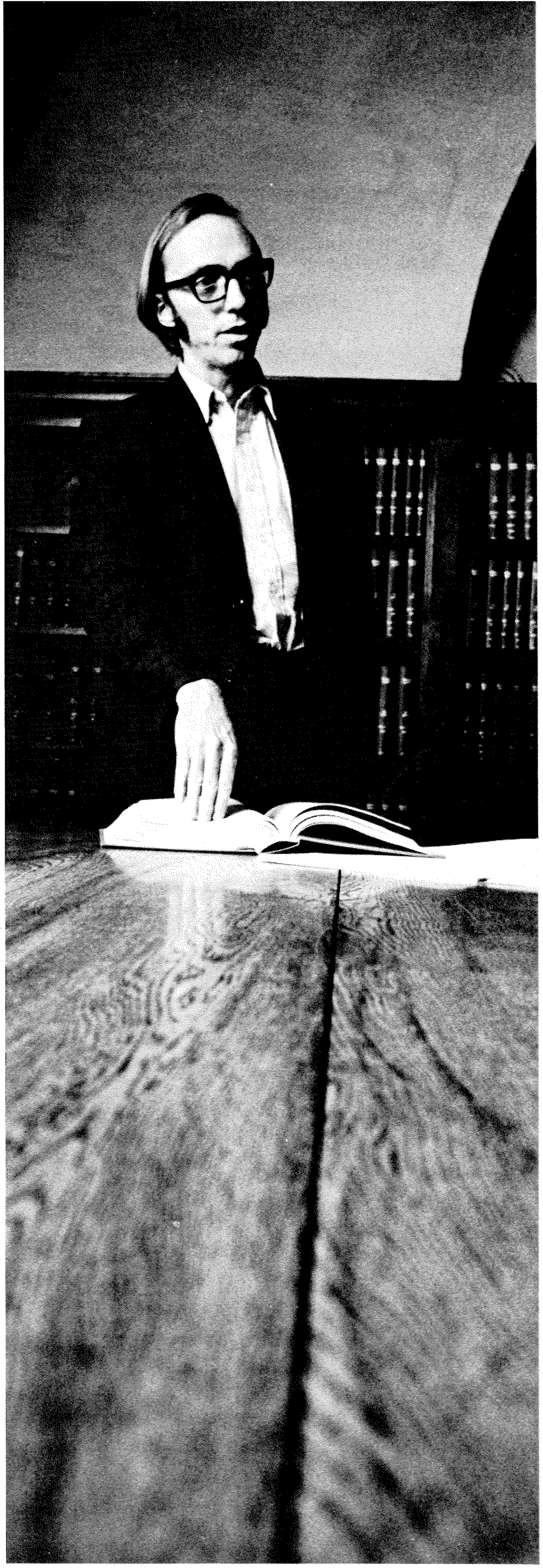


The Death of a Star

by Kip S. Thorne

A star is only a glowing pause in the inescapable contraction of a gas cloud to an uncertain, sometimes fantastic, end

Nuclear fuel is the lifeblood of a star. By steadily burning nuclear fuel in its deep interior, a star replenishes the heat that radiates from its hot surface into the cold depths of interstellar space. Each day our sun burns 10^{13} of its 10^{27} tons of fuel in the center of its million-mile sphere. Unfortunately for any star, its fuel supply is limited. Eventually—after about 10 billion years for the sun, after only 5 million years for a star 30 times as massive—a star exhausts its nuclear fuel, and dies.

What throes convulse a star when its fuel is consumed? What remnants does it produce? These questions have intrigued astronomers and physicists for half a century. The first glimmerings of an answer were provided nearly 40 years ago, but only since 1963 has the entire picture been brought into sharper focus. That picture is characterized by extremes: temperatures of billions of degrees, densities of tons per cubic inch, explosions that can rip stars apart, and the sudden and complete collapse of entire stars. Surges of cosmic rays, gravitational waves, neutrinos, and X rays announce a stellar death. Nothing else in the universe, except the distant blaze of a quasar and the birth of the universe itself, has been as violent.

The fate of a star is determined largely by its mass when it exhausts its nuclear fuel. Small stars die the gentlest of stellar deaths. They shrink to about the radius of the earth and rest there forever as white dwarf stars, gradually dimming as they slowly cool to zero temperature. The earth itself, being 330,000 times less massive than the sun, has always been in a dead, cooling state.

Larger stars die violently. They contract slowly at first and then collapse catastrophically. A sudden release of energy may convert this collapse into a supernova explosion, ripping the star apart and scattering the fragments into interstellar space. In some cases, the star may shrink with increasing rapidity, not stopping until it becomes an ultradense neutron star. The collapse may even be unstoppable; the star may totally disappear from

Kip Thorne, associate professor of physics the rest of the universe into a "black hole" in space.

White dwarf stars and supernova explosions have been observed and studied in detail by astronomers, and neutron stars are probably being observed now in the guise of pulsars. The laws of gravity and of the structure of matter convince us that black holes must also exist. In describing them, however, we theoretical physicists are out on a limb. We have no firm observational support. In the coming decade, astronomers may put us on firmer footing —or they may destroy our theories altogether.

Most stars in the universe are small—less heavy than 1.4 suns. Consider first the plight of such a star when it has consumed all the nuclear fuel in its interior. Kept hot, boiling gases could resist the relentless crush of gravity. But the dying star continues radiating its remaining heat; its heat pressure weakens, and gravity pulls it inward. The gravitational compression reheats the interior, and half the heat generated flows outward to the star's surface, where it radiates away. The other half, which is trapped in the interior, pushes the temperature upward, and the increased radiation and gas pressure act to retard the contraction of the star.

Gravitational compression and heating cannot continue indefinitely. When, after millions of years, the star has diminished from hundreds of thousands of miles to several thousand miles in diameter, its central temperature has climbed to nearly a billion degrees. The density of matter at its center has risen from several pounds to several tons per cubic inch. According to Newton's law, the force of gravity within the star increases too, as the star grows smaller, by the inverse square of its radius. Despite the growth of gravity, the compression of a small star gradually stops. The star is now a white dwarf.

Electrons in the star's atoms prevent the compression from reaching still higher densities and temperatures. According to the uncertainty principle, no particle likes to be compressed. The smaller the particle's mass and the smaller the volume into which it is compressed, the larger is its resistance to further compression. In the star, at densities of a few tons per cubic inch, the opposing pressure from lightweight electrons becomes large enough to counterbalance forever the pull of gravity.

After billions of years, a white dwarf cools to a "black cinder," drifting endlessly through space. Such will be the fate of more than a thousand hot, but dim, white dwarfs that astronomers have studied through their telescopes. Such must be the eventual fate of our sun.

Like smaller stars, a star larger than 1.4 suns is crushed by gravity after it exhausts its life-sustaining fuel. Unlike smaller stars, however, it cannot create sufficient electron pressure to halt its contraction. When the compression has reached white-dwarf densities, the force of gravity within the star has become so huge that it overwhelms the combined pressures of electrons, heat, and light. With each contraction, gravity's advantage increases. Every part of the star rapidly accelerates its fall toward the center.

Whether and how this collapse halts is determined by the star's mass, its chemical composition, and how fast it is spinning. Only another decade of intensive work by theoretical astrophysicists and observational astronomers may tell us exactly how each property fixes the fate of a specific star. We know today, however, what possible fates a star can suffer, and we are quite certain that some stars encounter each of them as they die.

The collapse of large stars may generate a gigantic nuclear explosion, as was first pointed out by Fred Hoyle and Caltech's William A. Fowler. The star's outer layers, if incompletely burned, may suddenly ignite and explode as a supernova, blowing themselves into interstellar space, to shine for a few months as brightly as a billion normal stars.

In other cases the nuclear explosion may be too weak to eject the outer shell. The entire star may continue to collapse, with rising densities and temperatures, until its core, falling fastest, becomes as dense as an atomic nucleus. This, and subsequent events, have been predicted by large electronic computers at Caltech and elsewhere, using highly complex mathematical techniques developed to design hydrogen bombs. (The conditions in a collapsing star, although enormously more severe than those at the center of an exploding hydrogen bomb, generate similar shock waves in the hot gas shells.)

During the core's collapse, which lasts only a few seconds, the electrons in its atoms, unable to resist, are squeezed into the atomic nuclei, transmuting protons into neutrons. The collapse quickly packs 10^{57} neutrons side by side, as in a giant atomic nucleus. At such close range they exert an enormous repulsion. If the collapsing star weighs less than two suns, the neutrons absolutely resist further compression and halt the collapse almost instantly.

As the outer shells of the star fall violently onto this hard neutron sphere, their impact creates enormous heat, which converts their collapse into an explosion. The core's surface temperature zooms to hundreds of billions of degrees for a fraction of a second, then drops to 10 billion degrees as most of the heat energy changes into neutrinos.

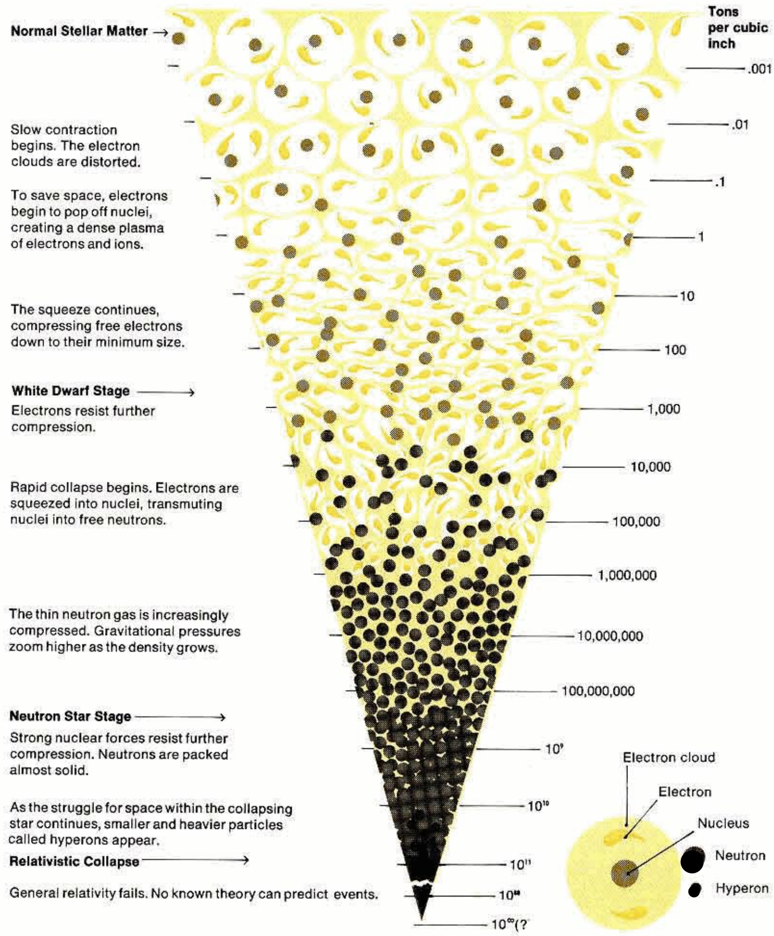
Neutrinos are near-massless particles, like photons (particles of light); but in enormous numbers they can carry large amounts of energy. Under normal conditions a neutrino can hardly "see" matter at all. For example, all but one in a billion neutrinos emitted by the nuclear reactions at the sun's center pass unhindered through the sun into interstellar space. In a collapsing star, however, because the densities and temperatures are so much higher, neutrinos can travel only a few yards before they scatter off the collapsing matter. They diffuse outward through the infalling layers, losing much of their enormous energy and heating the star's outer layers to tens of billions of degrees. These temperatures produce such huge pressures that the collapse of the layers is reversed. The outer layers eject explosively, and, like the layers ejected by a nuclear explosion, they may produce brilliant supernova fireworks.

The entire collapse—past white-dwarf densities to neutron core, the infall of matter onto the core, heating, liberation of neutrinos, and transfer of their energy to the outer layers of the star—takes only a few seconds. The explosion may shine as brightly as a billion stars for several months, however, and the glow of the remnant gas clouds can persist for thousands of years.

Whether produced by a nuclear explosion or by the formation of a neutron core, one such supernova explosion is observed each year in a hundred million million stars; in our Galaxy, about one every three centuries. On July 4, 1054, for example, Chinese astronomers observed a supernova explosion that lasted for about a year. Today we still see the luminous remnant of that star's outer layers as the beautiful Crab Nebula. Now several light-years across, the nebula is still energetic enough to emit radio waves, X rays, and light of all colors.

Studies of gaseous supernova remnants, plus detailed observations of scores of supernovae in distant galaxies, help motivate and guide theoretical calculations of stellar collapse. Although these calculations give us a good explanation for the observations, we are not certain it is the right explanation.

Matter's Struggle for Space in the Crush of Collapse



The heavier a particle, the smaller the volume it is able to occupy. Atoms in a shrinking star are thus crushed, in turn, to electrons and nuclei, neutrons, and increasingly heavier hyperons. Whether each can counter gravity depends on the star's mass: Less than 1.4 suns, free electrons stop the slow compression; less than 2 suns, neutrons will halt the collapse; more than 2 suns, no particle is able to resist gravity.

If it is correct, deep within the starburst of some supernovae should be a collapsed neutron core, or neutron star. It should weigh between one-fifth and twice the mass of the sun, and be packed in a sphere between 8 and 400 miles in diameter. Its density will thus be about a billion tons per cubic inch. When first formed, it should have a temperature of billions of degrees at the center and several hundred million degrees at the surface. During the first few seconds of its life, it should emit as much energy —about 10^{52} ergs—in gravitational waves and neutrinos as a star emits as light and heat during its entire normal lifetime. For several thousand years a neutron star should be a brighter source of X rays than the sun is of light. Its surface will not cool to a few thousand degrees until 100 million years after its formation.

In August 1967 a team of astronomers at the Mullard Radio Astronomy Observatory in Cambridge, England, detected strange signals—radio-wave bursts spaced with perfect regularity, one each 1.33730109 seconds. When their discovery was announced in February 1968, it aroused great excitement. Were these strange pulsars (about 50 others had been discovered by mid-1969) the communication beacons of an advanced civilization? Or were they a natural phenomenon?

By now we know with confidence that the radio bursts of pulsars are natural; they probably come from rapidly rotating neutron stars that beam narrow "pencils" of radio waves in our direction once or twice during each rotation. (The term "pulsar" is a misnomer; "rotator" would be better.) The most rapidly rotating of the pulsars lies in the heart of the Crab Nebula. It, like the nebula, is a remnant of the supernova of 1054 A.D.; and it emits not only beams of radio waves but also beams of light and of X rays.

According to the computer simulations, many neutron stars may form without accompanying supernova fireworks. Some stars should collapse to neutron stars without ejecting their outer layers; others may eject these layers, but the gases will be so opaque that the bright inner light cannot escape. Moreover, the violent collapse need not produce a neutron star. In fact, if its neutron core weighs more than two solar masses, it cannot become a neutron star. The increased mass strengthens the gravitational attraction sufficiently to overwhelm even the strong repulsive forces between neutrons. Gravity takes over and pulls the core back into catastrophic collapse, a collapse that quickly makes the star so small—less than 4 miles in diameter—that even light can no longer escape from its intense gravitational pull. In essence, the star creates and plunges into a black hole in space.

Black holes cannot be understood by using Newton's laws of gravitation. Gravity is so strong near a black hole that these laws break down and must be replaced by the laws of general relativity theory, which Albert Einstein formulated in 1915. Einstein's laws were first applied to the study of gravitational collapse in 1939 by American physicist J. Robert Oppenheimer and one of his students, Hartland Snyder, at Caltech and the University of California, Berkeley. Their prediction, that gravitational forces could grow so strong that starlight would not leave the star, was so startling that, had not World War II intervened, it would probably have become a subject of intense investigation. Shortly after his pioneering study of gravitational collapse, Oppenheimer turned his attention to the development of the atomic bomb.

Oppenheimer did not renew his study of collapsing stars after the war, and relativistic collapse remained mainly in the backs of the minds of astronomers and physicists. "A strange phenomenon indeed," they tended to think, "but of no relevance for the astronomy of our times." In 1963 that attitude changed suddenly. Quasi-stellar radio sources, or quasars, had been discovered, and the enormous difficulty of explaining their large power output —10^{40} watts—forced astrophysicists to consider collapse as a likely energy source. At the same time, Stirling Colgate and Richard White at the University of California's Lawrence Radiation Laboratory were just completing their first computer simulations of supernovae and had

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verified the Hoyle-Fowler prediction of the central role played by collapse.

By 1967 hundreds of theoretical physicists had converged on the problem of collapse from a variety of directions: relativity theory, mathematical physics, astrophysics, plasma physics, high-energy physics, nuclear physics, and nuclear weapons research. Astronomers, too, had begun to ask themselves whether collapse might explain other astronomical phenomena, and how they might observationally verify or discredit the ideas of the theoretical physicists.

As a result of the recent research, it is evident that the collapse of a star cannot be halted if its collapsed neutron core has more than two solar masses. In fact, according to Einstein's theory of relativity, from this point on, any resistance—no matter how large—will itself generate a still larger gravitational attraction. Gravity inevitably wins. It crushes the entire star through the black hole, down to infinite density. A region forms in space and time inside the black hole that has zero volume and possesses infinitely strong gravity at its boundary. This region is called a singularity of space-time. Within it will be the entire collapsed star. Any object—light, particle, man, or planet —that subsequently wanders too near can never escape. It is swept quickly into the unseen singularity at the hole's center. Overwhelming gravitational forces stretch the object out of shape and compress it, like the star, to infinite density.

How near the singularity dare a spaceship approach before it would be captured forever by gravity, no matter how strong its rocket engines? The point of no return, called the gravitational radius, is the edge of the black hole itself. To an outside viewer, the edge is a sphere 25 miles in circumference that surrounds a singularity containing a collapsed star twice as heavy as the sun. The circumference is proportionately larger if the star is more massive. If a quasar a billion times heavier than the sun were to collapse to a singularity, its black hole would be 12 billion miles, or .002 light-year, in circumference.

It will be impossible for an astronomer—or any other observer—to ever see the singularity of a collapsed star because no light ever escapes from a black hole. He might see the star collapse, however. A nearby observer would see the star shrink rapidly at first, but as it nears the gravitational radius, starlight is caught and held for a long time by gravitational forces, escaping only slowly toward his eyes. Even at the speed of light, photons and particles take a long time to traverse the rapidly stretching space just outside the black hole. The collapse will thus appear

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to the observer to slow down. Light emitted from the star's receding surface requires successively longer times to reach him. No matter how long the observer waits, he will never receive light emitted after the star falls into the black hole, but will always—at least in principle—be receiving the last few photons that are emitted from just outside it.

The outside observer, then, will have great difficulty witnessing catastrophic collapse. The collapse will grind to a halt at the gravitational radius, and the star will hover there, quickly turning redder and darker but not smaller. After a few seconds for a normal star—or after a few days for a collapsing mass as heavy as a billion suns—it will be virtually black and invisible. Only its intense gravitational field will be left. Moreover, the "winking out" of a star should usually be hidden from the eyes of astronomers by the luminous outer layers that the star has ejected before plunging within its gravitational radius.

Both neutron stars and black holes should have strong gravitational fields, and this may help to reveal their presence. Since most stars are not alone (like the sun) but come in pairs (binary systems) revolving about each other, it is likely that many neutron stars and black holes will be orbiting with normal stars. An optical astronomer looking at the normal star will see its spectral lines shift back and forth in wavelength as it moves in orbit alternately toward and away from the earth. About 799 stars with such shifting spectral lines have been studied by astronomers over the last 50 years. In about half of these cases the companion star has been seen, and it is perfectly normal. But in several hundred cases the companion star is unseen. In most such "single line binaries" the unseen star is probably a small, normal star, whose light pales in the brilliance of its larger companion. But in 10 cases the shifting spectral lines indicate that the unseen star is heavier than the visible star—between 1.4 and 25 solar masses. Some of the unseen stars might be black holes or neutron stars. These 10 cases, and others, will be studied intensively in the coming years.

In some binary systems, matter ejected from the normal star may pour down onto the surface of the neutron star or into the black hole. The infalling matter should be heated by collisions to million-degree temperatures and higher, and emit X rays and gamma rays. This might be the explanation for some of the X-ray sources observed by telescopes carried aboard balloons, rockets, and satellites. Neutron stars younger than 1,000 years should be hot enough to emit X rays even without infalling matter.

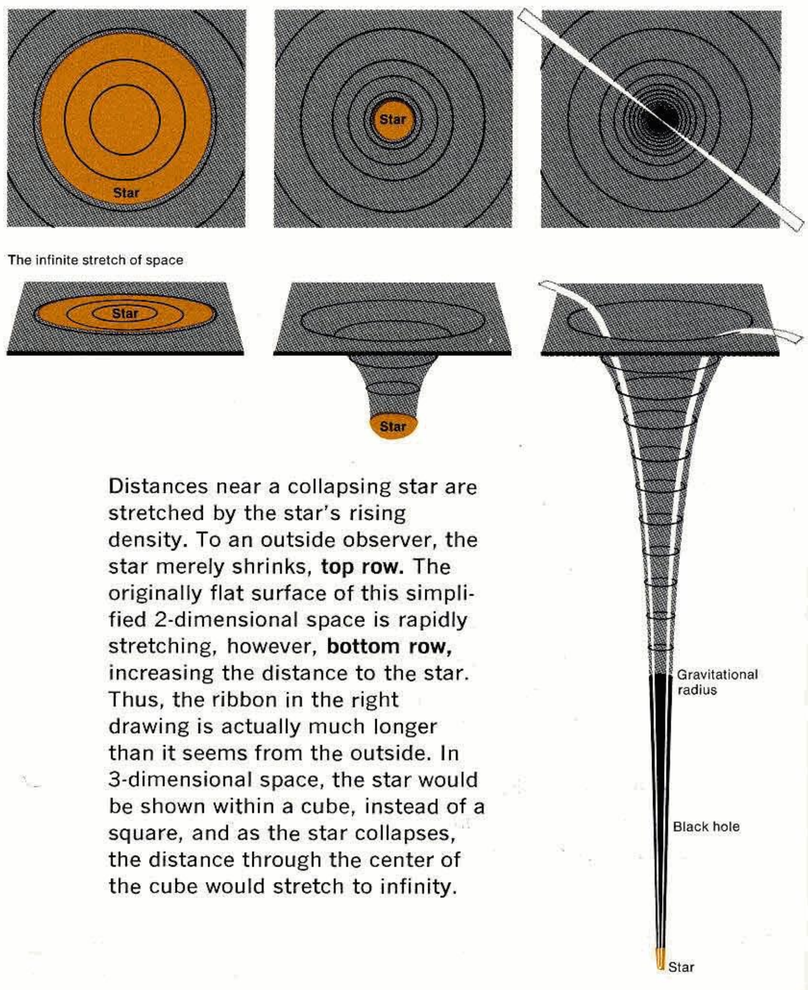
For the few seconds as they form, neutron stars and collapsing stars should emit large numbers of high-energy neutrinos. Since matter is almost transparent to neutrinos, they are quite difficult to detect. Forerunners of cosmic neutrino observatories began operating, however, in 1966 and 1967. To reduce interference from cosmic rays, they were built in deep mine shafts in South Africa, South Dakota, and Utah.

As a neutron star or collapsed star forms, it should also emit huge energy as gravitational waves. The first serious gravitational wave detectors were built by physicist Joseph Weber at the University of Maryland. Since 1967 those detectors, giant aluminum cylinders which should vibrate when hit by a gravitational wave, have been sensing about one "event" per month. To theorists this is simultaneously exciting and disturbing: The wavelengths (about 200 kilometers) and duration (a few seconds or less) of the waves that Weber seems to see are just what a collapsing star should produce; but the number of events is higher than expected by several orders of magnitude! Either something is wrong with the theory, or something is wrong with the experiment, or both.

Although astronomers have firm observational evidence

Space Swallows a Star

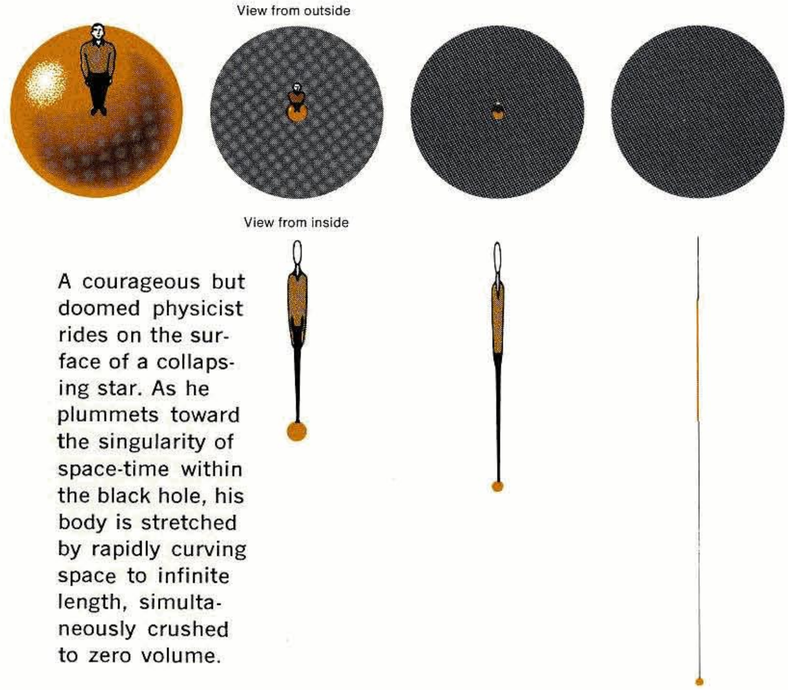
The outside view of a collapsing star



Distances near a collapsing star are stretched by the star's rising density. To an outside observer, the star merely shrinks, **top row.** The originally flat surface of this simplified 2-dimensional space is rapidly stretching, however, **bottom row,** increasing the distance to the star. Thus, the ribbon in the right drawing is actually much longer than it seems from the outside. In 3-dimensional space, the star would be shown within a cube, instead of a square, and as the star collapses, the distance through the center of the cube would stretch to infinity.

for the existence of white dwarfs and neutron stars, there is as yet no firm evidence for black holes or the collapse that forms them. How then, without proof, can physicists take seriously a theory that predicts a fantastic crushing of stars to zero volume and infinite density? General relativity theory, which makes these predictions, is inadequately tested by experiments. But the only competitive gravitation theory that agrees as well with experiment, the scalar-tensor theory developed in 1961 by physicist Robert Dicke and his student Carl Brans at Princeton University, predicts an almost identical end for the collapse. There too, calculations suggest, a singularity arises, and matter falling into it becomes infinitely dense.

Two Views of Gravitational Suicide



A courageous but doomed physicist rides on the surface of a collapsing star. As he plummets toward the singularity of space-time within the black hole, his body is stretched by rapidly curving space to infinite length, simultaneously crushed to zero volume.

Deep inside the black hole, though, Einstein's theory of gravitation must fail, just as Newton's theory failed throughout the black hole. Einstein's theory might be valid, however, until the density reaches about 10^{88} tons per cubic inch, which is 10^{79} times as dense as a neutron star. This density would be obtained by crushing the sun to one-millionth the diameter of an atomic nucleus. The theory that predicts behavior in such extreme conditions is not yet known. Thus a star might conceivably escape complete crushing, but it is certain that nearly complete crushing and a near-singularity must arise.

The problem is further complicated by the fact that real stars are not perfect spheres, but are slightly twisted and deformed. As they collapse, their deformations should grow. Although the relativistic collapse of idealized spherical stars is now well understood, theoretical physicists are only starting to make headway in understanding how deformations will affect collapse. The most powerful mathematical techniques are proving barely adequate to analyze the problem.

The most significant result is due to Roger Penrose, a mathematical physicist at Birkbeck College, University of London. Making reasonable assumptions about the universe, he showed that, once an entire star collapses within its gravitational radius, no deformation can prevent it from creating a singularity.

Penrose's theorem does not say, though, that all—or even any—matter in the collapsing star will be caught and crushed in the singularity. In a spherical collapse, the entire star must be crushed. In a nonspherical collapse, surprisingly, although a singularity will be created, all or part of the star might survive in some cases. This conclusion is supported by a mathematical example of collapse, due to former Caltech student James Bardeen and the Russian Igor Novikov, in which an entire star collapsed into the black hole but completely avoided its singularity.

This star could not remain, however, at the same point in space where it collapsed, but instead would have to burst forth at some other, distant point in the universe or in some universe different from our own. The deformed black hole acted as a "wormhole" to sweep the star from one region of space and time to another. Several physicists, including Novikov and the Israeli Yuval Ne'eman, have speculated that quasars might be the explosive reemergence of massive collapsed stars.

Although we know that some collapses should completely crush a star, and that others should lead to its reexplosion elsewhere, we do not know which fate is most common. Einstein's theory, when we understand it better, may predict that crushing occurs almost always; or it may predict that crushing occurs almost never. No external observer will ever be able to see into the blackness within the gravitational radius to tell us which is right. The events that theoretical physicists predict happen there can never be proved.

Almost never, that is. The gravitational collapse of a star, as viewed from its interior, is but a trifling preview of the ultimate contraction that may crush our presently expanding universe in another 70 billion years. Our universe seems to have exploded to create this space and time, and we are trapped inside its gravitational radius. No light can escape from the universe. Although man need never collapse with a star, he cannot avoid collapsing with the entire cosmos, if he still exists 70 billion years hence. He may discover then whether the universe avoids the singularity to reemerge again.

For the time being, a dedicated physicist can only (in principle) ride down on the surface of a collapsing star—or jump into the black hole after it—to test his theories about the black hole's interior. Of course, he could never get back out or communicate his results to the outside. But who—aside from legislators enacting antisuicide laws—is to deny a man the right to his own personal pursuit of knowledge?