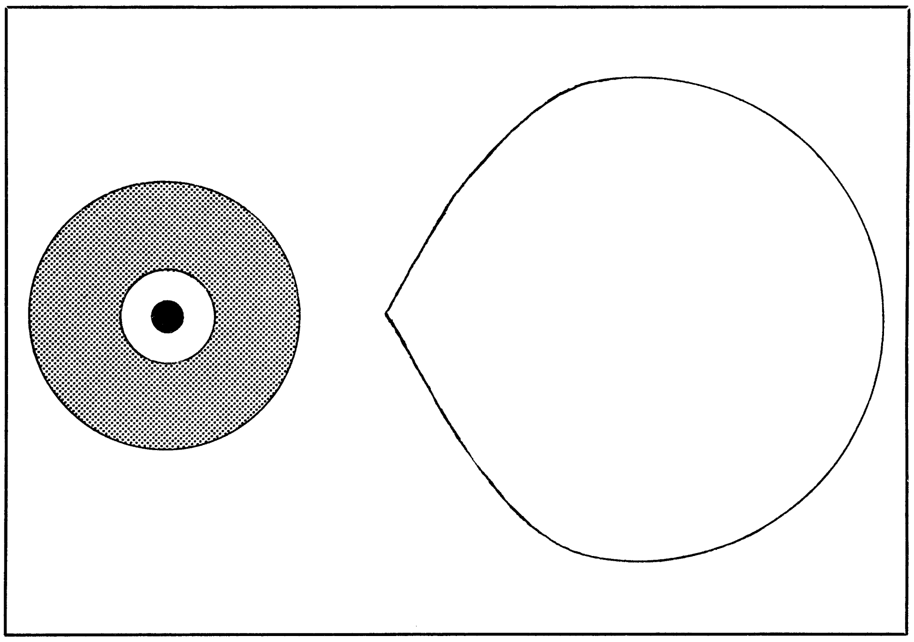
Black holes: No longer hypothetical

Astronomers believe they now see at least two

by Dietrick E. Thomsen



The very strong gravitational pull of a black hole distorts its companion.

A few years after Albert Einstein published his theory of general relativity, Karl Schwarzschild used it to calculate what would happen to a body that collapsed under the influence of its own gravitation. It came out that for every body there is a characteristic Schwarzschild radius: If the body happens to compress itself to a size within the Schwarzschild radius, runaway collapse occurs, and the object becomes a black hole. A black hole is effectively cut off from the rest of the universe since its surface gravity has become so strong that neither matter nor radiation can escape from it.

Most familiar bodies have sufficient material strength to prevent gravitational collapse and are in no danger of becoming black holes. But in stars gravitational fields are quite large and strength-of-materials forces somewhat less. Gravitational collapse plays a role in the life cycle of stars according to the generally accepted theory of stellar evolution, and astronomers noted that a black hole might be a fitting end for certain stars. Then, since black holes were supposed to be invisible, the astronomers went back to studying things they could see.

At the Sixth Texas Symposium on Relativistic Astrophysics, held in New York in December, Remo Ruffini of Princeton University, a specialist in general relativity and particularly in the theory of black holes, told the assembled astrophysicists that they may be looking at two black holes, dark condensed objects in the binary-star X-ray sources Cygnus X-1 and Small Magellanic Cloud X-1. With regard to Cyg X-1 the belief has been growing for sometime. Some observers have suggested that the source might contain a black hole (SN: 11/4/72, p. 293). Ruffini says flat out: "It has to be a black hole."

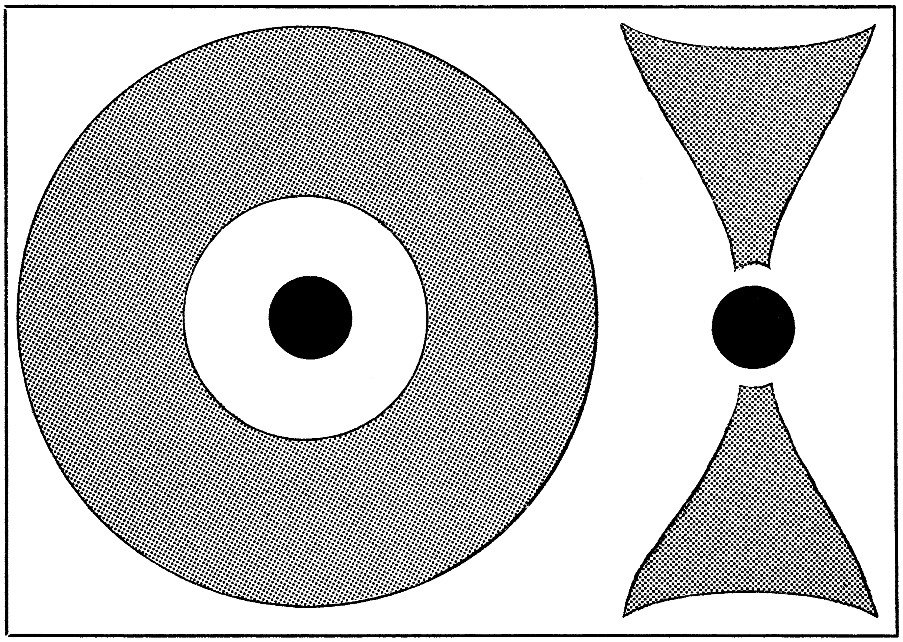
With regard to SMC X-1 Ruffini was immediately contradicted. William Liller of the Harvard College Observatory argued that the mass of the supposed black hole in that object is less than 1.5 times the mass of the sun, and therefore the body is not a black hole. Ruffini's general conclusion drew fire from Kip Thorne of California Institute of Technology who pointed out that the extreme importance to astrophysics of the discovery of an actual black hole called for extreme caution in making any claims. Thorne asked for another season's observation before any definite pronouncement. Nevertheless most of the audience seemed to accept Ruffini's remarks.

The disagreement between Ruffini and Liller points up one of the difficulties that perhaps underlies Thorne's objection: For a collapsing star to become a black hole its mass must be greater than a certain minimum. Otherwise strength-of-materials forces will intervene, and it will become either a neutron star (SN: 2/27/71, p. 151) or a white dwarf. Ruffini presented three different calculations of what this minimum should be. They yield 0.7 solar masses, 1.5 solar masses and 3.2 solar masses. Ruffini proposes accepting bodies with more than 3.2 solar masses as black holes. If the mass of the collapsed object in SMC X-1 is indeed 1.5 solar masses, its claim to black-hole status is dubious. Ruffini presents calculations of the mass of the collapsed object in Cyg X-1 that range from 5.5 to 30 solar masses. Since all these estimates are above 3.2, Ruffini is convinced that it is a black hole.

Not some others, however. These critics attack the basis on which the mass estimates were figured. Study of the light variations in these binaries can lead to determination of their orbital data. Knowing the orbital data and the mass of the visible component, one can calculate the mass of the other. In these cases the mass of the visible star is determined from knowledge of its spectral class. Though this is a standard procedure, error is possible. B. Paczynski of the Institute of Astronomy in Warsaw, a specialist in the evolution of binary stars, had warned the symposium of the dangers of inferring a star's mass from its spectral class, and this warning was quoted against Ruffini.

If there is a black hole in Cyg X-1 and if, as Ruffini says, Cyg X-1 is representative of a new class of objects waiting to be discovered, the black hole can explain how these systems can be X-ray sources. As Thorne described it for the meeting, a black hole in such a binary system should cause matter to flow toward it from the visible companion. Because of rotations in the system, this matter would possess angular momentum, and instead of falling directly into the black hole it would spiral around it. The accreting matter would thus form a disk around the black hole, and the disk would be a stable phenomenon because as matter fell into the black hole from its inner edge, new matter would be added to its outer edge.

The heat generated by the gas atoms colliding with each other in the disk would produce the X-rays. The disk would be subject to the recurrent appearance of small hotspots. The hot-



A black hole's disk of infalling matter shown in flat and cross section.

spots should cause fluctuations in the X-ray output on the order of a few milliseconds in length, and Thorne suggests that observers look for such fluctuations as evidence that the hotspots exist and that the disk dynamics is as he describes it.

Whether or not 1972 was the year of the discovery of the black hole, astrophysicists are becoming convinced that they will soon have to deal with black holes as members of astrophysical systems. Thus there is great interest in theoretical studies of how black holes should behave. A very fundamental contribution was provided by S. W. Hawking of the University of Cambridge in England who has derived what he calls the "four laws of black hole mechanics." Since three of these laws are formally analogous to the laws of thermodynamics, Hawking numbers them from zero to three so that the numbers of the black-hole laws may be the same as their thermodynamic analogues.

Hawking's first law gives a formula for calculating the change in the mass of a black hole under a small interaction with something else. The mathematical form of the law leads to the conclusion that the surface gravity of a black hole is analogous to the temperature in thermodynamics. (It should be remembered, however, that the surface gravity is distinct from the actual temperature of a black hole, which is absolute zero.)

The second black-hole law says that the area of the event horizon (the surface defined by the Schwarzschild radius) of a black hole may not decrease. It can only increase or remain stationary. Thus the area of the event horizon takes the place of entropy in thermodynamics.

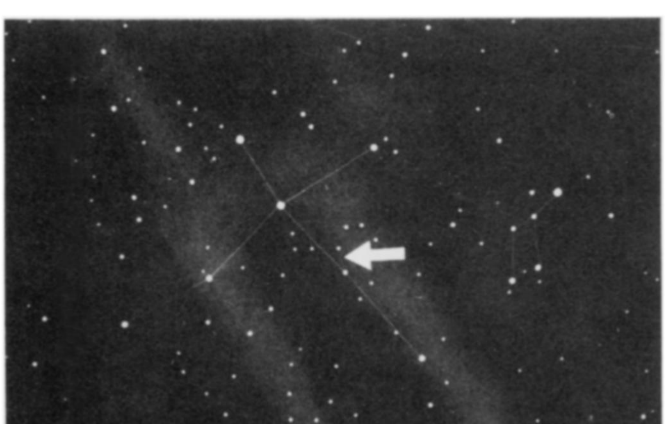
The third law builds on the first. Corresponding to the thermodynamic law that one cannot reach absolute zero by a finite sequence of temperature reductions, Hawking's third law says that the surface gravity of a black hole cannot be reduced to zero by a finite sequence of any sort of physical operations.

Finally Hawking presents his zeroth law on the analogy of the thermdynamic principle that the temperature of a body in equilibrium is the same at all points: The surface gravity of a black hole is the same at all points of the event horizon.

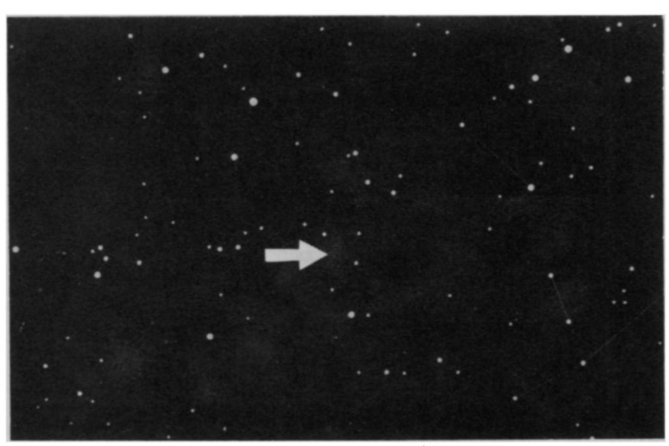
If one has black holes living in astrophysical systems can anything be gotten out of them? Surprisingly the answer is yes, if they rotate. (Schwarzschild's original solutions where nothing came out were for nonrotating black holes.) William Press of Caltech described two possibilities. One of these, the so-called Penrose process, has been discussed before (SN: 12/26/70, p. 480). Rotating black holes have not a single horizon but two: an inner one within which matter is trapped, and an outer one where radiation is infinitely shifted to the red. A body entering the space between the two limits might be broken in such a way that part fell down the hole, and the outer part escaped with a boost in energy derived from the rotational energy of the black hole.

Press described a radiation analogue of this: A wave entering in a particular way might be diffracted so that part went down the hole and the rest came out amplified. Thus a black hole might serve as an amplifier for gravitational or electromagnetic waves. This leads to a rather facetious suggestion of a black-hole bomb: Surround a black hole with reflecting material. An amplified wave is thus reflected back into the black hole, and amplified further. This process would go on until enough energy had been built up to explode the mirror.

Whether or not they explode, black holes seem to be here to stay. The last year or so has seen, as the meeting amply demonstrated, the beginning of a new branch of physics, the physics of black holes. □



The constellation Cygnus; the arrow points to Cyg X-1.



Atlas of the Sky, Macmillan & Co., Ltd.

The arrow points to the Small Magellanic Cloud X-1.