Stellar Old Age (III): Black Holes and Gravitational Collapse

According to the current understanding of stellar evolution, dying stars that are too massive to become white dwarfs or neutron stars collapse into black holes. This alternative end state of stellar evolution is predicted by Einstein's theory of general relativity, as J. R. Oppenheimer and H. Snyder pointed out in 1939. For many years thereafter black holes remained in the background of research on general relativity. Now, however, rapid progress is being made in understanding the properties of these collapsed objects. Although black holes were so named because no mass or light can escape from them, it has become clear that as much as half of the energy of rotating magnetic black holes could be extracted. That black holes do exist has not been observationally demonstrated, although many astrophysicists are convinced that they will eventually be found. But there is some indirect evidence for their existence.

In addition to the implications of black holes for stellar evolution they are of interest in cosmology because they constitute a small-scale model for the possible gravitational collapse of the universe—a collapse that is not ruled out by Einstein's theory. The details of this theory and the broader consequences of general relativity have attracted increasing attention lately among theoretical physicists, and a number of the recent advances in this subject were summarized by Roger Penrose of Birbeck College in London when he spoke last month at the American Physical Society (APS) meeting in New York. The achievements include a better understanding of gravitational waves and their possible generation by black holes, as well as mathematical proofs that solutions to Einstein's equations contain singularities—regions where the radius of curvature in the geometry of space becomes infinite. Examples of such singularities include the "big bang" that is presumed to have begun the universe, as well as local singularities like black holes. Some features of these singularities and rules restricting their occurrence have been worked out.

Other theoretical work has concentrated on the properties of the black holes themselves. Among the results to emerge from the investigations at Princeton University by John Wheeler and Remo Ruffini, at the University of Alberta by Werner Israel, at Cambridge University by Brandon Carter, and elsewhere, is the finding that black holes are apparently characterized by only three parameters—mass, charge, and angular momentum. According to this view other identifying properties of matter, including the quantum properties of elementary particles, are lost during the formation of a black hole; it would be impossible, for example, to distinguish a black hole made of antimatter from one made of ordinary matter.

The interiors of black holes are believed to have some remarkable properties. Inside the outer surface of these collapsed objects, for example, distance and time switch roles—according to the theory. Distance becomes a timelike coordinate, so that the distance of a particle from the center of the hole must always decrease in the same way that time must go forward under ordinary circumstances.

Apparently there are four kinds of black holes. The simplest—named after Karl Schwarzschild—has no charge and is not rotating. The more complicated geometry that results in the second type which has both mass and angular momentum was first worked out by Roy Kerr; this type of black hole has an inner surface known as the event horizon, from which no light or mass can escape, and an outer surface known as the stationary limit. These two surfaces coincide in the Schwarzschild type. A third type of black hole is characterized by mass and charge. The most general type, the fourth, combines all three properties—mass, charge, and angular momentum. According to Wheeler and Ruffini, transitions are possible from one form of black hole to another by, for example, the accretion of particles.

Although neither mass nor electromagnetic radiation can escape from a black hole, it appears that under certain circumstances rotational and electromagnetic energy, which may account for 50 percent of the total energy in a charged, rapidly rotating black hole, can be extracted. Penrose and R. Floyd, also of Birbeck College, have shown that, if a particle falls into the region between the event horizon and the outer surface of a Kerr black hole, it could split in half, one part falling into the black hole and the other escaping with more energy than the incident particle. Hence it is theoretically possible for black holes to be a source of energy, although it is not known whether this property is of any astrophysical importance.

Astronomers have never found any black holes—perhaps in part because it is not yet clear how they would be identified—but evidence presented by Al Cameron of Yeshiva University in New York at the APS meeting offers some indirect support for their existence. The high ratio of mass to light in galactic clusters, which is deduced from their motions and luminosities, is usually explained in terms of the presence of unseen gas. For this to be true, however, the gas would have to have a temperature close to 10^6 degrees, since at higher temperatures gas would be expected to give off x-rays and at lower temperatures it should be detectable by means of its radio emissions. Cameron thinks it unlikely that the temperature of the gas would be the same for all sizes of clusters and instead suggests that the missing mass—which could amount to as much as 90 percent of the mass in the universe—is in the form of black holes. The suggestion is based on indications from the chemical history of the universe that the earliest generations of stars were so massive that black holes would be the expected end state of their evolution.

There is also a possibility that a black hole has been discovered in our galaxy as the secondary star of the binary star system Epsilon Aurigae. The secondary component, which has never been observed, is known to be about 23 solar masses and gives rise to unusual spectra when it passes in front of the primary star during an eclipse. The least unlikely explanation, according to Cameron, is that this star is a black hole with a disk of stellar debris in orbit around it. Whether this explanation turns out to be correct or not, the hunt for black holes and the investigation of their properties is gathering new momentum among physicists and astronomers.—Allen L. Hammond