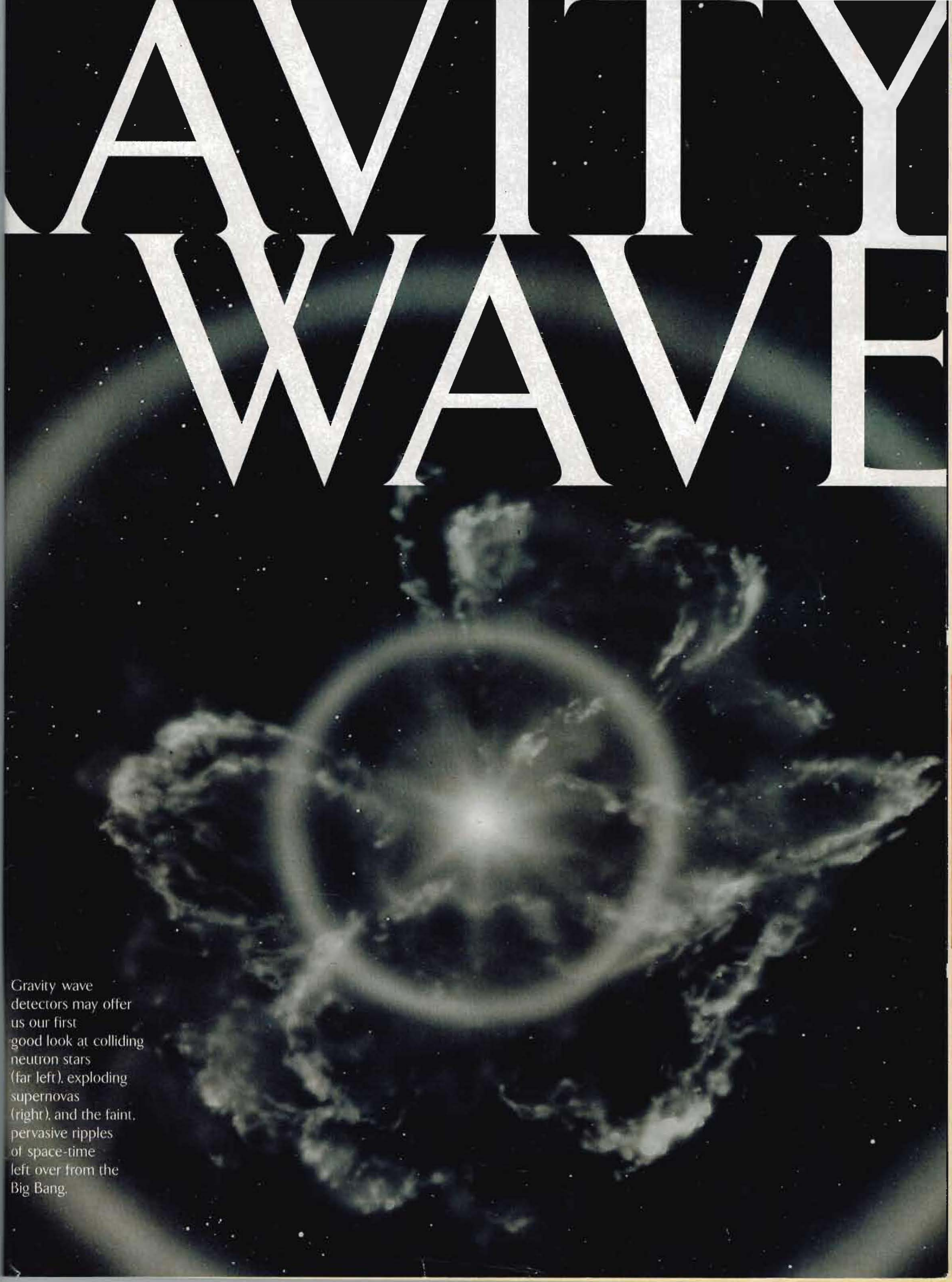
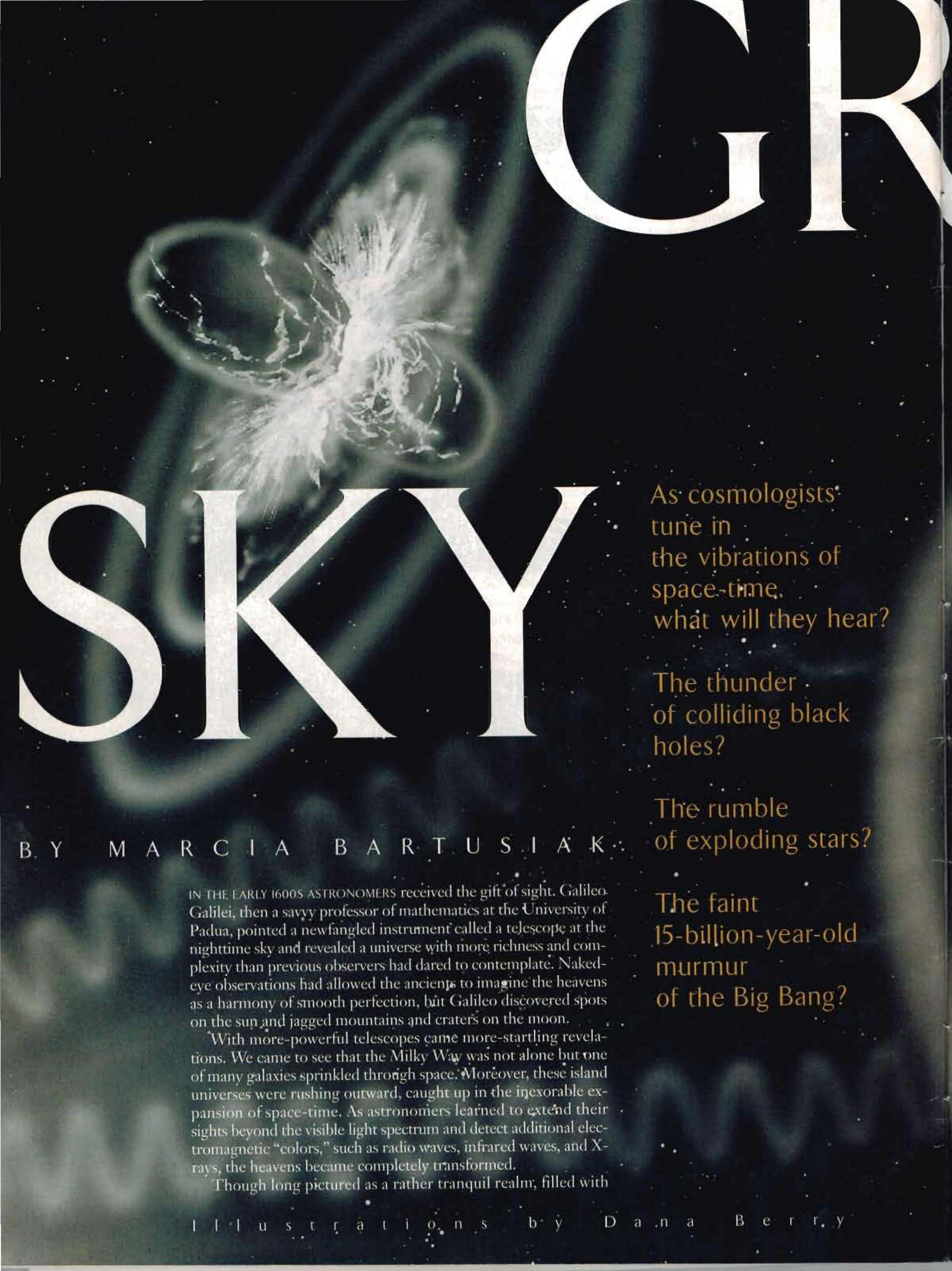
AVITY
WAVE



Gravity wave detectors may offer us our first good look at colliding neutron stars (far left), exploding supernovas (right), and the faint, pervasive ripples of space-time left over from the Big Bang.



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SKY

As cosmologists tune in the vibrations of space-time, what will they hear?

The thunder of colliding black holes?

The rumble of exploding stars?

The faint 15-billion-year-old murmur of the Big Bang?

BY MARCIA BARTUSIAK

IN THE EARLY 1600S ASTRONOMERS received the gift of sight. Galileo Galilei, then a savvy professor of mathematics at the University of Padua, pointed a newfangled instrument called a telescope at the nighttime sky and revealed a universe with more richness and complexity than previous observers had dared to contemplate. Naked-eye observations had allowed the ancients to imagine the heavens as a harmony of smooth perfection, but Galileo discovered spots on the sun and jagged mountains and craters on the moon.

With more-powerful telescopes came more-startling revelations. We came to see that the Milky Way was not alone but one of many galaxies sprinkled through space. Moreover, these island universes were rushing outward, caught up in the inexorable expansion of space-time. As astronomers learned to extend their sights beyond the visible light spectrum and detect additional electromagnetic "colors," such as radio waves, infrared waves, and X-rays, the heavens became completely transformed.

Though long pictured as a rather tranquil realm, filled with

Illustrations by Dana Berry

Scraping Space-Time

A small bump forms on the surface of a newborn neutron star. As the massive star whirls, this dense mini-mountain rhythmically thumps the rubberlike mat of space-time and sends out a periodic gravity wave.

well-behaved stars and stately spiraling galaxies, the cosmos was now revealed as a place of almost frenetic activity and violence. Arrays of radio telescopes, aimed toward the edge of the visible universe, observed luminous young galaxies called quasars spewing the energy of a trillion suns out of a space no larger than our solar system. Focusing closer in, within our own stellar neighborhood, these same radio telescopes watched neutron stars—ten-mile-wide balls of pure nuclear matter, the collapsed remnants of massive stars—spinning like crazed tops, dozens of times each second. Meanwhile X-ray telescopes discovered huge amounts of X-ray-emitting gas, unobservable with optical telescopes, hovering around large clusters of galaxies. The invisible became visible.

The twenty-first century may see the sky remade once again. It will happen as soon as astronomers are able to detect gravity waves, "spacequakes" produced by nature's most awesome celestial events. But unlike visible light waves, radio waves, and X-rays, these ripples in space-time will not be "seen"—gravity waves are not electromagnetic in nature. Rather, each gravity wave that passes by Earth will be "felt"—perceived, perhaps, as a subtle vibration, a vibrant boom, or even a low-key cosmic rumble.

When that first happens, astronomy will be changed forever. Gravity waves will do more than offer us an additional window on space—they will provide us with a radically new perception of it. It's as if in studying the sky we've been watching a silent movie. Gravity waves, in a way, will at last be adding sound and touch to our cosmic senses, turning the silent universe into a talkie, one in which we might "hear" the thunder of colliding black holes or the whoosh of a collapsing star.

That gravity waves might exist is not a new idea. Einstein first conceived of them more than 70 years ago. They were a natural consequence of his theory of general relativity, which redefined how we think about gravity. According to general relativity, massive bodies, such as stars, indent the space around them (much the way a bowling ball sitting on an elastic mat would create a depression). Planets and comets are then attracted to the star simply because they are following the curved space-time highway carved out by it.

In theory, gravity waves are generated whenever space is fiercely disturbed—say, when a star is jostled. Such titanic movements should cause ripples of gravitational energy to radiate outward in all directions along the rubberlike mat of space-time. These waves are not traveling through space; they are an agitation of space itself. This vibration of the

ASTRONOMERS WILL TRANSLATE GRAVITY WAVE RHYTHMS INTO A NEW MAP OF THE HEAVENS, A CLANDESTINE COSMOS NOW IMPOSSIBLE TO SEE.

space-time fabric conveys information very different from that carried by the electromagnetic spectrum, just as sound tells us different things than light does. Electromagnetic waves, whether of visible light, radio, or infrared, are released by individual atoms and electrons and generally reveal a celestial object's physical condition—how hot it is, how fast it's moving, or what it's made of. But they are continuously absorbed by cosmic debris—stars, gas clouds, and such—as they roam the universe.

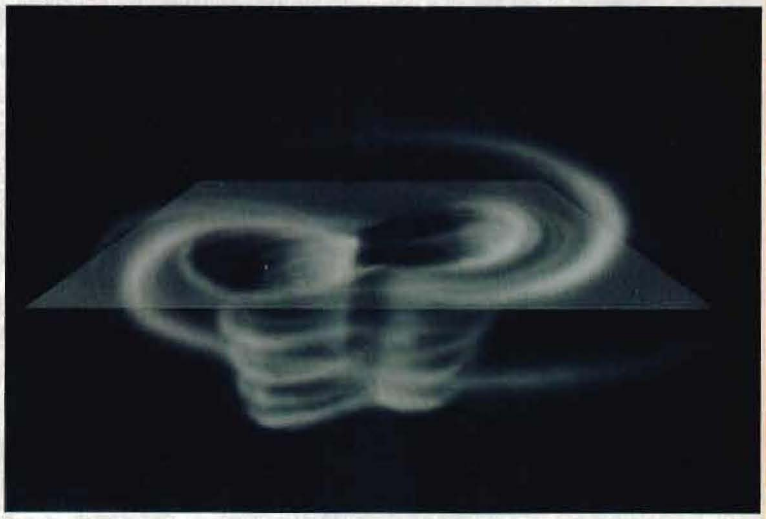
Gravity waves, by contrast, can travel right through such obstacles with nary a disturbance. They can even race right out of the heart of a supernova explosion, where photons of light get smothered and absorbed. Instead of giving us information about an object's physical condition, they will tell us about the overall motions of massive celestial objects—how a neutron star collapses or a black hole moves around. According to general relativity, the swells in space-time created by these colossal movements will race outward at the speed of light, like ripples spreading out from a giant pebble dropped into a cosmic pond, until they rumble onto the shores of Earth, where finely tuned instruments await their arrival. Our planet, like all objects embedded in space-time, will also be subtly deformed by these ripples—but the effects of gravity waves on solid objects should be even smaller than their effects on empty space-time because of the overwhelming nature of electrical and nuclear forces that glue matter together.

A gravity wave telescope will act essentially like a geologic seismometer, but a seismometer that is placed on the fabric of space-time to register its temblors. Researchers around the world are now readying such instruments, working on making them sensitive enough to detect subtle space-time quivers. Some are designed as truck-size cylindrical bars that will "ring" like bells whenever a sizable gravity wave passes through them; others involve a set of weights, suspended masses that will appear to sway as the peaks and troughs of the traversing gravity wave alternately squeeze and stretch the space between them (although these movements will be exquisitely tiny, the displacement being thousands of times smaller than the width of an atomic nucleus). A network of detectors will act as

Holes in Collision

Two black holes, embedded in space-time, circle each other, emitting a steady stream of weak gravity waves.

As gravity pulls them closer together, their whine rises in pitch like the sound of an oncoming ambulance.



Shedding energy, the holes orbit ever faster until, at close to the speed of light, they emit a birdlike trill of closely packed waves.

A cymballike crash accompanies their apocalyptic collision and merger. The two holes become one.

TO CATCH A GRAVITY WAVE

WITH LUCK, IT COULD TURN OUT TO BE a serendipitous encounter of the most productive kind. This spring three spacecraft zooming away from Earth in three different directions just happened to be in the right place at the right time to—just possibly—snare an elusive gravity wave. But the odds against it are long.

The experiment took place between March 21 and April 11. NASA's *Mars Observer* was headed for the Red Planet, its *Galileo* probe was bound for Jupiter, and the European Space Agency's *Ulysses* (pictured) was on its way to study the poles of the sun. A team of American and Italian scientists decided to take advantage of the situation by beaming radio signals of precisely controlled frequencies toward the three spacecraft from a network of ten antennas situated all over the globe. Each spacecraft then amplified the signal it received and sent it back to Earth for comparison and analysis. The researchers' reasoning was that if, during the transmission, a gravity wave passed through the solar system, Earth and the three spacecraft would have been gently rocked by the disruption of space-time—they would have bobbed ever so slightly, like corks on the surface of a lake as a ripple passes by. This bobbing would have shifted the frequencies of the radio transmission by a minuscule amount.

"The spacecraft are all in their interplanetary cruise phase, and it was just sort of fortuitous that we were able to track them all at the same time," says Frank Estabrook, of NASA's Jet Propulsion Laboratory. The low-budget experiment was possible because all three interplanetary voyagers are in the night sky, minimizing interference to the radio signals from the solar wind's charged particles.

Any one of the three spacecraft could have registered the kind of frequency shift that would be caused by a passing space-time ripple. A single such anomaly could also be caused by a number of technological quirks; if the signals to all three spacecraft were affected, however, the evidence would be far more convincing. In addition, with three sources of information, scientists would probably be able to pinpoint the direction of the gravity wave emitter by using simple trigonometry, just as geologists can pinpoint the epicenter of an earthquake if they have readings from three seismometers.

"Our experiment is a long shot," concedes Estabrook. Although the team used a superaccurate atomic clock to calibrate both the transmitter and the receiver, the frequency could be controlled only to a few parts in a million billion. While that may sound impressive from a technological standpoint, gravity waves are thought to be so feeble that only waves from extremely massive sources would cause enough disruption in space-time to shift the frequency by even that much.

Making matters even more difficult, the experiment was sensitive only to extremely low frequency gravity waves, those with typical periods between 2 and 15 minutes. These low-frequency waves could come only from large sources like supermassive black holes in nearby galaxies; less massive objects would send out shorter pulses. However, Estabrook says it's conceivable that the makeshift detector could also have caught gravity waves emanating from certain kinds of bizarre sources in more-distant galaxies, such as the collapse of hundreds of thousands of stars into a black hole.

Before the scientists can know for sure whether they've captured their quarry, they will have to account for variations in the frequency caused by the motions of Earth and the spacecraft through space, the effects of interference from the solar wind, and the distortion from Earth's atmosphere. "We're going to be very cautious analyzing the data before we announce anything," says Estabrook. The final results might not be known until the end of the year. *—Robert Naeye*

Courtesy NASA

surveyor's stakes in pinpointing the source in the sky; by carefully monitoring the differing times that a gravity wave arrives at various detectors set around the globe, astronomers will be able to determine its origin.

A gravity wave signal could be rhythmic or erratic, steady or sporadic. We will discern, in essence, a cosmic symphony of beats. Gravity wave astronomers will translate these syncopated rhythms—the whines, the bursts, the random roars—into a new map of the heavens, a clandestine cosmos now impossible to see.

Picture two black holes slowly circling each other like a pair of wary prizefighters in the ring. Tens of millions of years earlier they were simply stars, but eventually they exhausted all their fuel and collapsed into the most compact state imaginable. Black holes are more than mere indentations in space-time. They are bottomless pits, gravitational abysses out of which no light or matter can climb. While normal telescopes can gather indirect evidence of black holes' existence, they can't actually see them. Theorists can only imagine them. Only a gravity wave telescope has a chance to sense directly the presence of these unfathomable space-time wells.

The sighting will occur at one decisive moment, after the two black holes have been slowly orbiting each other for perhaps millions of years. During this time the pair has been emitting a steady stream of very weak gravity waves, a wake that, as the black holes circled about, spread outward along the canvas of space-time like the spiraling pattern of a spinning pinwheel. Gradually losing energy in this fashion, the two black holes relentlessly draw together. And the closer they get, the faster they orbit each other.

In the final minute of this fateful dance, the gravity waves being emitted become strong enough to be detectable—just as wakes produced by two boats pile up as they draw near. Instruments on Earth will register a sort of whine, a series of waves that rapidly rise in pitch, like the sound of an ambulance siren that is swiftly approaching. As the twirling black holes are about to meet, spiraling inward faster and faster at close to the speed of light, the whine turns into a "chirp," a birdlike trill that races up the scale in a matter of seconds. A cymbal-like crash, a mere millisecond long, heralds the final collision and merger. The two black holes become one. A decrescendo, like the fading sound of a

> A TSUNAMI OF A WAVE MIGHT HIT OUR SHORES ONCE IN A WHILE, GENERATED WHEN A STAR IN OUR GALAXY EXPLODES AS A BRILLIANT SUPERNOVA.

struck gong, follows as the new entity—a pit in space-time that swirls around like the fearsome tornado in *The Wizard of Oz*—wobbles a bit and then settles down. The masses of the two black holes can be determined from the total duration of their phenomenal coupling: the heavier the holes, the greater their attraction to each other and the faster the merger.

Gravity wave telescopes might register a few of these black-hole collisions each year if they are sensitive enough to detect signals arriving from as far away as the dense Virgo cluster of galaxies, some 50 million light-years distant. This may be the way that physicists finally clinch the existence of the black hole, nature's strangest star. It would give itself away by the melody of its gravity wave "song," the distinctive ripples of space-time curvature transmitted throughout the heavens. Listening to these tunes, astronomers might even discern supermassive black holes, each containing the mass of a million or more suns, being constructed in the centers of far-off galaxies as the holes gobble up and swallow their celestial victims.

The universe could be filled with gravity wave emitters. Astronomers already know that neutron stars, for example, can come in pairs (several are known to reside in our home galaxy), and such binary systems will broadcast their own sets of whines and chirps. Because they are more lightweight than black holes, a pair of neutron stars will take longer to merge, with their final recordable signal lasting minutes instead of seconds.

Gravity wave telescopes will register a sine wave that sweeps to higher and higher frequencies as the two city-size balls spiral into each other. About three minutes before their lethal meeting, the two neutron stars will be a few hundred miles apart and orbiting each other about ten times each second, at nearly a tenth the speed of light. In the final moments, they'll be severely stretched by tidal forces and will circle around each other as much as 1,000 times a second, dragging space-time around with them. As soon as they touch, the two stars will be shredded to pieces, possibly releasing a burst of gamma rays.

What happens afterward, no one can say for sure. The remnants might coalesce into a new, more massive neutron star. Or, if heavy enough, they might condense to utter invisibility, forging a black hole. Only a gravity wave telescope will be able to reveal the final outcome. Gravity wave astronomers suspect such events may turn out to be the bread and butter of their trade. Peering outward a few hundred million light-years to other galaxies, they might pick up a few of these neutron-star collisions each year.

ANOTHER TYPE of signal in the gravity wave sky was once touted as almost a sure thing but is now considered a long shot. A solitary tsunami of a wave might hit our shores every once in a while, generated at the very moment that a star in our galaxy explodes as a brilliant supernova, its core crumpling up to form a dense neutron star. Amid the chirps, the space-time seismometers might occasionally record this singular burst, the resounding clap of a collapsing stellar core.

Whether this burst would be detected depends on how the star dies. Gravity waves would be emitted only if the collapse is a messy affair, with the newborn neutron star squishing flat like a pancake and then stretching out like a football before settling down. If the collapse proceeds smoothly and symmetrically, the gravity waves on one side would exactly cancel those on the other; the signal would be damped out, and astronomers would hear not a peep.

All the while, playing in the background of this gravity wave symphony, could be ongoing rhythms, a steady beat. When a neutron star forms, for instance, it might briefly vibrate and develop a bump on its surface, an inch-high "wave" that grows and freezes into place. And as the neutron star feverishly whirls around, this deformation, jutting out like a finger, would transmit a periodic gravity wave as it continually "scraped" the space around it. Lumpy neutron stars could serve as gravity wave lighthouses scattered over the heavens, each blinking away until its lump smoothed out. Older neutron stars, meanwhile, might let out an occasional gravity wave burp, released if the massive object underwent a "starquake." This could happen when the outer crust of the neutron star occasionally slipped over its superfluid core.

And beneath the chirps, pops, and beats emanating from the gravity wave sky, there could be an underlying murmur—constant, unvarying, and as delicate as a whisper. This all-pervasive buzz would be the faint reverberation of our universe's creation, its remnant thunder echoing down the corridors of time, similar to the residual microwave heat already detected from the Big Bang. But those microwaves started their journey 300,000 years after the Big Bang—the time when atoms first formed and light could at last travel through the universe, unimpeded by a jumble of particles. If we attempt to look further back in time, we perceive only a fog.

Primordial gravity waves, on the other hand, can cut right through that fog. They would be fossils from the very instant of creation, quantum jiggles in space pumped up by an explosive burst of expansion that took place a scant 10^{-35} second into the universe's birth. No other signal survives from that era of "inflation." These relic waves would bring us the closest ever to our origins, perhaps even verifying that the universe emerged as a sort of quantum fluctuation out of nothingness. At the same time, they might tell us how fast the universe expanded during the inflationary period and whether there is enough matter in the heavens to bring this cosmic marathon to a halt in the far, far future.

Perhaps more exciting is the prospect of encountering the unanticipated. Not until astronomers scanned the heavens with radio telescopes did they discover pulsars and quasars. Neutron stars had been contemplated, but not as pulsing radio beacons; quasars were never even fantasized. What else may be skulking about in the darkness of space, as yet unseen? Even stranger celestial creatures may greet us as soon as we place our hands upon the fabric of space-time and feel the rhythms of the universe. D