

Black holes light up the universe

*Black holes are the source of the universe's most powerful radiation, as well as to jets that can stretch many thousands of light years out into space. **Roger Blandford's** theoretical work deals with the violent processes behind these phenomena. **Roy Kerr** laid the foundation for this research early on, when he discovered a mathematical description of rotating black holes before anyone had even seen them. This became one of the most important theoretical discoveries in modern cosmology.*



ESO/WFI (visible); MPIfR/ESO/APEX/A. Weiss et al. (microwave); NASA/CXC/CfA/R. Kraft et al. (X-ray).

They bend space and distort the passage of time. Everything that gets close to a black hole falls in and nothing gets out, not even light. Black holes remain invisible; they have long been a mystery and still hold many secrets. However, some of these have been revealed, so we now know that a massive black hole can spin quickly and make its closest surroundings shine brighter than anything else in the universe.

Black holes are the strangest result of the general theory of relativity. When Albert Einstein finally presented his theory in November 1915, all previous concepts of time and space were turned upside-down. Instead of the familiar Newtonian gravity that makes an apple fall straight to the Earth, Einstein described gravity as a geometric property of space and time

connected in a four-dimensional spacetime. According to Einstein's theory, gravity is not a force – instead it is a consequence of spacetime being bent. This also affects the passage of time – seen from the outside, time moves more slowly close to a large mass.

All massive space objects bend spacetime; they create a pit into which other, smaller, objects can fall. Gravity is therefore an illusion; the apple falls because it follows the trajectory that is caused by the Earth's mass. The larger the mass, the more spacetime bends. For small masses and short distances this effect is the same, regardless of whether one uses Einstein's general theory of relativity or Newton's laws of motion, which are more than 200 years older.

The equations of the general theory of relativity are famous for being very technically complicated to solve. Despite this, just a few weeks after publication, the German astrophysicist Karl Schwarzschild was able to provide Einstein with a precise solution for the shape of a gravity field surrounding a spherical star that does not rotate. In fact, the solution included a description of what later came to be called a black hole. But even if there had been historic discussions of invisible stars, it took almost 50 years to start seriously studying something as bizarre as black holes. The name itself – black hole – first appeared at the end of the 1960s.

Schwarzschild's calculations showed that it was possible to determine a spherical surface, an event horizon, for every heavenly body. Time stops at the event horizon (for the external observer) and a black hole, once formed, remains forever hidden behind its event horizon. Inside it, spacetime is so bent that no light can escape. And, furthest in, hides an abyss with no bottom, a singularity in which density, according to the theory of relativity, approaches infinity, as does the curvature of spacetime. In this singularity, time comes to an end. However, the theory of relativity may be wrong; to establish what really happens inside a black hole requires a quantum theory for gravity and, as yet, no such theory exists.

The heavier the hole, the greater the event horizon – the area that delimits the hole from its surroundings. To form a black hole and disappear from our view, the Earth would need to be compressed to a radius of around nine millimetres, and the sun to about three kilometres.

Long before Einstein, scientists were speculating – purely theoretically – that massive stars could be transformed into extremely heavy objects. Now, with the help of the general theory of relativity, among other things, it was possible to calculate how this could happen. Towards the end of the life of a really massive star's life, one of around 10 solar masses or more, when its nuclear fuel is running out and the gas pressure outwards is gradually declining, that star has less energy for resisting its own, inwardly-directed gravity. A gravitational collapse becomes unavoidable. At its moment of death, the star explodes as a supernova and an extremely tightly compressed remnant is left behind – a neutron star or a black hole.

A neutron star can be just a few kilometres across but have a mass greater than the sun's. However, this only applies to neutron stars up to 2–3 solar masses. Large neutron stars cannot withstand gravity, which means it is impossible to resist further collapse – irrevocably leading to the formation of a black hole. At the end of the 1930s, the first calculation of this transformation from a massive star to a black hole was led by physicist Robert Oppenheimer, later the legendary leader of the Manhattan Project, which built the American atomic bomb.

Black holes were still regarded as speculative theoretical monstrosities, because most people believed that in reality nature would carefully shy away from them. This could also have been due to a misunderstanding, as it wasn't easy to order the passage of time in the various frames of reference: if one were to observe a star collapse into a black hole it would take an infinitely long time. This means that a black hole could never be formed, went the reasoning.

The explanation for this paradox is that everything depends on the frame of reference in which the calculations are carried out. From the star's perspective, its collapse would be completed in less than a millisecond if the star were a few times heavier than the sun. In the early 1960s, John Wheeler was one of a few leading researchers in the world who began to be interested in black holes, after long doubting their existence.

A breakthrough came with Roy Kerr's solutions to Einstein's notoriously complicated equations for what spacetime looks like around rotating stars and black holes. Almost fifty years after the general theory of relativity saw the light of day, Roy Kerr succeeded with something that nobody else had been able to do. So when he submitted his short article of 1½ pages, in July 1963, it was a real breakthrough.

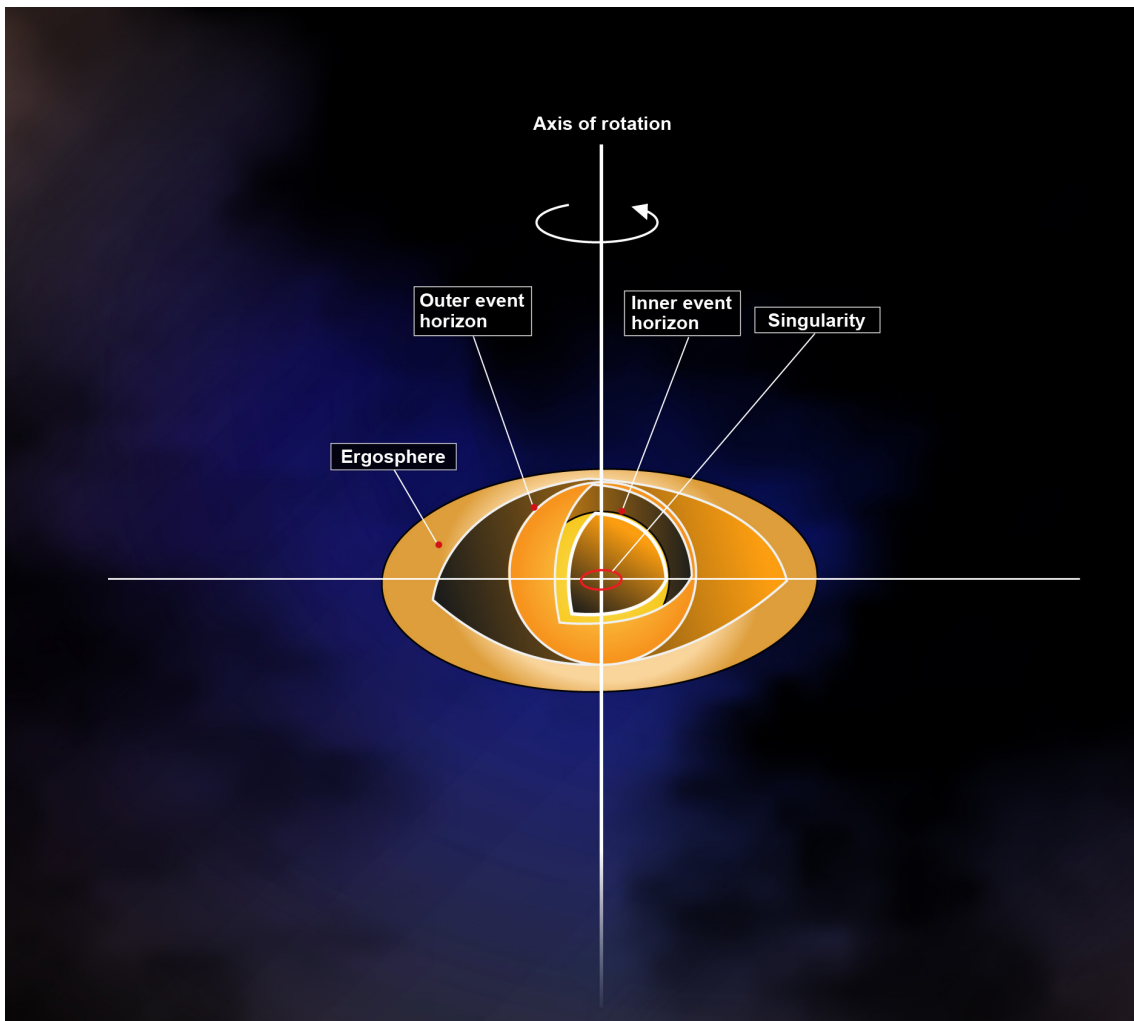
However, not many people realised what a landmark Kerr's achievement was. The previous Schwarzschild solution for stationary black holes was just an ideal image. It was now Kerr who came closest

to a real image of what actually happened in black holes, because almost all stars and black holes rotate. For example, our sun rotates once on its axis between 25 and 35 days.

Eventually, it was discovered that every black hole can be described using just two properties – its mass and its rotational speed. Whatever happened when a black hole was formed, the memory of the past is entirely hidden inside it. A black hole can thus appear to be a simple space object, but nothing could be more misleading, as it may be very complicated in its interior.

Kerr demonstrated that the rotation changes the black hole's surroundings. It is not just that the event horizon differs from Schwarzschild's, but two important boundaries are created around the black hole. Seen from the outside, there is first an outer horizon that is not completely spherical; it is flattened at the poles. Inside the outer horizon, an additional event horizon is formed, marking the area of no return. From the outside, the closer one comes to this outer horizon the slower time passes. Everything that passes this horizon is dragged, hopelessly, into the rotation of the black hole; even spacetime is twisted around it.

Outside these two event horizons is the ergosphere, a name that is linked to energy production (from the Greek *ergon* – work). Indeed, it is in the processes around and inside the ergosphere that the black hole's rotational energy drives the astonishingly strong radiation that can be seen throughout the universe. It is also from there that charged particles are shot out in each direction as



two narrow jets, travelling hundreds of thousands of light years out into space.

Ever since the mid-1970s, Roger Blandford has dedicated himself to – among other things – the issue of how this energy transformation takes place. Theoretical models are developed as new astronomical observations arrive. Telescopes on Earth and observations from satellites continually supply researchers with increasingly detailed images of what is happening around black holes.

The smaller black holes, which are around ten times heavier than the sun, are often found as part of a binary star, where the partner is an ordinary star. Around 25 such binary star systems are now known. The high-mass X-ray Cygnus X-1 in the Cygnus constellation has become the archetype of such binary systems, as it was the first to be discovered, in 1964. Gas from the black hole's neighbour star spills across it, spins around and forms an accretion disk. The friction in the disc makes the gas spiral in towards the edge of the black hole, but before it disappears entirely, the gas is heated so much that it emits powerful X-ray radiation. The luminous accretion discs are often followed around a black hole by a pair of hot gas flows, jets.

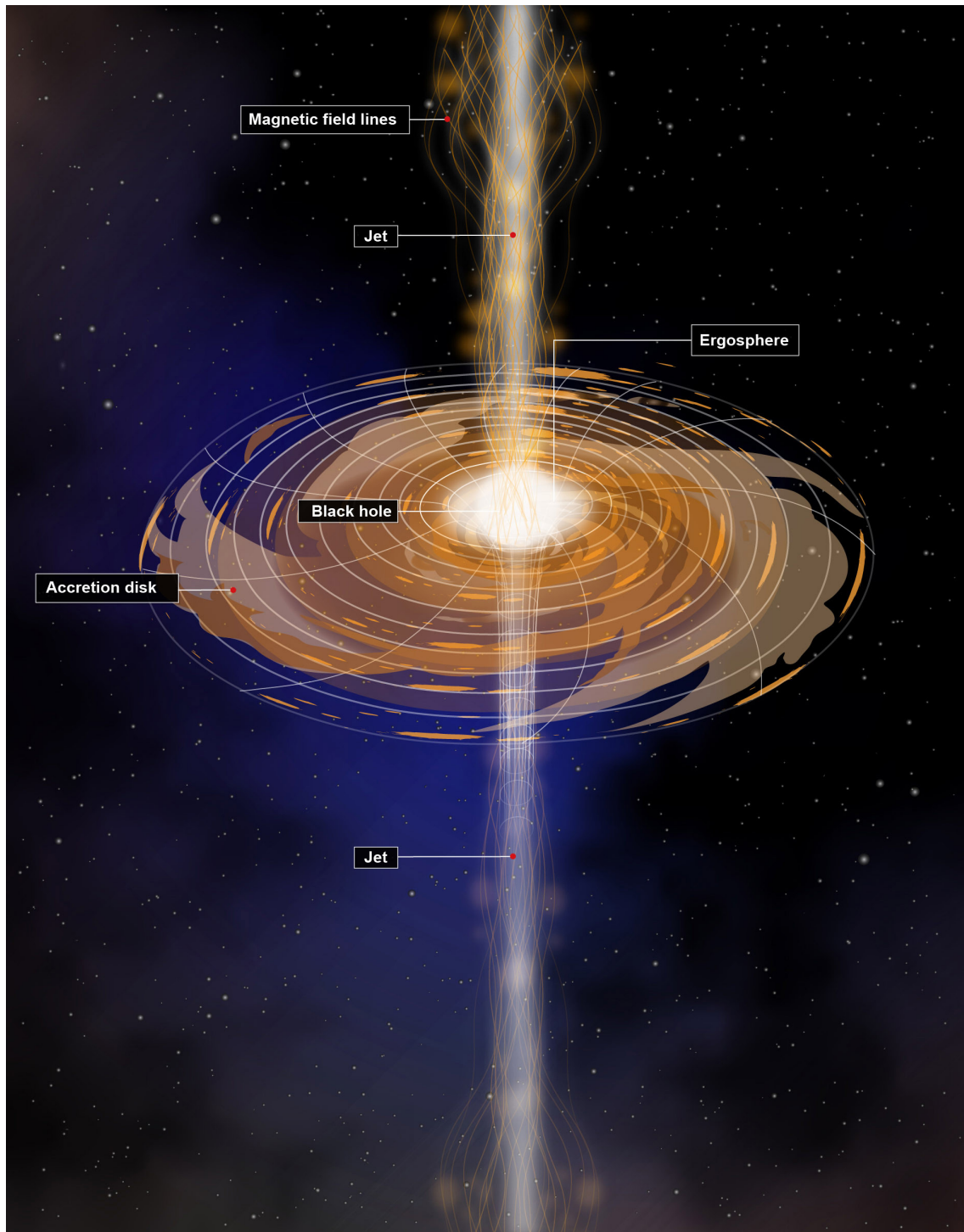
In 1963, a number of powerful but also mysterious sources of radio waves were discovered, such as the blinding 3C 273 in the Virgo constellation. It shines 4,000 billion times more brightly than the sun. This is far too strong to come from an ordinary star so it was named, like other similar objects, a quasistellar radio-source, quasar. In addition, the distance to the quasars was determined to be several billion light years from us, which means that they emitted their rays when the universe was young. The oldest now known quasar started radiating around a billion years after the big bang, almost 14 billion years ago.

Gigantic black holes are the only known energy source that can provide the quasars with adequate energy within the limited volume from which the radiation is emitted. With a mass from a few million to several billion solar masses, black holes are located in the centre of host galaxies that feed them with gas. Even if the galaxies themselves can be incredibly big, quasars often completely outshine them.

How is this enormous radiation energy created? How can a black hole send out two jets in opposite directions? Back in 1977, Roger Blandford and his colleagues were able to put forward a proposal for how this happens in the ergosphere of a rotating black hole. Now the models have been refined and are increasingly realistic.

The magnetic field is decisive here, in combination with fluid dynamics, the study of liquids and gases in motion. The gases that flow in, primarily hydrogen, get so hot from the friction that they glow and become radiant, while the heat also makes the hydrogen atoms decompose into positive atomic nuclei, protons, and negatively charged electrons. Their movements create a magnetic field that spins around the black hole's rotational axis. The lines of the magnetic field are woven into a spiral that conducts the electrically charged gas. The gas shoots out from the black hole in two opposite directions in the form of jets. These mostly consist of charged particles that cross space, thousands of light years away, at almost the speed of light.

The source of all of this power is the rotational energy of the black hole. These processes in the accretion disc are actually incredibly efficient. A rotating black hole can transform up to 40 per cent of the energy contained in material that falls into it, into radiation. This is many times more than is calculated for stationary black holes; these are only able to transform around six per cent of gravitational energy to radiation, while the core processes inside stars, such as the sun, only achieve up to



one per cent at the most.

All this work means that supermassive black holes lose energy so that their rotation slows down. Over time, the availability of fuel also dwindles in the quasars' host galaxies. After 10 to 100 million years, when the gases around it are becoming exhausted, the black hole goes out. In the youth of the universe there was much more gas available, which is why quasars then shone most brightly.

But it takes a long time for light to reach us, even if it travels at the greatest possible speed. The quasar light that we capture now was emitted long ago, when there were still abundant materials

available in the young days of the universe. It could also be that if the circular movement of a galaxy is disrupted, for example by coming too close to another galaxy, gas and stars are linked to the dark black hole at the centre so that the quasar is reignited, even if it's just for a while.

There is also a large supermassive black hole in the centre of our galaxy, the Milky Way – Sagittarius A*. It is smaller than the known giant quasars, but it is still estimated to weigh around four million solar masses. We are not exceptional, most galaxies have a black hole in their centres. Many of them are like our black hole – they sit there, quietly, only being recognisable when the trajectories of the stars around them are studied. Such studies of the Milky Way's black hole were rewarded with the Crafoord Prize in 2012.

No one nowadays doubts that there are many black holes in the universe. Some of them lead reserved lives in the centres of their galaxies, others are more lively and are found in the most luminous binary stars and the most powerful quasars. Altogether, black holes are estimated to emit as much as one-third of all the radiation in our universe. However, how they really work remains hidden, both literally and in the mind, because our knowledge of superdense materials and the most bent spacetime is still too inadequate.

THE LAUREATES

ROY KERR

Born 1934 in Kurow, New Zealand. Ph.D. 1959 at University of Cambridge, Great Britain. Emeritus Professor at University of Canterbury, New Zealand.

www.phys.canterbury.ac.nz/people/kerr.shtml

ROGER BLANDFORD

Born 1949 in Grantham, Great Britain. Ph.D. 1974 at University of Cambridge, Great Britain. Luke Blossom Professor in the School of Humanities and Sciences, Stanford University, CA, USA.

<https://physics.stanford.edu/people/faculty/roger-blandford>

LINKS AND FURTHER READING

More information about this year's prize is available at www.crafoordprize.se and the Royal Swedish Academy of Sciences' website, <http://kva.se/crafoordprize>

Books

Kip S. Thorne. 1994. *Black Holes and Time Warps: Einstein's Outrageous Legacy*. W.W. Norton & Company.
Susskind, L. 2008. *Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics*. Little, Brown.

Scientific articles

Begelman, M. och Rees, M. 2010. Gravity's Fatal Attraction: Black Holes in the Universe. *Cambridge University Press*.

Melia, F. 2009. Cracking the Einstein Code. Relativity and the Birth of Black Hole Physics. *University of Chicago Press*.

Editorial board:
Experts from The Royal Swedish Academy of Sciences
Text: Joanna Rose
Illustrations: Anna-Lena Lindqvist, Lindqvist Grafik & InfoDesign AB
Editor: Hans Reuterskiöld
©The Royal Swedish Academy of Sciences