal and now routinely generated in light-carrying fibers, the solitary, long-lasting waves called solitons have now been seen in yet another medium: sound. In the 15 November *Physical Review Letters*, a team of researchers in Japan describes how they produced acoustic solitary waves by altering the propagation of sound through an air-filled tube.

In 1834 a British naval architect, John Scott Russell, was the first to spot a soliton, racing away from the prow of a boat on the Edinburgh-Glasgow Canal. Working in a 9-meter tank that he built in his garden, Russell discovered that such waves survive because they avoid dispersing. A single water pulse contains waves at many different frequencies, and two effects balance out to keep the waves from separating. Lower frequency waves travel faster and would tend to outrun the pulse—except that the steepness of the water surface within the pulse speeds up higher frequency waves just enough to compensate. Optical fibers can also host solitons, because similar effects conspire to keep light pulses from dispersing in glass. But air—the usual medium for sound waves—behaves in just the wrong way to host a soliton. The speed of sound in air varies with intensity only, not frequency, which causes intense blasts of sound to pile up into shock waves.

"Originally, my motive was to suppress shock formation in tunnels generated by the entry of a high-speed train," says Nobumasa Sugimoto of the University of Osaka in Japan. Sugimoto and his colleagues took a steel tube, 7.4 meters long and 8 centimeters in diameter, and grafted onto it 148 so-called Helmholtz resonators, which resonate at specific frequencies (see image). They sent sound pulses through the tube and tracked how the sound propagated. The team found that the pulses kept their smooth profile, without forming shock waves. What's more, the Helmholtz resonators apparently altered the sound speed depending on frequency, creating the right conditions for the acoustic solitary waves.



Acoustics researcher Junru Wu of the University of Vermont, Burlington, who says he tried and failed to produce acoustic solitons 15 years ago in a similar experiment, thinks the work could have applications outside the laboratory. By adding side branches like those in Sugimoto's lab to exhaust pipes and other machinery, engineers might tame noise, transforming the shocks into milder solitary waves. And because the solitary waves can transport energy steadily over a long distance, Sugimoto and collaborators at Sanyo Electric Co. in Osaka are exploring potential applications in acoustic compressors, heat engines, and even heat pumps. —**ALEXANDER HELLEMANS**

Alexander Hellemans is a writer in Naples, Italy.

CREDIT: SUGIMOTO *ET AL.*