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Introducing the black hole

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According to present cosmology, certain stars end their careers in a total gravitational collapse that transcends the ordinary laws of physics.

At the time of this article, **Remo Ruffini** and **John Wheeler** were both at Princeton University; Wheeler, on leave from Princeton, was spending a year at the California Institute of Technology and Moscow State University.

The quasi-stellar object, the pulsar, the neutron star have all come onto the scene of physics within the space of a few years. Is the next entrant destined to be the black hole? If so, it is difficult to think of any development that could be of greater significance. A black hole, whether of “ordinary size” (approximately one solar mass, $1 M_{\odot}$) or much larger (around $10^6 M_{\odot}$ to $10^{10} M_{\odot}$, as proposed in the nuclei of some galaxies), provides our “laboratory model” for the gravitational collapse, predicted by Einstein’s theory, of the universe itself.

A black hole is what is left behind after an object has undergone complete gravitational collapse. Spacetime is so

strongly curved that no light can come out, no matter can be ejected, and no measuring rod can ever survive being put in. Any kind of object that falls into the black hole loses its separate identity, preserving only its mass, charge, angular momentum, and linear momentum (see figure 1). No one has yet found a way to distinguish between two black holes constructed out of the most different kinds of matter if they have the same mass, charge, and angular momentum. Measurement of these three determinants is permitted by their effect on the Kepler orbits of test objects, charged and uncharged, in revolution about the black hole.

How the physics of a black hole looks depends more upon an act of choice by the observer himself than on anything else. Suppose he decides to follow the collapsing matter through its collapse down into the black hole. Then he will see it crushed to indefinitely high density, and he himself will be torn apart eventually by indefinitely increasing tidal forces. No restraining force whatsoever has the power to hold him away from this catastrophe, once he crossed a certain critical surface known as the “horizon.” The final collapse occurs a finite time after the passage of this surface, but it is inevitable. Time and space are interchanged inside a black hole in

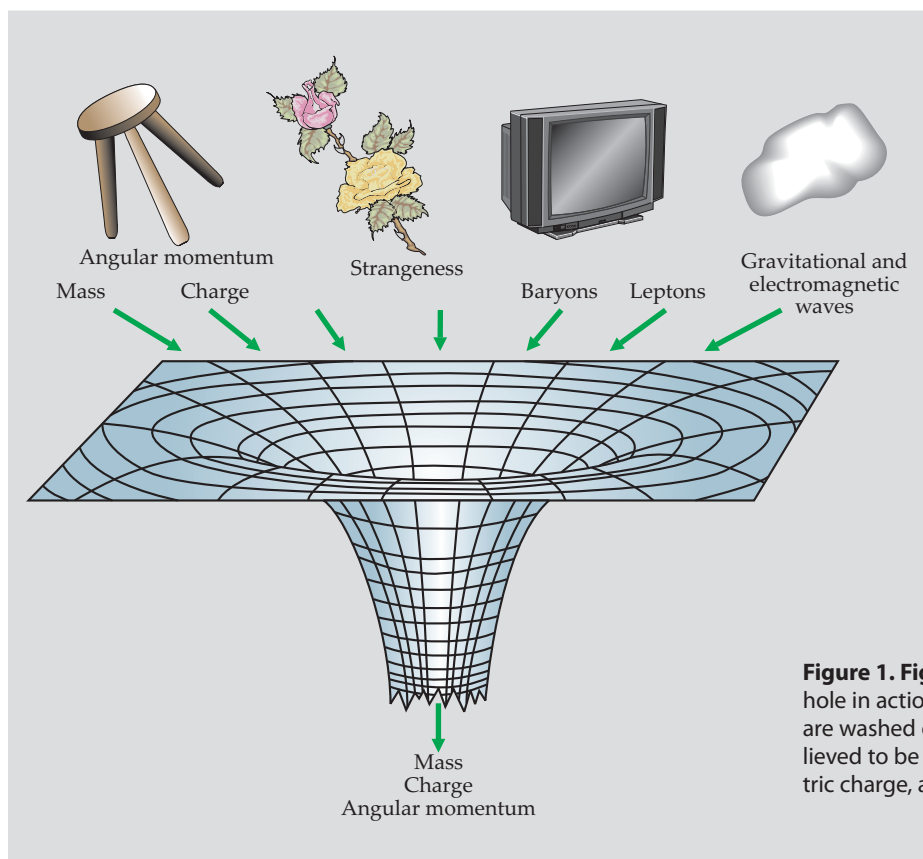


Figure 1. Figurative representation of a black hole in action. All details of the infalling matter are washed out. The final configuration is believed to be uniquely determined by mass, electric charge, and angular momentum.

an unusual way; the direction of increasing proper time for the observer is the direction of decreasing values of the coordinate r . The observer has no more power to return to a larger r value than he has power to turn back the hands on the clock of life itself. He can not even stay where he is, and for a simple reason: No one has the power to stop the advance of time.

Suppose the observer decides instead to observe the collapse from far away. Then, as the price for his own safety, he is deprived of any chance to see more than the first steps on the way to collapse. All signals and all information from the later phases of collapse never escape; they are caught up in the collapse of the geometry itself.

That a sufficient mass of cold matter will necessarily collapse to a black hole (J. [Robert] Oppenheimer and [Hartland] Snyder¹) is one of the most spectacular of all the predictions of Einstein's standard 1915 general relativity. The geometry around a collapsed object of spherical symmetry (nonrotating!) was worked out by Karl Schwarzschild of Göttingen, father of the American astrophysicist Martin Schwarzschild, as early as 1916. In 1963 Roy Kerr² found the geometry associated with a rotating collapsed object. James Bardeen has recently emphasized that all stars have angular momentum and that most stars—or star cores—will have so much angular momentum that the black hole formed upon collapse will be rotating at the maximum rate, or near the maximum rate, allowed for a black hole (“surface velocity” equal to the speed of light). Roger Penrose³ has shown that a particle coming from a distance into the immediate neighborhood of a black hole (the “ergosphere”) can extract energy from the black hole. Demetrios Christodoulou⁴ has shown that the total mass–energy of a black hole can be split into three parts,

$$E^2 = m_{ir}^2 + L^2/4m_{ir}^2 + p^2.$$

The first part is “irreducible” (left constant in “reversible transformations”; always increased in “irreversible transformations”), and the second and third parts (arising from a rotational angular momentum L and a linear momentum p) can be added and subtracted at will.

The three most promising ways now envisaged to detect black holes are:

- Pulses and trains of gravitational radiation given out at the time of formation (see PHYSICS TODAY, August 1969, page 61, and August 1970, page 41, for accounts of Joseph Weber's pioneering attempts to detect gravitational radiation).
- Broadband electromagnetic radiation extending into the hard x-ray and gamma-ray regions emitted by matter falling into a black hole after it has been formed (this is the concept of [Yakov] B. Zel'dovich and [Igor] D. Novikov. The radiation is not emitted by the individual particles as they fall in but by the gas as a whole as it is compressed and heated to 10^{10} or 10^{11} K by the “funnel effect” on its way towards the black hole).
- Jets and other activity produced in the ergosphere of rotating black holes.

Equilibrium configurations

The mass of a superdense star (reached in collapse that does not go to a black hole) is determined uniquely by its central density, provided that the equation of state linking pressure and density is specified. Then, by integrating the equation for relativistic hydrostatic equilibrium⁵ outwards to the point where the pressure drops to zero, we find the total mass corresponding to each value of the central density. The idea that a sufficiently massive star would contract without limit under the influence of its own gravitational field was suggested by study of the white dwarf stars. These are very

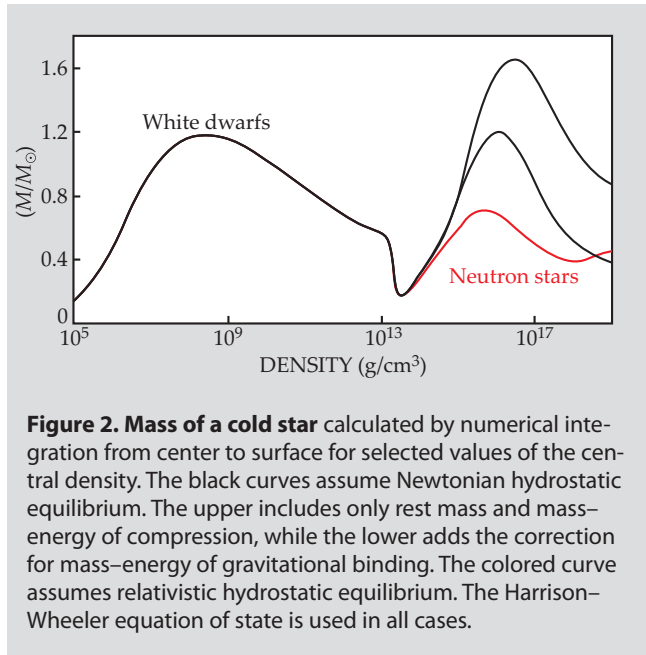


Figure 2. Mass of a cold star calculated by numerical integration from center to surface for selected values of the central density. The black curves assume Newtonian hydrostatic equilibrium. The upper includes only rest mass and mass–energy of compression, while the lower adds the correction for mass–energy of gravitational binding. The colored curve assumes relativistic hydrostatic equilibrium. The Harrison–Wheeler equation of state is used in all cases.

dense stars in which the pressure arises primarily from a degenerate Fermi gas of electrons. No stable solution exists for a white dwarf with a mass above the Chandrasekhar limit, which is about 1.2 solar masses. What is the endpoint of stellar evolution for a star more massive than this critical mass?

The answer depends on the “local physics,” summarized in the equation of state, and the “global properties” determined by the gravitational field. One would hope that the different predictions of the Newton, Einstein, and Jordan-Brans-Dicke theories would provide a way to discriminate between the theories. However, the equation of state must take into account all physical phenomena, including high-energy physics. Ignorance of the equation of state at supranuclear

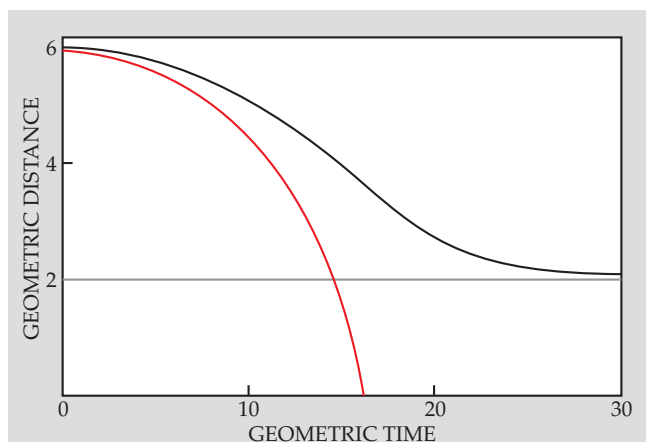


Figure 3. Fall towards a Schwarzschild black hole as seen by a comoving observer (color) and a distant observer (black). The proper time for the free fall to the center is finite, although the approach to the Schwarzschild radius as seen by a distant observer is asymptotic in time. “Geometric distance” and “geometric time” are measured in units of the mass of the black hole.

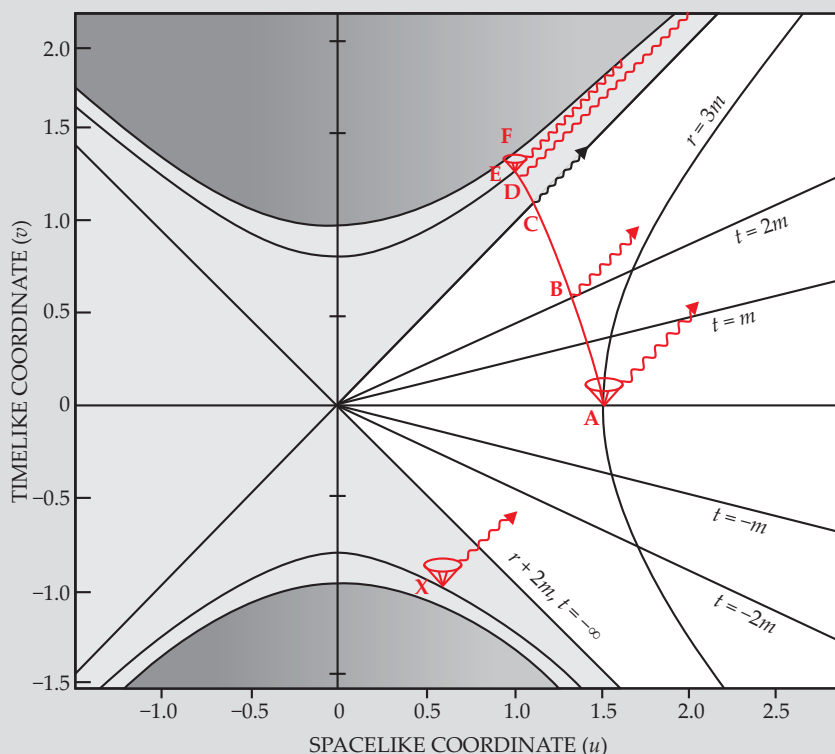


Figure 4. Kruskal coordinates for Schwarzschild spacetime, showing the relation to the usual coordinates (r, t) . Radial light rays are straight lines with slope $= \pm 1$. Only the unshaded region is covered by the usual range of coordinates: $2m < r < \infty$, $-\infty < t < +\infty$. The colored line is the world line of a particle that starts at A and falls straight towards the black hole. A distant observer receives the signal it gives out at A and B. The ray emitted at C is the last ray that can escape to infinity, and it only gets to a distant observer after an infinite Schwarzschild time. Rays D and E are caught in the collapse of the geometry and never reach a distant observer. The curvature is nonsingular at C but rises toward infinity as F ($r = 0$) is approached. Point F is reached in a finite proper time. There is as little reason to expect a photon to escape from inside a black hole at X and to cross the inner boundary of everyday space, $r = 2m$, as there is to expect advanced electromagnetic waves to travel inward from infinity.

densities blurs distinction between the contending gravitational theories. Nevertheless, a family of stable neutron stars exists for all reasonable equations of state. The minimum mass of this family is about 0.16 solar mass, but the maximum mass is uncertain by about a factor of four. In figure 2, mass is plotted versus central density with the assumption of a particular equation of state (the Harrison–Wheeler equation) to show the difference between Newtonian gravitation and general relativity in the neutron-star region.

Neutron star or black hole?

The physics of the formation of a neutron star or a black hole is more complicated than the physics of either object itself. It is believed that in this process, the core of a star, possibly a late giant, collapses from its original radius of a few thousand kilometers to a compact object with a radius of a few tens of kilometers. The core has slowly evolved over thousands of years to a degree where it is unstable against gravitational collapse. This does not necessarily mean that its mass lies precisely at 1.2 solar masses, the first peak in figure 2. It may be two or five or ten times more massive and still not collapse, when inflated by sufficiently high temperatures. But cooling such a system will automatically bring it to the point of collapse. Sterling Colgate, [Michael] M. May, and [Richard] H. White^{6,7} have made computer investigations of what happens, under the simplifying assumption of spherical symmetry. The material of the star starts moving inwards, at first slowly, then more and more rapidly, with a characteristic speedup time of less than a tenth of a second. Soon, a substantial portion of this mass, the inner part of the core, contracts sufficiently to increase greatly the strength of the gravitational fields drawing the inner core together. As a consequence, the core accelerates more rapidly than the surrounding envelope.

Two very different outcomes ensue, depending on whether the core mass and its kinetic energy of implosion do or do not suffice to drive the system on beyond nuclear densities to the point of complete gravitational collapse. Complete collapse produces a “black hole.” On the other hand, when the mass is too small or the velocity of implosion is too low the collapse is halted at nuclear or near-nuclear density. The stopping of so large a mass implies the sudden conversion of an enormous kinetic energy into thermal energy, as if a “charge of dynamite” had been set off at the center of the system. The high temperature (about 10^{12} K) develops high pressure. The envelope surrounding the inner core is falling more slowly and suddenly feels this pressure. The implosion is reversed. The envelope is propelled outward, producing cosmic rays and an expanding ion cloud. A famous example of such a supernova event is the Crab nebula, with an estimated mass of the rough order of magnitude of a solar mass.

Rotation, and magnetic fields and magnetic fields coupled to rotation, can significantly change the character of the implosion, as shown by the recent work of [James] M. LeBlanc and [James] R. Wilson.⁸ As the center shrinks, it turns faster and faster to conserve angular momentum, winding up the magnetic lines of force like string on a spool. The Faraday–Maxwell repulsion between the lines of force causes the spool to elongate. The lines of force carry matter with them, shooting jets out from the two poles. It will be interesting to see how these effects will be modified when the calculation is expanded to include all the physical details of the Colgate–May–White analysis and nuclear reactions as well!

Continuing collapse

When the core of the collapsing star is too massive or imploding with too much kinetic energy, the implosion may still slow down as nuclear densities are encountered, but nuclear

Geometrical units

Albert Einstein's account of gravitation is purely geometrical, and every quantity that arises is expressed in units of length. From this point of view, the distinction between grams and meters, or between seconds and meters, is as artificial as the distinction between miles and feet.

Thus, in geometrical units:

1 cm of time (that is, 1 cm of light travel time) is $1 \text{ cm}/(3 \times 10^{10} \text{ cm/s}) = 3.3 \times 10^{-11} \text{ s} = 1/30 \text{ nanosecond}$.

1 cm of mass is $1 \text{ cm}/(G/c^2) = 1 \text{ cm}/(0.742 \times 10^{-28} \text{ cm/g}) = 1.4 \times 10^{28} \text{ g}$, which is comparable to the mass of the Earth. The mass of the Sun, $1.987 \times 10^{33} \text{ g}$ in conventional units, is 1.47 km in geometrical units. The deflection of light passing an object of mass m in geometrical units at a distance of closest approach b is $\theta = 4m/b$.

1 cm² of angular momentum is $1 \text{ cm}^2/(G/c^3) = 1 \text{ cm}^2/(2.47 \times 10^{-39} \text{ s/g}) = 4.05 \times 10^{38} \text{ g cm}^2 \text{ s}^{-1}$. The maximum angular momentum for a black hole of 1-km mass is $(1 \text{ km})^2$.

forces will not stop the implosion. Gravitational forces become overwhelming, the system zooms through the neutron-star stage, and complete collapse follows. The resulting system has been variously termed “continuing collapse,” a “frozen star,” and a “black hole.” Each name emphasizes a different aspect of the collapsing system. The collapse is continuing because even after an infinite time, as measured by a distant observer, the collapse is still not complete. Rather, the departure from a static configuration of Schwarzschild radius $r = 2m$ as seen by a distant observer diminishes exponentially in time, with a characteristic time of the order of $2m$, or about 10 microseconds for an object of one solar mass. The box explains the purely geometrical system of units employed in general relativity. In this sense, the system is a “frozen star.”

In another sense, the system is not frozen at all. On the contrary, the dimensions shrink to indefinitely small values in a finite and very short proper time for an observer moving with the collapsing matter (see figure 3). Moreover, a spherical system appears black from outside; no light can escape. Light shot at it falls in. A particle shot at it falls in. A “meter stick” would be let down in vain to measure the dimensions of the object. The stick is pulled to pieces by tidal forces, and the broken-off pieces fall in without a trace. In these senses, the system is a black hole.

Process of formation

At least three processes suggest themselves for the formation of a black hole:

- Direct catastrophic collapse of a star with a white-dwarf core, a collapse going through neutron-star densities without a stop.
- A two-step process: the collapse of a star with a white-dwarf core to a hot neutron star followed by cooling and collapse to a black hole.
- A multistep process, with first the formation of a stable neutron star and then the slow accretion of enough matter to raise the mass above the critical value for collapse.

What happens in the collapse has been well analyzed in the case of a system of spherical symmetry, and for small departures from spherical symmetry that lend themselves to analysis by perturbation methods. However, in the general and very important case of large departures from spherical symmetry, only a few highly simplified situations have so far been treated. This fascinating field is largely unexplored. The central question is easily stated: Does every system after complete gravitational collapse go to a “standard final state,” uniquely fixed by its mass, charge, and angular momentum and by no other adjustable parameter?

A dust cloud

Start with a cloud of dust of specific density 10^{-16} and radius $1.7 \times 10^{19} \text{ cm}$. Let the cloud be imagined to draw itself together by its own gravitational attraction until its radius falls to 10^{-5} of its original value, or $1.7 \times 10^{14} \text{ cm}$. The dust is still dust. No pressure will arise to prevent the continuing collapse. However, despite the everyday nature of the local dynamics, the global dynamics has clearly reached extreme relativistic conditions. How then does one properly describe what is going on?

A variety of treatments of this problem have been given, from the original analysis of J. Robert Oppenheimer and H. Snyder¹ to treatments of [Oskar] Klein⁹ and others. The simplest analysis for our purposes is that of [David] L. Beckedorff and [Charles] W. Misner¹⁰ in which the geometry interior to the cloud of dust is identical with that of a Friedmann universe, that is, a three-sphere of uniform curvature.

The geometry within the three-sphere is

$$ds^2 = a^2(\eta) [-d\eta^2 + d\chi^2 + \sin^2\chi(d\theta^2 + \sin^2\theta d\phi^2)],$$

where $a(\eta)$ is the radius of curvature, and the hyperspherical angle χ would go from 0 to π if the sphere were complete. It is not; it extends only from the center to the surface of the cloud.

The density of the cloud at the starting instant is related to the initial curvature a_0 by the standard formula for the Friedmann universe $\rho_0 = 3/8\pi a_0^2$. As the collapse proceeds, an increasing fraction of the gravitational energy of the dust cloud is converted into kinetic energy. However, the total mass–energy remains constant.

Outside the dust cloud, the geometry remains the static geometry of Schwarzschild (Birkhoff theorem),

$$ds^2 = -(1 - 2m/r)dt^2 + (1 - 2m/r)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2).$$

The Friedmann geometry and the Schwarzschild geometry match at the boundary of the dust cloud. A particle located at this boundary falls according to different laws as calculated from the Friedmann and Schwarzschild solution. But the results must agree, and they do.

Light cone

Light given off from a particle at the periphery of the dust cloud, before arrival at the Schwarzschild radius, will always escape if emitted radially outward. However, if it makes an angle to the radial direction in its own local Lorentz frame, it will make a still larger angle to the radial direction in a local Lorentz frame that happens to have zero velocity at the moment in question. The photon will be trapped unless emitted

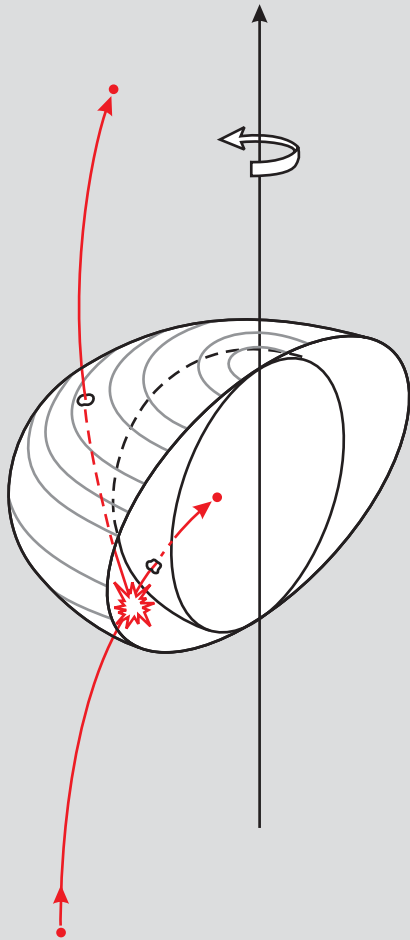


Figure 5. Ergosphere of a rotating black hole. The region between the surface of infinite redshift (outer) and the event horizon (inner), here shown in a cutaway view, is called the “ergosphere.” When a particle disintegrates in this region and one of the fragments falls into the black hole, the other fragment can escape to infinity with more rest plus kinetic energy than the original particle.

in an allowed cone around the outward direction. The allowed cone shrinks to extinction when the dust cloud contracts to the Schwarzschild radius. Light that emerges radially “outwards” after the cloud has contracted within the Schwarzschild radius never escapes to a faraway observer. It is caught, not in the matter but in the collapse of the geometry surrounding the matter.

The Kruskal diagram

According to figure 3, the fall of a test particle towards a black hole ends at $r = 2m$ as seen by a distant observer. The fall ends at $r = 0$ according to someone falling with the test mass itself. How can two such different versions of the truth be compatible? For an answer, it is enough to focus attention on the Schwarzschild geometry itself and on a test particle falling in this geometry.

The central point is simple. The range of coordinates $2m < r < \infty$, $-\infty < t < +\infty$ fails to cover all the Schwarzschild spacetime. Time “goes beyond infinity” just as Achilles goes beyond the tortoise in the famous paradox of Zeno. In no way

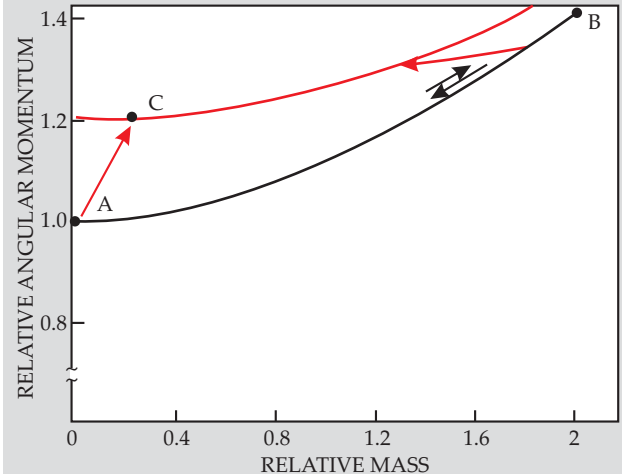


Figure 6. Transformations of a black hole between the static Schwarzschild case (A) and the extreme Kerr case of maximum angular momentum (B) are accomplished by accretion of particles. The “irreducible mass” (mass in the absence of rotation) remains constant in reversible transformations (black), which involve capture at grazing incidence to the black hole. In the irreversible transformation $A \rightarrow C$, the irreducible mass increases from $1.0m_{ir}$ to $1.2m_{ir}$. The “relative mass” is an abbreviation for “mass in units of the original value of the irreducible mass.” The “relative angular momentum” is in units of m_{ir}^2 , as explained on page 50.

can one see the incompleteness of the usual coordinate range more clearly than by reference to the Kruskal coordinates¹¹ as shown in figure 4.

In this diagram, u is spacelike and v is timelike. Points of the same t -value lie on the straight line $v/u = \text{constant}$. Points of the same r -value lie on the hyperbola $u^2 - v^2 = \text{constant}$, with asymptote $u = \pm v$. A light ray traveling radially outward is always represented by a straight line of slope $dv/du = +1$; one traveling radially inward, by a line of slope $dv/du = -1$.

One sees that r is a reasonable “position coordinate” for values of r greater than $2m$; but for values of r less than $2m$ this coordinate changes character; it becomes a time coordinate rather than a space coordinate. The reverse happens to t ; it changes from a time coordinate to a position coordinate. One can maintain oneself at a fixed value of r , with r greater than $2m$, by means of a rocket lift or otherwise. However, one can not maintain oneself at a fixed r less than $2m$ any more than one can make time stand still. The evolution of time forces such a person from $r = 1.9m$ to $r = 1.8m$ and so on, all the way to $r = 0$. No escape is possible; he is hemmed in by the light cone.

Departures from symmetry

A spherical cloud of dust falls into a Schwarzschild “black hole.” What happens if the cloud departs in a minor way from sphericity? If it is not endowed with angular momentum, it still collapses to a Schwarzschild black hole. If it has less than a critical angular momentum, it ends up as a uniquely defined but distorted black hole, given by the Kerr geometry, which is appropriate to a rotating system.

The “standard solution” for a black hole of given mass and angular momentum has certain well-defined quadrupole

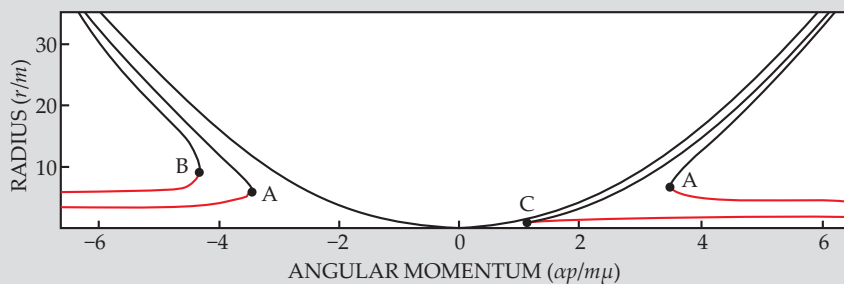


Figure 7. Closest stable circular orbits for the Schwarzschild and Kerr black holes. For Newtonian gravity there are stable orbits of all radii down to zero. The parabola gives the radius of each orbit as a function of angular momentum. For the curved geometries, there are both a minimum (black) and a maximum (color) in the effective potential for each value of the angular momentum down to a critical value

below which there is only a point of inflection—hence no stable orbits. A is the minimum Schwarzschild stable orbit; B and C are the minimum stable Kerr orbits for counterrotating and corotating particles, respectively. These results have great significance for the amount of gravitational radiation a particle can emit before falling into a black hole.

and higher moments. One finds^{12,13} that any perturbation from the standard Kerr solution decreases exponentially with time. To the outside observer, all details of the gravitational field get washed out except mass and angular momentum, provided that the original perturbation was not too large.

In a similar way, all distributions of charge near a black hole appear to a distant observer to have spherical symmetry. The extreme gravitational field near a black hole greatly distorts the lines of force from the normal pattern. Far from the black hole, the lines appear to diverge from a point much closer to the center of the sphere than the actual location of the charge. The dipole moment goes to zero as the charge approaches $2m$. Nothing in the final pattern reveals the true location of the charge. We see in the black hole simply mass plus charge, and no other details. The law for the disappearance of the dipole, p , as given by R. Price, is¹⁴

$$p \propto (\log t)/t^4.$$

This disappearance of the dipole takes place according to the same kind of law as the fadeout of perturbations of the quadrupole and higher moments of the mass distribution.

The collapse leads to a black hole endowed with mass and charge and angular momentum but, so far as we can now judge, no other adjustable parameters: "A black hole has no hair." Make one black hole out of matter; another, of the same mass, angular momentum, and charge, out of antimatter. No one has ever been able to propose a workable way to tell which is which. Nor is any way known to distinguish either from a third black hole, formed by collapse of a much smaller amount of matter and then built up to the specified mass and angular momentum by firing in enough photons, or neutrinos, or gravitons. And on an equal footing is a fourth black hole, developed by collapse of a cloud of radiation altogether free from any "matter."

Electric charge is a distinguishable quantity because it carries a long-range force (conservation of flux; Gauss's law). Baryon number and strangeness carry no such long-range force. They have no Gauss's law. It is true that no attempt to observe a change in baryon number has ever succeeded. Nor has anyone ever been able to give a convincing reason to expect a direct and spontaneous violation of the principle of conservation of baryon number. In gravitational collapse, however, that principle is not directly violated; it is transcended. It is transcended because in collapse one loses the possibility of measuring baryon number, and therefore this

quantity can not be well defined for a collapsed object. Similarly, strangeness is no longer conserved.

Angular momentum

The third property of a black hole is angular momentum. When it is nonzero, the geometry becomes more complicated. One deals with the Kerr solution² to the field equations instead of the Schwarzschild solution. There are two interesting surfaces associated with the Kerr geometry, the "surface of infinite redshift" and inside it, the "event horizon." An object at or within the event horizon can send no photons to a distant observer, independent of the object's state of motion or the direction of photon emission. For this reason, the event horizon is also called the "one-way membrane."

The Schwarzschild geometry represents the degenerate case of the Kerr geometry, in which the surface of infinite redshift and the event horizon coincide. In the general case, the two surfaces are separated everywhere except at the poles, as shown in figure 5. The very interesting region between these surfaces is called the "ergosphere." A particle that comes within the ergosphere can still, if properly powered, escape again to infinity. However, its life in this region has an unusual feature; there is no way for it to remain at rest, rocket powered or not!

Energy can be extracted from the ergosphere by a mechanism that may occasionally have significance for a cosmic ray. Consider a particle that enters the ergosphere and disintegrates, one fragment falling into the hole and the other escaping to infinity (see figure 5). R. Penrose³ has shown that the process can be so arranged that the emerging fragment has more energy at infinity than the original particle.

The extra energy is effectively extracted from the rotational energy of the black hole. If a particle can dip through the ergosphere and escape with some of the energy and angular momentum of the black hole, it is also true that a particle that is captured can increase the energy and angular momentum of the black hole. Capture is possible when the particle passes by sufficiently close to the black hole. The critical impact is smaller for a capture that increases the angular momentum of the system. Therefore, random accretion of particles leads to a gradual decrease of the angular momentum of the system. Selective accretion of particles with the maximum positive impact parameter is more appropriate to a black hole immersed in the debris from the collapse of a rotating star. Such favorable accretion can increase the angular

momentum of the black hole to a critical value $L = m^2 = 2m_{ir}^2$, at which 29% the total energy of the black hole is rotational energy. When this value is reached, further speedup is impossible.

The possibility of increasing and decreasing the angular momentum of the black hole leads to a “phase diagram” somewhat similar to those in thermodynamics. In figure 6, due to Demetrios Christodoulou, reversible changes in angular momentum are made by the accretion of a particle out of the most favorable orbit, at grazing incidence to the black hole. If the angular momentum is changed by the capture of a particle out of a less favorable orbit, the “irreducible mass” (the mass of the black hole in the absence of rotation) must increase. There is no process whereby the irreducible mass can be caused to decrease. Therefore transformations accomplished by the accretion of particles from unfavorable orbits (for example, from head-on impact) are irreversible and lead to a steady movement upwards on the “phase diagram” of mass versus angular momentum.

Gravitational radiation

The discovery of quasars, objects with enormous energy release, led many workers to investigate gravitational collapse as a mechanism superior to fission or fusion for converting mass to energy. A closer look caused discouragement.

The difficulty can be understood by a study of figure 7, which shows the radii of orbits of different angular momentum in the Kerr, Schwarzschild, and Newtonian cases. In the Newtonian case, there are stable circular orbits of all radii down to zero. The one-dimensional potential for the radial motion has a minimum for all values of the angular momentum. This is not the case for general relativity. There is a lowest value for the angular momentum and a corresponding radius for which there is a minimum in the potential. This is the stable orbit closest to the black hole.

When a particle emits gravitational radiation, it spirals into the black hole, moving to lower and lower orbits as it loses energy. When the energy of the particle decreases below the value in the last stable orbit, the particle is captured directly without further radiation. For the Schwarzschild black hole, the closest stable orbit is quite far from the center, and the particle can emit only about 5.7% of its mass as gravitational radiation before it precipitously falls into the black hole (point A in figure 7). If the particle is orbiting contrary to the rotation of the Kerr black hole, it leaps in from an even greater distance where it has lost only 3.8% of its energy (point B in figure 7). But if the particle is *corotating* with the black hole, it remains in stable orbit until it radiates 42.3% of its mass as gravitational energy (point C in figure 7). These results, obtained by James Bardeen, give a great incentive for reexamining other energy-release mechanisms in the context of the Kerr geometry.

Search for black holes

The existence of black holes has been predicted for over thirty years. No one who accepts general relativity has seen any way to escape their existence. Moreover, a black hole is a characteristic geometrodynamical entity. A neutron star could still exist in Newtonian theory; not so a black hole.

It took 34 years from the prediction of a neutron star by [Fritz] Zwicky¹⁵ in 1934 to its discovery as a pulsar by Antony Hewish and others¹⁶ in 1968. If the prediction of black holes by Oppenheimer and Snyder in 1939 is also followed after 34 years by their discovery, what will be the technique by which they are detected in 1973?

Of all objects that one can conceive to be traveling

through empty space, few offer poorer prospects of detection than a solitary black hole of solar mass. No light comes directly from it. It can not be seen by its lens action or other effect on a more distant star. It is difficult enough to see Venus, 12 000 km in diameter, swimming across the disk of the Sun; looking for a 15-km object moving across a far-off stellar light source would be unimaginably difficult.

Therefore, we turn to a black hole that is not isolated:

- ▶ A black hole that affects a companion normal star only through its gravitational pull (Ya. Zel'dovich and O. Guseynov).¹⁷
- ▶ One close enough to draw in matter from the normal star ([Iosif] S. Shklovsky).¹⁸
- ▶ One embedded in a normal star.
- ▶ A black hole moving through a cloud of dispersed matter.

The possibility of capitalizing on a double-star system is most favorable when the black hole is so near to a normal star that it draws in matter from its companion. Such a flow from one star to another is well known in close binary systems,^{19,20} but no unusual radiation emerges. When one of the components is a neutron star or a black hole, a strong emission in the x-ray region is expected.

Gas being funneled down into a black hole undergoes heating by compression.²¹ The temperature is extremely high (10^{10} – 10^{12} K), but only a fraction of the radiation escapes, because it comes from a region of high redshift close to the Schwarzschild radius of the black hole. Zel'dovich, Novikov, and Schwarzmans conclude that the bulk of the radiation emerges in the visible part of the spectrum or in the x-ray and gamma-ray region, depending on the mass of the black hole.

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