More Than One Way to Skin a Black Hole

A changing point of view changes the paradigm

By DIETRICK E. THOMSEN

Sometimes in science the way you look at a given phenomenon depends on what you want to get out of it. Black holes are an example. For decades black holes were a theoretical artifact, a prediction of general relativity. Now they have become important in astrophysics, and as a result the view of them is changing radically.

The usual scientific picture of a black hole used to be and still is expressed in a Penrose diagram (named for Roger Penrose of Oxford University) — a schematic representation in four-dimensional space-time of the collapse of some object and the formation of a black hole. It features clocks that run at widely varying rates depending on where they are — time goes very slowly for a clock riding the collapse; it can go very fast for an observer watching from a distance.

The climactic moment in the Penrose process comes when the object gets small enough to be within its event horizon, the boundary that cuts it off from communication with the rest of the world. Much mental effort has been spent on imagining what happens inside the communications barrier and especially at the singularity in the center, the place where space and time come to an abrupt halt, and matter and energy disappear. Are singularities always clothed in block holes with impenetrable event horizons? Or can there be naked singularities, offering their apocalyptic threat to all and sundry? The arguments over these questions go by such curious names as "the cosmic censorship theorem," or "the cosmic no-hair theorem."

Today, however, black holes have gravitated toward the realm of astrophysical phenomena. Astronomers are tending to see them everywhere in the sky that there are highly energetic goings-on in small spaces — especially in the centers of quasars, objects that look as small as stars but radiate energy in amounts typical of whole galaxies. Astrophysicists find it necessary to consider black holes in relation to their surroundings, and particularly in relation to the electric and magnetic processes that produce the radiation we observe from the objects in which black holes are suspected to lie.

As Kip S. Thorne of the California Institute of Technology in Pasadena told the recent Orbis Scientiae meeting in Miami, the picture of a black hole is changing. Astrophysicists are not interested in the dynamics of black hole formation that fascinate general relativists. They are concerned with how a black hole that formed some time ago now interacts with its surroundings. The new view is still cataclysmic but much less apocalyptic. "The paradigm has shifted," Thorne says.

"Paradigm" is the technical term for scientists' total picture of a phenomenon or group of related phenomena in the philosophical analysis of scientific thought processes by the philosopher of science Thomas S. Kuhn. Kuhn was concerned with how scientific revolutions, such as the shift from the Ptolemaic view of the solar system to the Copernican view, take place, and he elaborated a theory of paradigm building and sudden paradigm shifts to explain it. Proclaiming a paradigm shift while it is happening is rather self-conscious philosophizing. However, physicists are generally favorable to Kuhn's explanations. As more than one physicist has suggested, this may be because Kuhn started out as a physicist and understands from the inside how physicists think. Explicit Kuhnian analysis by physicists of their own doings may be returning a compliment.

The shift in the black hole paradigm is in some ways a historical backward step. It consists of a move from the Einsteinian point of view with its four-dimensional space-time and its widely varying clock rates to a quasi-Newtonian view of a three-dimensional space and a universal time that flows everywhere at one rate. Only this three-dimensional space is not Newtonian as Newton would have recognized it: it is not flat, but curved.

The event horizon of the black hole is viewed as a "membrane," a two-dimensional surface or skin suspended in the curved three-dimensional space. (The idea of the membrane is attributed to a young French physicist, Damour.) The focus of interest shifts to this membrane and the region of space immediately outside it. What lies within it, singularities naked or hairy and the places where ordinary laws of physics are weirdly violated, are of great concern in the Penrose analysis but are not faced in this paradigm. The interest is in the membrane, its electric and magnetic fields and how they interact with the accretion disk, a disk of matter that is drawn from the surroundings by the black hole's gravity and surrounds the black hole in its equatorial plane.

The event horizon of a black hole is a boundary in space-time at which the behavior of matter and energy changes radically. It is not a material thing. But in this membrane paradigm it gets a quasiphysical name and some quasimaterial properties. It can carry electric charge and sustain electric currents. That it can do this is a fiction, says Thorne, but a useful fiction.*

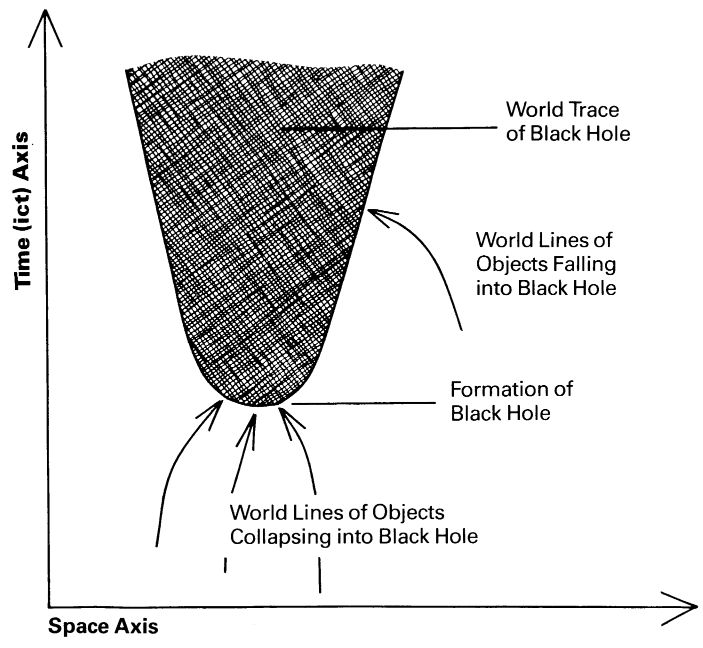
The fiction allows the membrane to be considered the terminator of electric and magnetic fields, so the observer does not have to look inside it at the general relativistic complications that are a main feature of the other paradigm. The black hole itself becomes a kind of black box, into which we do not look.

The reward for thus turning the picture almost inside out and for adopting this Newtonian frame of reference is that the black hole in this paradigm obeys some basic laws of physics that black holes viewed in the other paradigm's Einsteinian perspective spectacularly violate. In the new paradigm black holes have finite temperature and entropy and obey the laws of thermodynamics. (In the old paradigm Stephen Hawking of Cambridge University had to invent a whole new set of thermodynamic laws for black holes because of the infinite and paradoxical ways they violate the ordinary ones.) In the new paradigm, also, black holes abide by Maxwell's equations and Ohm's law and so can be treated by ordinary electromagnetics. This is important because the accretion disks consist of ionized gases and the black holes' main interactions with their immediate surroundings are electromagnetic.

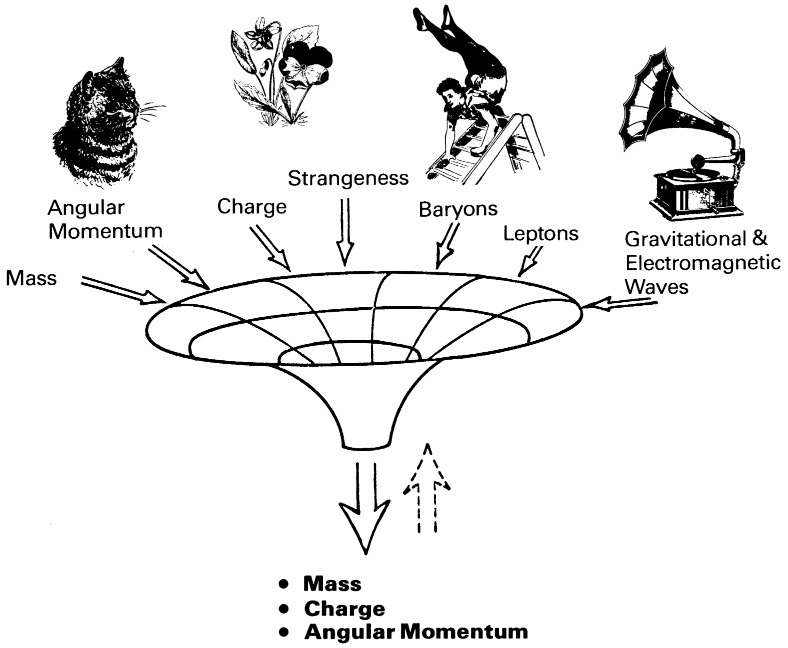
Black holes condense from stars. Stars generally rotate, so it is assumed that real black holes rotate too. In the new paradigm the rotation of the black hole in the three-dimensional space produces a gravitomagnetic effect that plays a crucial role in the astrophysics. (If both paradigms are equally valid ways of looking at the phenomenon, scientists have to be able to show that they are mathematically equivalent. This can be done, and the exercise shows that this gravitomagnetic effect is a kind of artifact of the change from four-dimensional Einsteinian space-time to the three-dimensional curved Newtonian space with its universal time. The effect arises out of the mathematical differences between the two kinds of framework.) The gravitomagnetic effect tends to produce magnetic fields that interact with the accretion disk in ways that warp the shape of the disk and result in orderly magnetic fields in the whole region, "combing out" the chaotic magnetic field that the ionized gas in the disk would normally have. The result is a field that has nice regular loops over the accretion disk, and on the membrane itself does not loop, but simply runs outward more or less in the directions of the black hole's poles of rotation.

Electric and magnetic effects combine to produce a charge separation on the membrane with negative particles going in at the poles and positive ones coming out at the equator. (The charges are produced by pair production, the transformation of photons of light produced by friction and heat in the accretion disk into pairs of electrons and positrons under the influences of the forces present.) So the whole thing functions as a kind of magnetic battery driving a DC current that runs far out into the magnetosphere surrounding the membrane and back to the membrane. This current can serve as an accelerator for other particles and as a driver for various magnetohydrodynamic effects that produce the observed radiation.

Thus there is a paradigm of black holes as powerhouses of quasars that is useful for astrophysics. It is tractable, avoiding many of the general relativistic difficulties, and it is tailored for plasma physics and magnetohydrodynamic calculations, which are hard to do in Einsteinian space-time. Thorne says he doesn't believe there really can be electric charge on an event horizon, "but it sure helps." □



A variety of Penrose diagram (above). Its emphasis is on the temporal sequence of events by which a black hole forms.



Another way to visualize black hole formation. Everything in the world disappears down the drain including some important physical conservation laws. What remains is an object with only three properties: mass, angular momentum (rotation) and electric charge. The new paradigm starts from these properties.

**The use of deliberate fictions in the accompanying analysis may startle some readers, but it is not an uncommon technique in physics. A classic and very old example in classical physics is the Coriolis effect:*

If a projectile is fired on the face of the earth, it will fall to the right of where the cannoneer thought it was aimed in the Northern Hemisphere and to the left in the Southern. This is an effect of the rotation of the earth. It can be analyzed geometrically, but that makes forbiddingly complex mathematics.

Early in the game physicists realized that if they adopted the fiction that the earth does not rotate (as the cannoneer is likely to do anyhow) the analysis is easier. But then there appears to be a force, called the Coriolis force, pushing the projectile sideways. In reality no such force exists; it is a fictitious force, an artifact of adopting a certain point of view, but it makes the analysis of the problem much easier. Centrifugal force is another such fiction. Similar, but more complicated, things are being done in the quasar case.