Wormholes and other strange beasts once populated the universe that Einstein built; now theorists are having second thoughts

CELESTIAL ZOO

BY MARCIA BARTUSIAK

Exploding quasars. Spinning neutron stars. Interstellar molecules that sing out pure radio tones amid the dissonant chatter of the universe. Over the last 30 years these astounding discoveries have made it seem that the heavens are getting a bit crowded. The population explosion looked particularly acute when theorists suggested that the cosmic zoo might harbor even stranger creatures: black holes, white holes, wormholes, and tunnels through hyperspace.

It was a false alarm. While black holes are alive and well, those other celestial beasts have fast become extinct. "The general public has had fun believing in these bizarre objects, because they fitted in so nicely with science fiction," says Kip Thorne. "But to theoretical physicists, they're only part of a game, a fascinating mathematical game."

Thorne should know. As professor of theoretical physics at the California Institute of Technology, he has built up one of the world's leading centers of black-hole research. Since 1966 this notable forty-two-year-old astrophysicist has guided more than 40 graduate students and postdoctoral researchers through the labyrinthine byways of Einstein's famous equations of relativity.

His students don't have to worry about reserving telescope time; their study of the cosmos is strictly cerebral. Only an occasional visit to the computer breaks their musings. For Thorne it means sitting in his cluttered, book-filled office and poking his nose into every nook and cranny of the Einsteinian universe with only a pencil and piece of paper, his favorite grapefruit soda near at hand.

Many who fall under the spell of Einstein's vision feel a little like Alice waking up in Wonderland. Suddenly the universe looks "curiouser and curiouser." Matter turns out to be frozen energy; ob-

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jects shrink as they travel faster; light beams bend as they skim the surface of the sun; and gravity is no longer a force. Instead it is a curvature of space-time itself. The more massive an object, the more it bends that baffling dimension continuum. To picture it, imagine the universe as an infinite flat rubber mat. Heavenly bodies make indentations in the sheet, dimpling it around themselves. According to this scheme, the planets are not held in orbit by some mysterious attraction to the sun; they simply follow the curve that the sun creates in this flexible sheet of space-time.

These drastic changes in our view of the universe have turned out to be merely a sample of the strange effects that turn up when Einstein's theories are taken to the most twisted regions of space-time. "While solving the equations of relativity for the most extreme cases—that is, when gravity becomes very, very strong—mathematical physicists found a veritable zoo of bizarre objects," Thorne says. "By the time I was a graduate student at Princeton University in the early 1960s, the black hole, white hole, wormhole, and tunnel through hyperspace were all on the scene—honest-to-God, exact solutions to Einstein's equations. We were trying to keep them quiet, because we had no reason to believe that any of them existed in the real universe." But by the early 1970s the zoo had been opened to the public.

The black hole, of course, is the proposed remnant of a dying star that has collapsed down and become an object so dense that not even light can escape its awesome gravitational field. "People love to hear about black holes," says Douglas Eardley, of the Harvard-Smithsonian Center for Astronophysics, once a postdoctoral researcher under Thorne. "They're a tremendous threat, the Darth Vaders of astronomy." Magazine headlines seem to bear him out: Black holes have become THE DARKEST RIDDLE OF THE UNIVERSE, THE DAZZLING DEATH SPASM OF A STAR, and even THE BLOB THAT ATE PHYSICS.

White holes are mirror images of black ones; like cosmic geysers, they spew matter into the universe. And wormholes and tunnels through hyperspace are even stranger creatures. In those mathematical fantasies, the indentations in space-time become so deep that they punch through hyperspace land, opening up passageways to other universes—perhaps even into our own distant past. "Remember," Thorne cautions, "hyperspace is not real. It's just the popular term for that fictitious space in which we place our simplified curve sheets of space-time. I use the word *hyperspace* only to help us visualize the curvature."

Science-fiction fans were ecstatic over the tunnels. Science seemed to be handing them an outlandish, yet legitimate, means of jumping around both space and time. Such well-worn plot devices as hyperspace drives and time machines were beginning to look a little more plausible.

And therein lies a big problem for relativists. "Through theoretical and observational tests, we are getting more and more confident that black holes really do exist," Thorne says. "But all those other bizarre objects have nothing to do with reality! It's ironic. We've had persuasive proofs against white holes and hyperspace tunnels for ten years or more—since about the time these solutions were making their first big splash in the popular press." Thorne himself hopes to correct some of those false impressions. Punching holes in the wormhole myth has been his favorite topic on the lecture circuit, and for the past year he has been hunched over his word processor, working on a book that will put these members of the cosmic zoo in their proper perspective.

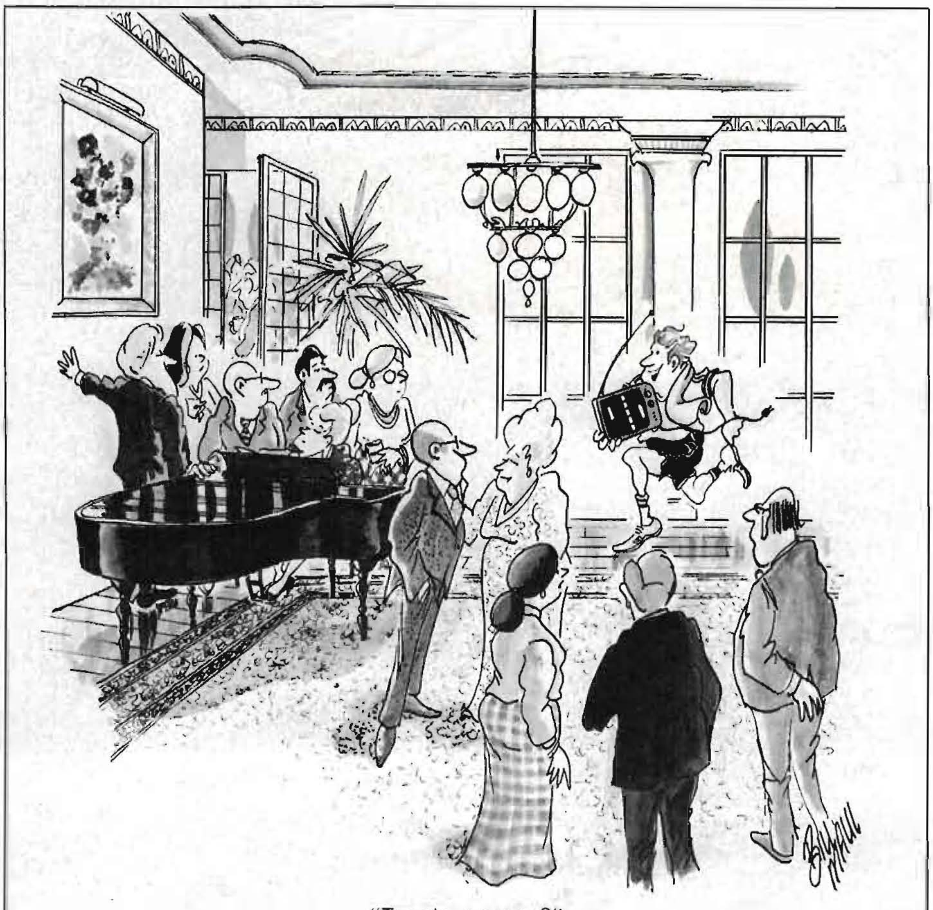
At first glance, Thorne appears to be an unlikely spokesman on the inner workings of theoretical physics. His full beard, shoulder-length hair, and colorful shirts suggest more a bohemian craftsman of the Sixties than a physicist. But there could hardly be a more qualified expositor of relativity. In addition to his teaching work, with physicists John A. Wheeler and Charles Misner he has coauthored *Gravitation*, a text now considered by many to be the bible on general relativity.

> *Ahead of them a blackness was eating the sky. . . . He was dimly aware that they must have crossed the event horizon. The line where things vanished forever—time and space together.*
>
> —The Black Hole
> *by Alan Dean Foster*

The term *black hole* was coined in 1968 by the dean of American relativists, John A. Wheeler, now at the University of Texas at Austin. But the idea goes back much further than that. In the eighteenth century John Michell, an English physicist, and later Pierre Laplace, a French mathematician, suggested that if a heavenly body got big enough, its gravity would become so powerful that not even light could escape from its surface; to an observer in space, it would be invisible. "They had the wrong theory of light and the wrong theory of gravity," Thorne says. "Yet when they combined the two, they got the right prediction."

But their black hole wasn't the real animal. The first step toward the modern concept came in 1916, when Karl Schwarzschild, a German astronomer, took Einstein's new theory of general relativity and asked what would happen if all the mass of an object were squeezed down to one point, what mathematicians call a "singularity." He found that around it would appear a spherical region of space out of which nothing—no signal, not a glimmer of light or bit of matter—could escape. This boundary is known as the "event horizon," because no event that occurs inside it can be observed from the outside. It is truly a *black* hole.

If Earth collapsed to a point, it would have an event horizon with a circumference of



"Tennis, anyone?"

about six centimeters—roughly two inches. A supercompressed object with the mass of ten suns would create a horizon 120 miles around. Once you stepped inside that horizon, there would be no way out, only a sure plummet into the singular abyss at the center of the black hole.

Schwarzschild's calculations were academic until 1939, when J. Robert Oppenheimer, the father of the atomic bomb, and Hartland Snyder, a graduate student, showed that our cosmos might well be churning out such singularities: Begin with a star that has exhausted all its fuel. With the heat from its nuclear fires gone, the star can no longer support itself against the pull of its own gravity, and the stellar corpse begins to shrink. If the star's mass is greater than about two-and-a-half times that of our own sun, the collapse never stops. The star is crushed down to the inconceivable singularity of a black hole, a place where all the laws of physics break down.

It was not a welcome discovery. One of the great minds of that era, Sir Arthur Eddington, said that "there should be a law of nature to prevent the star from behaving in this absurd way." Many agreed. So the astounding Oppenheimer-Snyder analysis remained a mathematical curiosity until the 1960s. "At that time, almost singlehandedly, John Wheeler led an effort at Princeton to bring these bizarre objects back to the field of physics," says William Press, professor of astronomy at Harvard. "Wheeler and his graduate students set out to find ways to take these mathematical solutions to Einstein's equations and connect them to the real world."

According to Thorne, their effort consisted of two key tests: Each of their arcane space beasts had to be born under conditions that can actually be found in the universe, and they had to be stable enough to survive. The black hole passed the first test with ease. "The initial conditions for making a black hole aren't very stringent," says Thorne. "You simply need a star that's a few times more massive than our sun. We see them all over the place."

Stability was a tougher criterion to meet. Throughout the Sixties many physicists pinned their hopes of killing off the black hole on the idea that it would fall apart under the slightest perturbation. About ten years ago Thorne's proficient graduate students cut off that escape.

Richard Price, for one, wondered whether a black hole could form if the collapsing star were not quite spherical. Suppose it had bumps on it. "I found that, as far as an observer on the outside can see, those bumps simply smooth out and radiate away as gravity waves," says Price, now professor of physics at the University of Utah. Further research by Larry Smarr, at the University of Illinois, and others has shown that even if you throw one black hole at another—one of the most cataclysmic events imaginable—all you get is a bigger, very stable black hole.

While students at Caltech in 1972, Wil-

liam Press and Saul Teukolsky discovered that the dying star's rotation wasn't going to throw a wrench into the works, either. "They certainly don't explode in a burst of gravitational waves, as some had hoped," says Press. Alas, the black hole's cousins—the wormhole, the tunnel through hyperspace, and the white hole—succumbed to the same conditions.

On the main viewer, the hyperspace spiraling of stars and fluid light suddenly narrowed into a vortex as if a plug had been pulled and the universe was being sucked spiraling down a cosmic sink drain.

"Wormhole!" Kirk snapped to Sulu. "Get us back on impulse power! Full reverse!"

Star Trek: The Motion Picture
by Gene Roddenberry

As early as 1916, Ludwig Flamm, an obscure Viennese physicist, took another look at Schwarzschild's version of the black hole and discovered an incredible effect. By adjusting the solution, he could make that flexible rubber mat of space-time bend down so deeply that it dropped through hyperspace and connected to another universe. And so the wormhole was born. Some 40 years later Wheeler became very enamored of wormholes—he developed them into a novel theory of electricity—and by 1957 he declared that the wormhole did not necessarily have to go to another universe; it could also connect distant regions contained within our own universe.

"All this was the hot topic of discussion over beer when I was a graduate student under Wheeler," Thorne recalls. "But we never took it seriously. It was just a cute mathematical twist to Einstein's equations. We had a gut-level feeling that it was just too bizarre really to occur."

Plasma physicist Martin Kruskal, of Princeton, came up with the first persuasive argument against wormholes. While playing around with relativity equations in 1959, he saw that the conditions required to create a wormhole were a lot to ask of the universe. A standard black hole, after all, is born in the collapse of a massive star—a real denizen of the heavens. But wormholes called for ready-made points of infinite density. And how were they going to appear out of nowhere? As Price points out, "You have to have a sort of religious conviction that these singularities were cast into our universe at the moment of its birth, just waiting to blossom into wormholes."

Working out the evolution of this incredible opening, Kruskal also discovered that the wormhole is extraordinarily short-lived. The two universes are disconnected at first, each with its own singularity sitting within it, biding its time. Then, like some cosmic accordion, the two singularities reach out through hyperspace, latch onto each other, form the wormhole for a short time, and just as quickly contract and separate. "The pinch-off occurs so fast that it's impossible for anything to get across, much to the chagrin of *Star Trek* fans," says Thorne. By the time the starship *Enterprise* got into the passageway, the throat would have closed off, consigning the explorers and their five-year mission to oblivion.

"You have until this time tomorrow."

Chinook went ever deeper into that field which the monstrously whirling monstrous mass created. . . . He felt no jump, no warp, nothing except free fall when the jet cut off. In his viewscreens, the universe appeared momentarily to stagger. It steadied at once; the effect was an optical illusion due to the persistence of vision. Everywhere around, he saw titanic serenity. . . . Chinook had passed through.

The Avatar
by Poul Anderson

Thoughts of magical jumps through space and time did not die with the wormhole. Tunnels through hyperspace also popped out of Einstein's equations when theoreticians took a hard look at more complicated cases—collapsing stars with a bit of electric charge on them or with angular momentum.

"Tunnels through hyperspace were first formulated back in 1917, when a German named Reissner and a Danish scientist named Nordstrøm looked at an electrically charged black hole," Thorne explains. "But we didn't realize they were tunnels until 1959, when two of John Wheeler's students, Dieter Brill and John Graves, worked out the evolution of the Reissner-Nordstrøm solution."

What they saw was this: Time slows down within a strong gravitational field, and black holes carry this effect to the extreme. An observer sitting on that charged, collapsing star after it sinks through the event horizon will have a fraction of a second tick away on his watch while many eons pass outside, in our own universe.

At some point during the collapse, a strong electrical repulsion builds up, becoming so great that the star begins to expand again. According to one scenario, this reexpanding matter tunnels through hyperspace and reemerges at the beginning of time in another universe, a cosmos that exists in our far, far future. Thorne elaborates: "This charged, collapsing star disconnects itself from our external universe and forms a little capsule, a little closed universe of its own, for a fraction of a second. Then it reattaches itself to this new universe and goes exploding out."

Einstein's equations don't really describe the exact geography of space-time. Relativists find it just as easy to connect that tunnel to a distant region of our own universe; and when they do that, the star ends up reexpanding sometime in our past. So there you have it: a time machine. (Or do you?)

Scientists don't really expect black holes to be electrically charged; the charged particles in space would soon neutralize such an object. But a rotating black hole has very similar effects. And when black holes are found, scientists expect to see

them rotating, just as the star from which they were formed.

The singularity at the center of a rotating black hole would be not a point, but a ring. Some have speculated that a well-aimed plunge through the ring's center would take you to those other universes and other times. "This speaks for something very deep in people," says Eardley. "It's an escape from death. You don't get killed after you fall into the black hole; you just come out somewhere else. It makes a great mythology."

And a myth it remains for serious relativists. Roger Penrose, a mathematical physicist at Oxford University, was the first to realize why such time tunnels could not work: Matter is around to muck up the results. Remember, as a few dozen microseconds tick away on that collapsing star behind the event horizon, the entire future of our own universe is flashing by outside. "What that means," says Thorne, "is that all the light from all the cosmic events taking place down through the eons falls into the hole and hits the collapsing star in a fraction of a second. That's an awful lot to get zapped with."

Penrose says that there would be a terrific pileup of radiation that would become more and more energetic as it passes the event horizon and plunges into the black hole. "You wind up with an infinite energy density," says Thorne, "which grabs hold of the curvature of space-time and seals off the tunnel before it even has the chance to form." Instead of a gate to a cosmic never-never land, you end up with an ordinary black hole that has an impenetrable singularity at its center.

To Price, the instability of such tunnels is "a sign of the good taste built into the general theory of relativity." The universe has retained its sanity. We no longer have to worry that our great-great-grandchildren could ever come back and kill us, thus cutting to shreds the principle of causality. Fiction, for now, remains stranger than truth.

Something else impossible was happening. Light. Light should not happen within the confines of a collapsar. . . . He imagined it had to be ahead. His speculations turned to the possible existence of white holes, knife wounds into other universes.

The Black Hole
by Alan Dean Foster

Twenty years ago astronomers were stunned to discover that some starlike objects were pouring out enormous amounts of radio energy. Located a few billion light-years from Earth, these "*quasi-stellar*" objects, or quasars, radiate the energy of 100 billion suns from a space only a few light-years across. In some cases astronomers could see that huge jets of matter were being shot out from the nucleus of these amazing beasts. Observers kept asking themselves what could possibly be running such a gargantuan cosmic engine.

In 1964 Israeli physicist Yuval Ne'eman, now Israel's minister of science, and a Russian astrophysicist, Igor Novikov, thought the white hole would be a possible answer. White holes are simply black holes in reverse. Instead of an event horizon, they have an antievent horizon, a region of space whence things can only come gushing forth but that nothing can enter.

Ne'eman and Novikov had an unusual explanation for how this could come about. They suggested that "lagging cores" remained scattered about after the cataclysm that gave birth to our universe. In a sense they were regions of space that had delayed their "bang." These infinitely dense bodies just sat there until they burst forth a few billion years later as quasars. Others suggested that collapsing black holes in other universes were tunneling through and erupting as white holes in our own cosmos. Such was the escape route for the intrepid astronauts in the movie *The Black Hole*.

"At the time a small handful of astrophysicists took this white-hole hypothesis very seriously," says Thorne. "It seemed impossible to explain the enormous power output of quasars in any other way." But in 1974 Douglas Eardley decided to take Einstein's equations and see what would happen if a bit of matter were hurled toward a lagging core.

The lagging core turns out to be quite a paradoxical creature. It has a gravitational field that draws matter ever closer, yet won't let anything in past the antievent horizon. Whatever falls toward it gets scrunched up at the antievent horizon, forbidden to enter, yet still being accelerated inward to higher and higher energies, like a car racing its engine against a stone wall. Soon the gravity of this energetic surface layer becomes so strong that a black hole forms around the lagging core. This would all happen just seconds after the Big Bang; so even if the core does explode to form a white hole, we'd never know about it. Also that fountain would be hidden behind the opaque walls of the black hole.

"If you believe in general relativity," Thorne says, "you have to accept the fact that white holes have nothing to do with reality. They are as unstable as the tunnels through hyperspace. They'd be destroyed by any stray radiation falling in toward them." Like the other bizarre members of the cosmic zoo, the white hole was born of an ideal mathematical solution, one that did not take into account a real universe filled with light and matter.

Ironically, many theorists now believe that a rotating black hole may be the cosmic dynamo responsible for the tremendous power of quasars, which are thought to be the brilliant nuclei of abnormally violent galaxies. According to the model, stars, interstellar gas, and magnetic fields are pulled inward by the powerful gravitational field of an immense black hole residing in the galactic center. This matter forms an accretion disk—a whirling cloud of matter resembling Saturn's rings—that rotates around the hole's equator. Huge amounts of energy are released as this material spirals toward the black abyss and is ripped apart by tidal forces. Electrical energy is released as the magnetic fields thread through the hole and whirl around with its rotation. This immense generator channels its energy along the black hole's spin axis, sending a perpetual deluge of particles out of each pole—the quasar's magnificent fountain of energy.

> *As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality.*
>
> *Albert Einstein, 1921*

Now that the chalk dust has settled from this flurry of proofs and counterproofs, only the black hole has survived. The challenge is to find conclusive proof that these monstrous creatures indeed exist. So far there are only indirect hints: that black-hole model explaining the energy of the quasar, and a number of puzzling X-ray sources that flicker very rapidly in the sky.

One of these exceptionally bright sources is found in the constellation Cygnus. Astronomers now know that Cygnus X-1's powerful X rays come from a double star system consisting of a giant blue star and a dark, invisible companion whose mass of 8 to 15 times that of our sun makes it a prime suspect to be a black hole. Observations and theory agree that matter is being drawn from the supergiant by its dark companion's powerful gravitational field and heated to enormous temperatures. X rays are given off as the hot gases spiral in toward the center and form a swirling disk around the black hole.

"Such phenomena as the quasar jets and Cygnus X-1 are easily explained by black holes," Thorne notes. "No one has found a better answer. But the evidence is circumstantial. We still don't have a signature, something jumping up and saying, 'I am truly a black hole.' That will likely come from detecting gravity waves."

General relativity predicts that as a massive object accelerates or vibrates in a certain way, it will send off gravitational waves—ripples in the four-dimensional sea of space-time. Theory says that very weak waves are produced as the earth orbits the sun. But detectable events will come only from more spectacular events, such as the formation of massive black holes.

In projects now being planned around the world, heavy cylinders magnetically suspended in space and laser beams reflected between multiple mirrors will be used to record the brief distortion of local space-time geometry as the ripples pass by. "I have a firm bet with Jerry Ostriker, a theoretical astrophysicist at Princeton, that they'll be discovered before the year 2000," Thorne reports. "That prediction is framed and hangs outside my office. The only uncertainty is how strong the waves will be."

In the meantime the black hole itself is taking on a new look. The brilliant British physicist Stephen Hawking suggests that black holes may not be so black after all, that they may give off elementary atomic particles. Space-time is so twisted near a black hole, Hawking says, that a pair of particles—a particle and its antiparticle—can form just outside the event horizon. One particle disappears into the black hole; the remaining one flies away, reducing the hole's mass a bit.

For a regular black hole, this evaporation is just about meaningless. A black hole with the mass of our sun would need more than 10^{67} years to evaporate. But Hawking says that miniblack holes could have been born during the first turbulent moments of the Big Bang, 20 billion years ago. If so, an object with the mass of a mountain squeezed to the size of an atomic nucleus would be dying about now with a powerful explosion of gamma rays. Astronomers are listening eagerly for that pop.

> *"Accelerating to warp one, sir." As Sulu began moving the helm controls, Kirk could feel the slight reverb of increasing power.*
>
> *Almost a century ago the first successful quantum leap of a starship into warp drive made hash of all those theories based on too narrow or unimaginative an interpretation of Einstein's work. . . .*
>
> Star Trek: The Motion Picture
> *by Gene Roddenberry*

It seems only yesterday that a few nineteenth-century scientists were firmly stating that the laws of physics would prevent man from flying heavier-than-air machines. Are today's relativists falling into the same trap by rejecting the more bizarre solutions to Einstein's equations? "We're all free to speculate that new, stable white-hole and wormhole solutions will be found once we're better at the mathematics," says Thorne. "But that's all it is right now, pure speculation."

Recently William Kinnersly, a mathematical physicist at Montana State University, discovered a very sophisticated mathematical technique that can generate endless solutions to Einstein's equations. Kinnersly and a dozen researchers around the world are now cranking out solutions faster than physicists can interpret them. "But we still have reason to suspect that the most interesting solutions have already been done," Thorne suggests. He and others seem confident that the black hole will be the only new exhibit in the cosmic zoo to come out of general relativity.

If there are any surprises around the corner, they are expected to come when science can finally unite gravity with quantum mechanics—the laws of physics at the atomic level—into one unifying theory. General relativity breaks down when it tries to face the infinite forces and densities of a singularity; quantum gravity may not.

"My guess is that bizarre things will be discovered fifty years from now," Thorne says. "But they won't be wormholes and white holes. They'll be things that we have not even imagined yet."