HOW BLACK IS A BLACK HOLE?

R. C. KAPOOR

About this painting ; When Matpam Luikham was asked to illustrate the article and the theme was explained to him, he brought the above drawing painted in early 1976. Curiously, at the time he painted it, he had not heard of black holes

> A luminous star of the same density as the Earth, and whose diameter should be two hundred and fifty times larger than that of the Sun, would not, in consequence of its attraction, allow any of its rays to arrive at us; it is, therefore, possible that the largest luminous bodies in the universe may, through this cause, be invisible.
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> — Pierre Simon Laplace (1795, in *Exposition du Systeme du Monde.* Part II, p. 305)

> When all thermonuclear sources of energy are exhausted, a sufficiently heavy star will collapse. Unless fission due to rotation, the radiation of mass, or the blowing off of mass by radiation, reduce the star's mass to the order of that of the Sun, this contraction will continue indefinitely, . . . ; as the contraction progresses, the radius of the star approaches asymptotically its gravitational radius . . . .
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> — J. Robert Oppenheimer and Hartland Snyder (1939, *Physical Review*, Sept. 1)

> When someone asks us to state the most important result of the symposium in a single sentence, it is difficult to do better than quote the words of our colleague, R. Giacconi, September 7: 'We now have strong evidence in favour of Cyg X-1 being a black hole
>
> — John Archibald Wheeler (1974, *Gravitational Radiation and Gravitational Collapse, the International Astronomical Union Symposium No: 64*).

The foregoing words highlight the most important landmarks in the history of black hole physics from the first speculation to the possible detection of a black hole. But, in between the speculation and the possible detection, lie a great deal of scepticism and decades of painstaking research: scepticism, because theories predicting black holes also imply that the centre of every black hole harbours a singularity (zero radius, infinite force of gravity) where laws of physics fail to hold their validity, and research, because the theories that predict black holes suggest no other go. In brief, a black hole represents the end-point of the evolution of certain massive stars where a large amount of mass is jammed in so small a volume that the force of its gravity is astronomically large in its vicinity. Newton's theory is inadequate to explain physics in such strong gravitational fields. A description of black holes and their surrounding space is possible only through Einstein's general theory of relativity. Black holes, as a result, provide an arena for a rigorous test of the predictions of the general relativity theory and for an exploration of physics in strong gravitational fields.

In view of a lot many exotic developments on the theoretical front, and the indications of the possible existence of black holes in X-ray emitting binary star systems like Cygnus X-1, it now seems they won't really let us live without them (see box on p. 20). In this article, it would not be feasible to talk about whatever has been written on black holes to date. I will discuss only some of the most interesting developments of the past few years.

Why 'black hole'? Pierre Laplace had conjectured the existence of

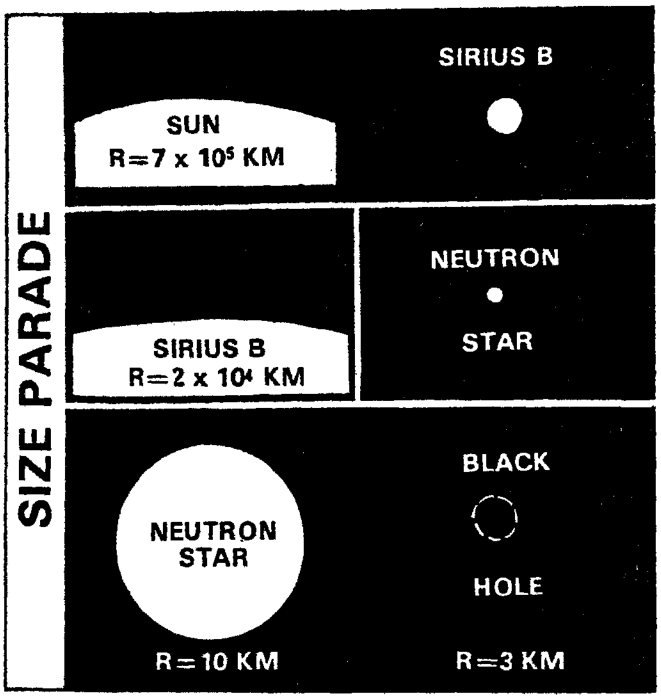


Fig. 1

'corps obscurs' way back in 1795 on the basis of Newton's theory of gravitation in his celebrated work *Exposition du Systeme du Monde*. (In the fifth edition of the work, however, the great natural philosopher and mathematician had deleted any reference to such 'dark objects'.) The notion of such black objects soon petered out into oblivion as no one visualised that these might ever be realised in the universe. It was not until the discovery of quasistellar objects, X-ray emitting stars and pulsars in the 1960s that serious attention was paid to the historical work of J. Robert Oppenheimer and his students in the late 30s on the final outcomes (neutron stars and black holes) in the evolution of stars more massive than the Sun. Pulsars, discovered in 1967, are known to be fast rotating neutron stars with magnetic fields of the order of 10^{12} gauss or so. In the case of X-ray sources, there exists no highly compact object with a mass at least of the order of the mass of the Sun ($M_S = 2 \times 10^{33}$ gm) other than a neutron star or a black hole that might lead to the release of high energy X-rays in copious amounts with certain characteristics. Similarly, about the quasistellar radio sources, or quasars as they are popularly known, no one knows what they are. Their compact size (less than a light year across) together with the enormous energy outputs ($10^{45,46}$ erg sec^{-1}) from those great depths of the universe, according to some theories, speak of supermassive stars in the phase of collapse or black holes (more than a million solar masses) devouring gaseous matter at work.

From start to finish, gravitation plays a decisive role in the career of a star. It forms by the gravitational collapse of a huge gaseous cloud, mainly hydrogen. By contraction, it gets hotter and when the temperature becomes large enough, hydrogen is burnt in nuclear fusion and its contraction is almost halted. What happens when all the nuclear fuel has been exhausted? The work of Oppenheimer and his students has made it obvious that stars of different masses evolve to end up as three distinct configurations. Those, like the Sun, whose masses fall short of a certain mass limit, known as Chandrasekhar mass limit (M_{Ch}), equal to $1 \cdot 2 M_S$, evolve peacefully after exhausting all their thermonuclear energy sources to end up as white dwarfs (radii ~ 10^4km). These stars gradually cool off and collapse to become so highly dense ($10^{5,6}$ gm cm^{-3}) that electrons get detached from the atomic nuclei in their material. It is the brisk movement of these electrons that provides the pressure to prevent further collapse and renders the configuration stable.

A star more massive than M_{Ch} ultimately explodes its outer layer in colossal explosions (the supernova explosion) and leaves a massive core behind. Being more massive than M_{Ch}, its collapse cannot be stopped at white dwarf densities because the force of gravitation overwhelms the pressure provided by the electrons. Consequently, it collapses and collapses to very high densities and very small radii when electrons are left with no other choice than to tunnel into atomic nuclei, interact with protons present there and produce neutrons. In the ever increasing tempo of the gravitational collapse, the neutronised atomic nuclei are cracked to release free neutrons. The material of the collapsing core now consists mostly of neutrons, and the very strong force of interaction between these ultimately builds up sufficiently to halt further contraction. The object which now measures some 20 km across and has a density of $10^{14,15}$ gm cm^{-3} is known as a 'neutron star'. With such a high density which may even exceed that of the atomic nucleus (3×10^{14} gm cm^{-3}), a cubic centimetre of the neutron star matter must outweigh all the 620 million Indians on the subcontinent!

A neutron star has a mass larger than M_{Ch} but smaller than another mass limit, known as the Oppenheimer-Volkoff mass limit (M_{OV}), discovered by Oppenheimer and his student G. Volkoff in 1939. It is now believed that this mass limit lies between $1 \cdot 5 - 3 \cdot 2$ M_S and draws a line between a stable (which a neutron star is) and unstable configuration. According to the theory of general relativity, pressure acts as a source of gravitation. If the neutron star were made a little more massive, then since pressure effectively contributes to the mass of the configuration, the latter must collapse further, making the pressure still larger and so on. Thus, if the neutron star could accrete one or two solar masses of gaseous matter, which it can do in a period of a billion years or so if it is present as one of the components in a close binary star system, so that ultimately the mass exceeds M_{OV}, the force of gravitation would overwhelm the pressure provided by the briskly moving neutrons. Or, if the collapsing core had a mass exceeding M_{OV} to begin with, its collapse could not be halted at neutron star densities to produce a stable configuration. For such masses, the weakest force of nature, gravity, all of a sudden becomes omnipotent and dooms all the mass of the collapsing star, or collapsar in short, inside its Schwarzschild radius in a small fraction of a second to evanesce from vision for ever. Strange death as it is: you kill yourself, you bury yourself into the graveyard that you become, the black hole!

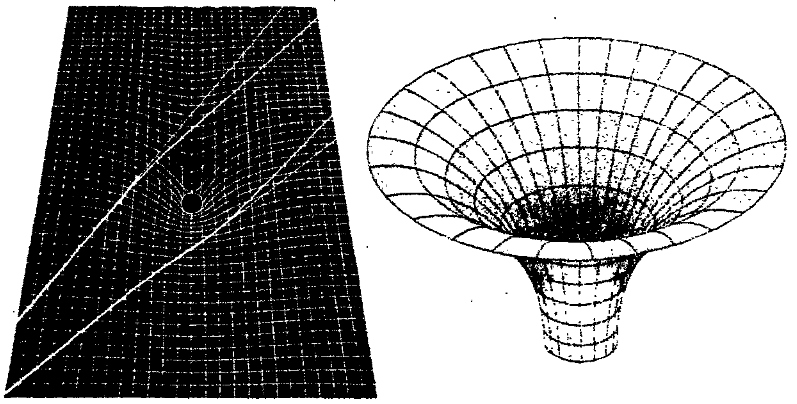
What is Schwarzschild radius? What is its significance? The formation of a black hole is a consequence of the fact that the force of gravitation is always attractive. It increases as the separation between two masses is decreased, with the amount of masses kept fixed. In the context of the collapse of a star, a decrease in the size is followed by an increase in the force of gravity experienced by a particle on its surface. It quadruples if we halve the size of the collapsar. In the language of general relativity, the notion of gravitational force is substituted by a more relevant one — the curvature of spacetime (see box alongside). Thus, when one says that the gravitational field on the surface of a collapsing object, or in its vicinity for that matter, increases, one essentially means that the spacetime around it becomes more and more curved. The larger the mass-to-radius ratio, the more severe is the spacetime curvature. This behaviour of the spacetime around a gravitational mass is best described by a solution of the field equations of general relativity, found for the first time by Karl Schwarzschild in 1916. This solution suggests that when the radius of an object becomes equal to a certain radius, known as Schwarzschild (or gravitational) radius (R_g), the curvature of spacetime becomes so large that it folds over into itself. No material particles, no, photons emitted from R_g, can ever make it to a distant observer. The object is cut off from our universe: it has become a black hole!

The Schwarzschild radius is given by $R_g = 2\ GM/c^2$ cm, with G the constant of gravitation, M the mass of the star and c the velocity of light — all expressed in cgs units (Fig. 1). For the Sun, R_g is 3 km, for a man of 100 kg, it is 3×10^{-23} cm, and for the universe ($\sim 10^{56}$ gm), it is $\sim 10^{28}$ cm (which is also the size of the universe!). Later work by Roy P. Kerr in 1963 and by E. T. Newman and co-workers in 1965 extended Schwarzschild's work so as to be applicable to a rotating and a charged rotating object, respectively. These solutions also suggest astronomically large spacetime curvature around an object with a certain radius, which is of the order of the Schwarzschild radius itself. A rotating black hole is known as a Kerr and a charged rotating one as a Kerr-Newman black hole, respectively.

But how do we justify the name 'black hole'? To find the answer let us appoint an agent to move inward with the surface layer of the collapsar, while we keep a safe distance from the venue of collapse. Although, for objects of the order of the solar mass, the agent is actually destined to die long before the surface collapses to R_g, we assume nothing fatal happens to him so that the experiment can be conducted smoothly. The agent is instructed to send us a light pulse every second. To start with, the gravitational field of the collapsar is not strong. The spacetime curvature is too small for the general relativistic effects (time dilation, gravitational redshift) to be noticeable. We continue to receive one pulse of light every second and find an agreement between the speed of the collapse that we record and what the agent does. However, when the collapse has sufficiently advanced, the spacetime curvature about the collapsar remains no longer flat. The interval of reception of pulses not only enlarges (time dilation), their energy and hence frequency also is reduced (gravitational redshift). To us, the collapse appears to be slowing down and it looks as if the surface would *never* be able to collapse through R_g. On the other hand, the agent feels the speed of collapse ever-increasing. It approaches that of light when R_g is approached. The pulses of light get severely redshifted and take an increasingly long time to reach us. Once the surface falls down R_g, the last photons sent by the agent while at R_g lose all their energy in their attempt to escape the confines of the object, that is, they are infinitely redshifted. All communication between us and the object would thus be broken. The object in effect is absolutely 'black'

THE SPACETIME CURVATURE

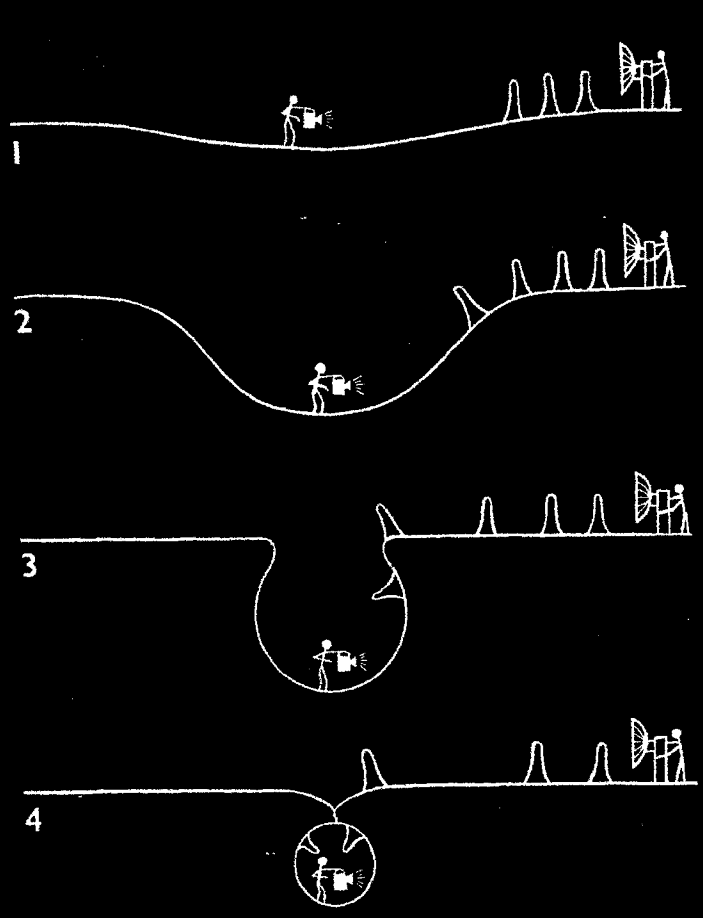
In the words of Euclid, the nature or geometry of space is flat irrespective of whether you stand in empty space or close to a celestial object. According to Einstein's theory of relativity, space and time are intimately related and the nature of spacetime is changed in the presence of a gravitational field. It is curved in the same way as a rubber sheet gets curved when a ball is placed on it. In free space, a light ray travels in a straight line. In a gravitational field, although it still tends to move in a path as straight as possible, because spacetime is curved, it gets bent from its original direction of emission (the phenomenon of gravitational bending of light). The extent of bending depends on how large the spacetime curvature is. This prediction of Einstein's general relativity was for the first time verified during the total solar eclipse of 1919.



In the presence of a strong gravitational field, spacetime is curved like a rubber sheet is curved when a ball is placed on it. The figure on the left shows bending of light rays in a curved space. The figure on the right shows the concept of curvature by what is known as an 'embedding diagram'

In the gravitational field of a mass, clocks slow down. Once again, the extent of slowing down depends on how large the curvature of spacetime is. Thus, according to a distant observer, clocks placed in the vicinity of a mass at different distances with respect to its centre appear to run at different speeds. He is so far off from the object that in his surroundings the curvature of spacetime is almost nil. His own clock would tick one second every second but the ones in the vicinity of the object take relatively longer to tick a second. This is the phenomenon of time dilation. A movie shot in slow motion perhaps illustrates best the phenomenon of time dilation.

Since any vibrating system can be used as a clock, a vibrating atom which is emitting radiation also acts as one. The frequency of its radiation can be taken as the unit time interval of the atomic clock. At the surface of a star, there are innumerable multitudes of such clocks. The radiation emitted by atoms at the surface of stars (the region of strong gravitational field) when compared to the radiation emitted by similar atoms in our laboratory (the region of weak gravitational field) turns out to have a smaller frequency. This is because the period between two 'beeps' of the atom in a strong gravitational field appears to be longer. This time dilation leads to the phenomenon of gravitational redshift. It depends on the mass-to-radius ratio of the object. The larger the ratio, the stronger is the redshift effect. The effect has been measured in the case of white dwarf stars, like Sirius B (the faint companion of the star Sirius in the constellation of Canis Major).



THE GRAVITATIONAL COLLAPSE OF A STAR

The gravitational collapse of a star can be well illustrated by the analogy of an agent standing on a collapsing rubber membrane (see text). The agent sends a light pulse every second. This is received by a distant observer. To start with, (1), before the collapse starts, the observer receives one light pulse every second. As the collapse advances, (2) and (3), the space-time in the vicinity of the agent would get increasingly curved and the observer would receive the pulses at longer and longer intervals (time dilation). Once the collapse goes through the Schwarzschild radius (R_s), the agent is trapped within the membrane, which closes on itself (4), and the pulses sent by him no more reach the observer.

Further, any probes sent down to trace whatever happened to the poor agent take an infinitely long time to reach R_s according to our clocks. Hence the name 'black hole'!

The Schwarzschild surface at R_S is a surface of infinite redshift and forms the boundary of all the events that can influence the outside world causally (that is, cause always preceding effect). The Schwarzschild surface is also known as the event horizon. Signals emitted from within R_S ought to move faster than light and nothing, as we know from the theory of relativity, can beat light. The Schwarzschild surface is, therefore, a one-way membrane: down the black hole is a one-way traffic, and, according to a relativist, a region of spacetime incapable of communicating with the rest of the world by way of photons or slower-than-light signals is a black hole.

Black holes of any mass are possible in general relativity. But, the limitations set by the stellar evolution theories and the unknown nature of the formation of supermassive stars allows only a certain mass range for black holes which might form today as a consequence of *natural* gravitational collapse. We can have stellar black holes in the mass range $\sim 1 - 100\ M_S$ which form at the end of the evolution of massive normal stars. In the range $\sim 10^5$ to $> 10^{12}\ M_S$ form supermassive black holes which represent the end-point in the career of supermassive stars, galactic nuclei or highly dense star clusters. Whatever the mass, all these black holes are exactly alike: they are perfectly black, don't radiate anything. Only during the infall of gaseous matter on to a black hole are vast amounts of energy let loose to escape away.

It was once believed that black holes with masses less than M_{OV} cannot be realised in nature. However, such beliefs have been shattered by Stephen Hawking's prediction of the possibility of formation of very light-weight black holes in the earliest period of the universe, that is, almost *immediately* after the universe originated in a Big Bang. These black holes are very peculiar; they radiate powerful X-rays, gamma rays and even subatomic (elementary) particles. This discovery by Hawking paves the way for a connection between the general theory of relativity and thermodynamics through quantum field theory, and is understood to be a theoretical development of great importance where the three different branches of physics, hitherto far apart, can now wrestle together. In order to understand these radiating black holes, we shall have to delve into the classical black hole saga more deeply.

A black hole has no hair

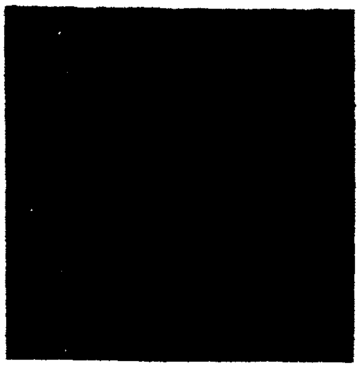
The phenomenon of gravitational collapse of a certain mass makes a very intricate subject of study. So far, we have studied the collapse of masses with a number of simplifying assumptions. One of these is that of spherical symmetry.

What happens if the geometry of the collapsing object departs from spherical symmetry? Could we still be left with a black hole? Rotation of the parent star undergoing collapse, with magnetic fields present, might attribute to nonsphericity. A nonspherical gravitational collapse is more likely to happen but much more difficult to study. Theoretical investigations have revealed that small departures away from perfect sphericity are radiated away in the form of gravitational waves and electromagnetic radiation. In fact, in his beautiful theorem, R. Price (in his PhD thesis) in 1970, summarised the situation by stating that in the relativistic gravitational collapse of a (little) nonspherical configuration, anything that *can be* radiated will be radiated away completely. The final outcome is a black hole characterised by only its mass, charge (if any) and angular momentum. If anything falls down a black hole, it would add to its mass, charge and angular momentum and nothing else. These three parameters, therefore, determine uniquely the external gravitational and electromagnetic fields of the hole. No other information about its interior (that is, the region interior to the horizon) is available.

Actually, this is stating in simpler words the fact, as demonstrated mathematically by a number of workers, that a black hole exerts only gravitational and electromagnetic forces on its surroundings. There are four types of forces or interactions that the elementary particles or systems thereof participate in. These are gravitational, electromagnetic, weak and strong forces (written here in order of their strength, the last being the strongest). A black hole does not exert weak or strong forces on anything in its exterior. What do we make of this?

From particle physics, we recall that neutrinos, electrons and mu mesons belong to the class of leptons which partake in weak interactions. The pi mesons, neutrons and protons belong to the class of hadrons which partake in strong interactions. The hadrons are further subdivided into baryons (protons, neutrons, etc) and mesons (pi mesons, etc). Experimentally, it is well established that the total number of baryons and leptons in the universe is conserved. What if either of these particles were sent down a black hole to probe how many baryons and leptons a black hole contains? This could be achieved if strong or weak interactions were possible between the test lepton/baryon and the black hole. Much to the disappointment of the experimenter, who fails to fulfil his ambitions, it turns out that the interaction with the lepton/baryon tends to zero at the horizon. He neither can find out the baryon/lepton content of the black hole nor can he establish that the baryon/lepton number of the black hole has increased by one!

Does that imply the violation of the laws of conservation of baryon and lepton number known to be so well established? Actually, the laws are not violated, they are transcended, in the sense of impossibility of their verification inside a black hole. J. A. Wheeler has summarised this whole affair in his historical statement: "*A black hole has no hair*"! (the hair is any distinguishing feature that would be externally measurable). Black holes with identical mass, charge and angular momentum cannot thus be distinguished from one another. Whether one is formed from baryons and the other(s) from antimatter or radiation, all black holes look exactly alike (Fig. 2). Further, the experimenter has no hair tonic for his black holes. They cannot grow hair because that would amount to destroying the horizon, and any attempt to destroy the horizon in whatever processes that are arranged to achieve this produces once again a black hole, with its mass, charge and angular momentum revised (Fig. 3, p. 18).



First detailed colour photograph of a black hole. Note features at upper left and centre, in good agreement with current theoretical predictions.

Fig. 2 The illustration above appeared in the March/June 1974 issue of *Mercury*, published by the Astronomical Society of the Pacific, San Francisco. (The author wishes to thank the editor of *Mercury* for permission to reproduce)

Hawking's theorem

Being what it is, a black hole would swallow material particles and radiation — everything that falls close enough to its horizon. However, it would not be pertinent to say that the mass-energy that falls down a black hole is trapped once and for all. Take for instance a Kerr-black hole. Roger Penrose in 1969 had suggested a way to extract energy from such a black hole. If the hole were rotating very fast, all of its energy of rotation, which is more than one-fourth of its total mass energy, can be tapped in a number of suitably arranged processes (known as the Penrose processes). The nature of the Penrose process is such that it cannot work for a Schwarzschild black hole.

Can we hope to get energy out of a Schwarzschild black hole, too? In the opinion of Stephen Hawking, it is surely possible. What needs to be done is to let two black holes move around each other. They move in spiralling orbits and by doing so release a lot of energy in the form of gravitational waves. Ultimately, the black holes collide (!) and form a single black hole. If the holes were equally massive, the energy output can be as high as 60 per cent of the mass-energy of a single black hole. For one solar mass, it once again is some 10^{54} ergs!

The mass of the resulting black hole is less than the sum total of the mass of the two black holes participating in the grand collision. What confounds a remote observer during the operation of the process is the irreversible increase in the black hole surface area (equal to $4\pi R_s^2$ for a Schwarzschild black hole). This fact was discovered independently by D. Christodoulou and S. Hawking around 1970-71 and forms one of the most important contributions to the physics of black holes. This is true for a Kerr-Newman black hole also. Hawking has demonstrated mathematically why it should be so and summarised his results in a theorem (Hawking's theorem) that states that whatever processes a Kerr-Newman black hole does undergo, from accretion of gaseous matter to collision with another black hole or the Penrose process to swallowing up the stars in toto, its surface area cannot decrease toward the future (unless you can reverse the flow of time). At most it can stay constant. Corollary: one cannot, therefore, slice a black hole. If area could be decreased, we could destroy horizon, too (the black hole grows hair). This gives rise to all sorts of violations of physics. However, it has been felt by a number of physicists that when the spacetime curvature is so large that quantum effects in gravity become important, violation of Hawking's theorem is possible. To this we shall return later.

Black hole thermodynamics

It is not out of place to regard a black hole as akin to a closed thermodynamic system. This is best made manifest by the irreversible increase of the horizon surface area which is somewhat reminiscent of the irreducibility of entropy in the second law of thermodynamics. Entropy is a measure of the amount of unavailable heat in a system. Any changes that take place in a closed thermodynamic system choose a preferred direction in time, one in which the entropy increases. An increase in entropy essentially implies that energy available to perform useful work gets reduced. We have seen that when something falls down a black hole, it adds ultimately to its mass, charge and rotation and nothing else and is lost for ever. An accompanying increase in the surface area of the black hole then implies just the same, that is, some energy has become unavailable to perform useful work, or that entropy has been increased. Therefore, J. D.

Bekenstein proposed in 1972, in his PhD thesis, that it is certainly plausible to regard the black hole area as its entropy. The area can be multiplied by a constant, constructed from the fundamental constants G (constant of gravitation), k (Boltzmann constant), c (velocity of light) and h (Planck's constant), to express black hole entropy in ergs per degree. For one solar mass black hole, the entropy is 10^{60} ergs per degree Kelvin which turns out to be billion billion times that of the Sun itself. Such a large number makes this fact clear that a black hole state is the maximum entropy state of a certain amount of matter.

But there is one snag. The ordinary second law of thermodynamics appears to be transcended (impossibility of its verification) in black hole physics. For instance, when we dropped that small chunk of matter (entropy) down the hole, the entropy of the exterior universe decreased, whereas there is no way of getting information about the black hole interior to enable an external observer to verify that the total entropy of the universe did not decrease in this process. That is what one means by the transcendence of the second law of thermodynamics in black hole physics. Therefore, to be applicable to black holes, the law needs to be redefined. A careful investigation shows that the black hole area would always increase by an amount that suffices to make up for the entropy lost down the hole. Hence if one can generalise entropy to incorporate the black hole entropy as well, the second law can be restated thus: the sum total of the entropy of the black hole (S_{BH}) and the ordinary entropy of every thing in its exterior (S_o) is irreducible: $\Delta(S_{BH} + S_o) \geqq 0$.

To further the analogy of black holes with a closed thermodynamic system, Bekenstein has suggested the black hole analog of the first law of thermodynamics. The first law of thermodynamics states the conservation of energy. While finding its black hole analog, out came the concept of a black hole temperature! If we express the mass of the black hole in gms, its temperature can be written as $T = 10^{26}/M$ degrees Kelvin. The inverse dependence of temperature on mass suggests that a black hole is a very peculiar object: it has a negative specific heat because it gets hotter if it loses energy. For stellar and supermassive black holes, T is fairly close to zero. Such a black hole cannot be in equilibrium with its surrounding. It sucks in energy much faster than it can emit and would for all practical purposes be cold and perfectly black. Recently, in 1974, Hawking has argued that T as expressed above is *the* temperature of a black hole and not merely an analog.

To stretch the analogy with classical thermodynamics, we could go still further. According to classical thermodynamics, a system is in a state of thermodynamic equilibrium when its members obey the principle of equipartition of energy so that there is no net exchange of energy. In such a system, therefore, the temperature remains at every point the same. This is known as the zeroeth law of thermodynamics. According to the third law, also called Nernst's theorem, this temperature cannot be reduced to absolute zero in any finite number of attempts. These laws of thermodynamics sound exactly similar when formulated in the black hole context. The zeroeth law of black hole thermodynamics states that the temperature of a black hole remains uniform over its horizon and the third law is a statement of the fact that the temperature of a black hole cannot be reduced to zero in any finite number of attempts. If we could do that, we could produce negative temperature also (the horizon is destroyed and all sorts of violations of physical laws take place).

Micro black holes

The identification of a black hole as a thermodynamic object has led to the concept of its temperature. For a black hole of one solar mass, $T = 10^{-7}\,^{\circ}K << 3^{\circ}K$. The 3°K microwave background radiation that fills the whole of the universe is a relic radiation from the primeval fireball. The radiation has the character of that from a black body at a temperature of 3°K. Heat can flow from one system to another only when the latter is at a temperature lower than that of the former. Thus, a one solar mass black hole in space absorbs radiation much faster than it could emit and 'looks' perfectly black for all practical purposes. What if the mass of a black hole were, say, a mere 10^{20} gm? The story is then totally different. It should have a temperature of a million degrees and start emitting X-rays. However, this contradicts what we have been arguing all along — that a black hole is a one-way sink. Actually, once we have a black hole temperature, we also have to invoke the necessity of energy emission. This can be explained by taking quantum effects into consideration. Could black holes with such large temperatures, that is, small masses, be realised?

Until 1970, it was believed that only massive stars which explode to become supernovae in the course of their evolution and leave cores with masses greater than M_{OV} have no end-point stable configuration. Masses shorter of the M_{OV} limit cannot produce black holes unless external pressure is applied to squeeze them to black hole dimensions. This essentially amounts to assisting gravitation to bring down the mass limit. No terrestrial machine would be able to produce the desired effect, but there had been a certain period in the evolution of the universe after the Big Bang occurred when conditions were just ripe to produce black holes out of as small masses as 10^{-5} gm (and upwards thereof). In its earliest phases, the universe wasn't completely uniform. In fact, departures from homogeneity (lumpiness) and isotropy may have been large enough

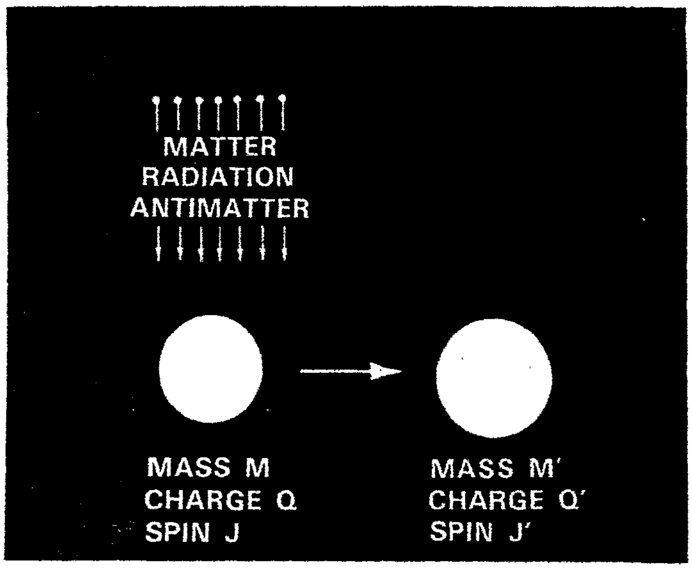


Fig. 3 Everything that falls down a black hole loses all particularities and attributes no colours to the hole except revise its mass, charge and angular momentum

About Stephen Hawking

He can move about only on a motorised wheelchair, because, at 34, Stephen Hawking is the victim of a crippling progressive degenerative disease of the nervous system (known as atypical amyotrophic lateral sclerosis). He can't write, and can speak with difficulty; yet he continues to lecture widely. The disease hasn't touched his mind; "he has made more progress in relativity than anyone in 20 years and perhaps since Einstein," says Jerry Ostriker of Princeton University. And remarkably, Stephen Hawking does all his calculations in his head as he did those that ultimately led to his recently proposed theory on the exploding death of micro black holes.

to produce forces that could overcome pressure forces and kinetic energy of expansion. Small chunks of matter would, therefore, have been crushed to produce micro black holes by force, such that the smallest mass black holes would have been produced in the earliest epochs of cosmology.

If we set the cosmic clock at time $t = o$ when the Big Bang occurred, then the earliest phase that the present day physics can reliably speak of is $t \sim 10^{-43}$ sec, known as the threshold epoch in cosmology. A black hole produced at this epoch should have a mass of $\sim 10^{-5}$ gm (Planck mass) and a dimension 10^{-33} cm (Planck length). The ones formed at later epochs must have been more massive. For dimensions less than 10^{-33} cm, quantum effects in gravity must take over and one requires a full-fledged quantum theory of gravitation which we do not have at our disposal. However, for masses upward of 10^{-5} gm and dimensions larger than 10^{-33} cm, a semiclassical approach is certainly plausible and one can discuss the quantum interactions of a micro black hole, namely, the interaction of its strong gravitational field with other particle fields (photons, neutrinos, pions, etc). Such a primordial black hole, being very small, would be very difficult to detect. However, a semiclassical study suggests that there is a quantum mechanical effect which is very important for such primordial black holes.

What happens is that, with respect to a distant observer, there occur particle states of negative energy inside the event horizon. It is then possible that pairs of virtual particles can be created spontaneously where one particle has negative and the other positive energy. If creation of the pair occurs near the event horizon of the micro black hole, quantum mechanical tunnelling may take place whereby the positive energy particle flees away to infinity before the pair could annihilate each other. The one with negative energy is left buried down the black hole. Not that it happens once and for all: the black hole loses mass continuously by virtue of particle emission.

To be able to radiate, a black hole should have a temperature greater than 3°K. The expression for black hole temperature suggests that a black hole hotter than 3°K should have a mass less than 10^{26} gm. Therefore, all primordial black holes with masses $< 10^{26}$ gm emit radiation, and, as they evaporate, the temperature rises still further. Emission becomes faster and faster till toward the end it becomes so large that the remaining mass is exploded away in a matter of a fraction of a second! At very high temperatures, even elementary particles can be radiated. For instance, once thermal energy kT corresponding to a temperature T exceeds the rest mass-energy of electron or mu meson, electrons and mu mesons can be radiated. When $T > 10^{12}$ °K, that is, $M < 10^{14}$ gm, hadrons are emitted. All primordial black holes with masses smaller than 10^{15} gm (a billion metric tons) must have evaporated away since their decay time (which is given as $\sim 10^{-28}\ M^3$ sec) is smaller than the age of the universe ($\sim 10^{10}$ years). However, the ones with masses of the order of 10^{15} gm (size 10^{-13} cm) or so must be in the last throes of their evaporation now. Experimentalists can, therefore, hope to detect the last puffs of such black holes in the form of X-rays and gamma rays. The total amount of emission from black holes of masses $10^{14,15}$ gm is $\sim 10^{35}$ ergs, and the power radiated in the last 0·1 sec is just 10^{30} ergs, in the range 100–500 mega electron volts. This is the energy range of hard gamma rays. The gamma ray detectors currently in operation are not sensitive enough to detect these. But, it is hoped that the next generation gamma ray detectors aboard orbitting satellites would be capable to detect the *last calls* from black holes of primordial origin. No one knows how many of them are around, but Don Page of Caltech, USA, has estimated a rate of one burst every month (at an average distance of 8 light years).

That brings us to the realisation that some black holes are not *that* black after all. And although the black hole area decreases in the process of evaporation (the quantum level violation of Hawking's theorem), the sum total entropy 'inside' and outside due to emitted particles increases. In this manner, a micro black hole is nothing but a machine that effects the conversion of baryons and leptons into entropy — an elegant explanation to why the number of photons in the universe is a hundred million times larger than that of baryons which are 10^{80} in all!

White holes, grey holes and worm holes

We were so engrossed in the outside story of black holes that we have forgotten to ask whatever happens to the agent we had appointed on the surface of the collapsing star and its matter, once everything gets into the event horizon. The story is as interesting as that of the black hole itself.

The collapse becomes relativistic when the horizon is approached. It is difficult to reverse now and impossible to reverse after the surface of the collapsar (mass M) together with the agent has got squeezed to a size smaller than its event horizon. Once past the horizon, not only does the agent see the whole lot getting crushed to smaller and smaller dimensions and indefinitely larger densities, he himself is torn apart by the towering influence of tidal forces, till everything is crushed beyond all recognition to the state of infinite density and zero radius. This happens in a time $10^{-5}\ M/M_S$ sec, as measured by the agent's clock.

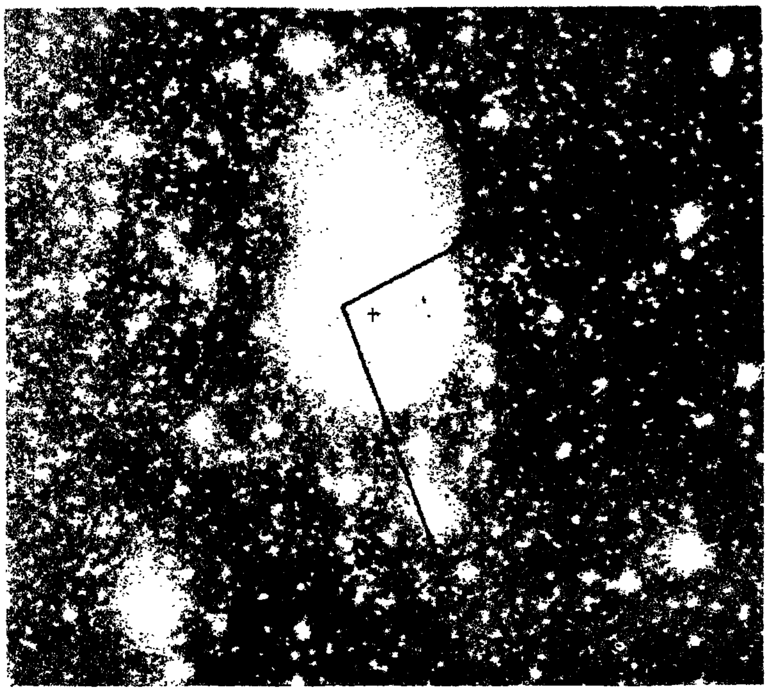
That is what relativity theory suggests. But then zero radius (infinite density, infinitely large spacetime curvature) is a singularity, heralding the breakdown of all known physical formalism. Does a singularity situation actually happen? The foregoing are inevitable in an idealised collapse (spherical, no complications like rotation, magnetic field, etc). Could a body endowed with rotation avoid in its collapse the occurrence of such a singularity? The phenomenon of occurrence of singularity in the case of gravitational collapse has been a subject of hectic research for over a decade now. Roger Penrose and S. Hawking's pioneering work in this connection has demonstrated that singularities necessarily develop, there is no way out. But there is an important disparity between the singularity that occurs in the idealised (spherical) collapse and the one that develops in a nonspherical collapse. In the case of spherical collapse, the fate of matter undergoing collapse is sealed: no other go for it except to be crushed to the state of infinite density and zero radius at the singularity. In the case of nonspherical collapse, the singularity may possess a non-zero, but small size. All or most of the chunk that falls down the horizon in the course of collapse may avoid being crushed to infinite densities. It may get jammed to a certain maximum density and explode into another, possibly distant, region of spacetime in our or some other universe. The emergence 'there' of all the mass that participated in the collapse to produce a rotating black hole through the event horizon 'here' is a great violent event and is called a *white hole.* If the explosion is not powerful enough, the matter may not emerge from the horizon 'there'. What you have then is a *grey hole.*

A white hole is thus a time-reverse of a black hole. Distinct from the latter, which accepts everything but acts the greatest of all misers, it churns out matter and radiation. Where do we look for the exploding 'ends' of rotating black holes in the sky? Suggestions are that, in the nuclei of some galaxies which, distinct from other galaxies, look eruptive and are gushing out matter and powerful radiation, and quasars, white holes may have erupted.

The two regions of spacetime, a black hole 'here' and a white hole 'there', are connected by a tunnel, called *worm hole,* through which matter flows to make the eruption 'there' possible. A rotating black hole can in this manner provide itself as the launching pad to send you off on a space odyssey to another universe. And, by suitably choosing your direction, not only could you come back to the Earth, but even a million years before or million years hence! The like of H. G. Wells' *Time Machine!*

BLACK HOLES: FROM SPECULATION TO REALITY

With properties so exquisite, the black holes look more like a make-believe fantasy than anything real. Micro black holes have indeed been a 'hot' subject for science fiction, as for instance, in Larry Niven's *A Hole in Space.* Nobody knows which direction in the sky to look for micro black holes, in the last throes of their boisterous existence. There have been suggestions about the places in the sky to look for stellar and supermassive black holes, but despite the fact that observational astronomy is pretty advanced, it has been hard to pin one down conclusively. The only compelling case is of Cygnus X-1, a powerful source of X-rays in the constellation of Cygnus. It is a binary star system where one of the companions, thought to be a black hole, swallows gas from its companion star which lets loose enormously large amounts of energy in the form of high energy radiation with characteristics of its own. The energy lost every second would suffice to keep the wheels of all the automobiles on the Earth moving for a hundred billion years, doing an average of a hundred kilometres every day. Three other X-ray sources, 2U 1700 — 37, 2U 0900 — 40 and SMC X-1, also pass for black hole suspect binary systems. The first two, detected by UHURU satellites, are within our galaxy whereas the last one is in the Smaller Magellanic Cloud, the satellite galaxy of our own. Black holes are syspected to form in the centres of globular clusters also. But how do we see them? The cluster stars in the course of their movement may venture too close to the hole, get captured and even tidally disrupted. An appreciable mass of gas released in the process, as well as gaseous matter shed by the stars in the course of their evolution, settle down toward the centre. In their fall into the black hole, their gravitational energy is released as powerful radiation. A number of globular clusters have been found to be X-ray sources, and, according to Jerry Ostriker and John Bahcall, these may be harbouring black holes as massive as a thousand Suns. Similar situations, but on much larger scale, are understood to exist in the centres of certain galaxies, and possibly quasars also. There was even a suggestion once that the universe itself is a black hole. But that is another story.



This photograph taken by Jerome Kristian with the 5-metre Mount Palomar telescope shows at its centre (largest white area) the star HDE 226868 which is believed to be associated with Cygnus X-1. The small cross indicates a radio source while the black outline shows the location of an X-ray source. The earlier ambiguity about Cygnus X-1's location (because X-ray telescopes have a low resolution) was resolved at the turn of the first quarter of 1971 when Cygnus X-1 " underwent a cataclysmic change . . . that caused it to begin emitting radio waves . . . " (quote from Kip S. Thorne in *Scientific American*), which helped identify its location

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1. Thorne, K. S. 1967 *Scientific American* (Nov).
2. Ruffini, R., and Wheeler. J. A. 1971 *Physics Today* (Jan).
3. Thorne, K. S. 1974 *Scientific American* (Dec).
4. Gibbons, G. 1976 *New Scientist*, **69**, 54.