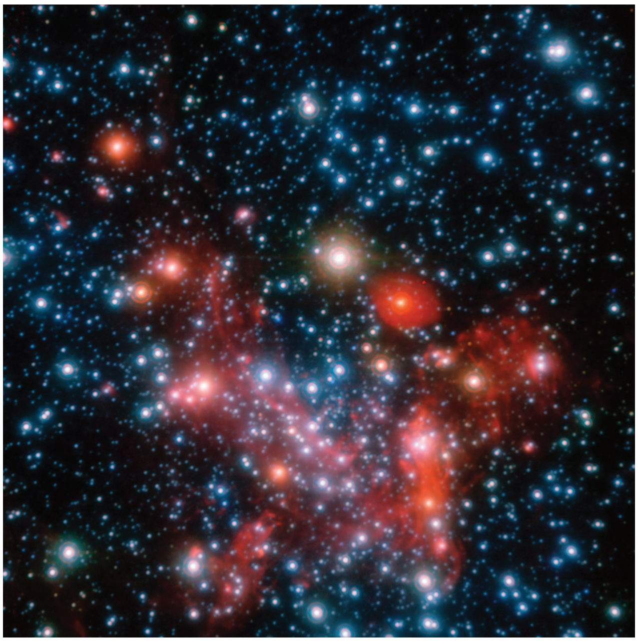
The dark heart of the Milky Way

Now it is proved: in the centre of our home galaxy, the Milky Way, dwells a monstrous black hole. This year's Crafoord Prize Laureates have found the most convincing evidence to date that supermassive black holes actually exist. For decades they tracked stars in the Galactic Centre of the Milky Way, and no better explanation can be found for what they saw. Guided by the stellar orbits, ***Reinhard Genzel*** *and* ***Andrea Ghez****, with their research groups, independently reached the same conclusions.*

What else would make the innermost stars in our galaxy revolve at such rapid speeds? Reinhard Genzel and Andrea Ghez, with their respective research teams, estimated that a mass of some four million solar masses forces these stars around in their orbits. And all this mass is compressed into an area smaller than our solar system. There is only one suspect: a supermassive black hole known today as Sagittarius A*. Any other explanation of what the astronomers saw would be even odder. Black holes are odd enough.



An image in infrared of the stars orbiting the Milky Way's central black hole, Sagittarius A*. The distance to the black hole is about 26 000 light years – the light we see today was sent away when the Earth still had full ice age. Photo: ESO/S. Gillessen et al.

Recent ideas about black holes are founded on Albert Einstein's theory of general relativity. The theory describes how matter warps space around itself. If huge amounts of matter assemble in the same place, the warping of space becomes infinite and a black hole forms. Everything that comes in the vicinity of a black hole vanishes into it.

At the core of every black hole resides a singularity. In mathematics, singularities arise when something is divided by zero: the answer is infinity. For physics, singularities remain an enigma. They imply that Einstein's theory is missing something essential in its description of reality. Today, no one knows what this may be.

One thing, however, is certain. The fate of anything that happens to fall into a black hole is sealed: it comes to an inevitable end in the death trap of the singularity. It is like a well without bottom: everything that falls into it is almost entirely annihilated. Not even light can get out. At the same time, the well has no volume – no extent.

But there is a distance associated with black holes. Referred to as the 'Schwarzschild radius' and also known as the 'event horizon', it describes a boundary around the black hole. Everything that comes within the boundary is pulled in, and the black hole obliterates almost all the traces.

All matter, if packed together sufficiently densely, can form a black hole. The greater the mass, the larger the Schwarzschild radius of the black hole becomes. For the Earth, it would mean being compressed to the size of a sugar cube before a black hole with the mass of the Earth formed, while a black hole with a solar mass would be characterized by a Schwarzschild radius of three kilometres. Reasoning in the opposite direction, this means that if the size of the Schwarzschild radius can be determined, the mass of the black hole can be worked out.

Scientists long believed that black holes were merely the stuff of fantasy. Although, already as early as in the 18th century, speculation arose about objects so dense that they did not even let any light escape. In 1939, Robert Oppenheimer, later renowned as the head of the Manhattan Project where the first atomic bomb was built, proposed, with his collaborators that singularities could form when extremely dense stars collapsed at the end of their life cycles.

The actual expression 'black hole' was coined as late as 1967 by John Wheeler, an American physicist. Like many other people in the 20th century, Wheeler was initially opposed to the idea of black holes. How, he asked, could the laws of physics lead to a violation of themselves? Later, he became one of the foremost proponents of the theory of gravity and its apocalyptic predictions. Nowadays, astronomers believe that they have detected signs that there really are black holes out there in space. But, as yet, not everyone is convinced.

The very smallest black holes of all could perforate space and, invisible as they are, might pose a real danger to us on Earth. More massive black holes may form when certain dense stars of more than 25 solar masses use up their nuclear fuel. What can happen then is that the star explodes as a supernova while at the same time its core collapses into a black hole of some three to 10 solar masses.

Then there are also the supermassive black holes, the most violent monsters in space, which can be as heavy as several billion solar masses. One of the largest behemoths of this kind is said to reside in the giant elliptical galaxy M87 in the Virgo constellation. This galaxy is 55 million light years away and thus one of our closest gigantic neighbours. Supermassive black holes may, it is believed nowadays, be found in the majority of large galaxies.

The largest of them make up the most active nuclei of galaxies – the quasars – that are among the brightest objects in the universe. Roughly a tenth of the known galaxies contain an active nucleus. The origin of the quasar's powerful radiation is assumed to lie in gas that whirls around the black hole before disappearing into it forever. The closer it is to the central hole, the faster the gas moves and the stronger the radiation that is emitted. This radiation indicates that it is in fact a black hole that is powering these phenomena.

Sagittarius A* in the Milky Way belongs to the family of supermassive black holes. But it is only the size of four million solar masses and, as such, a fairly modest hole to be included in the supermassive category. So how, if invisible, can it be found? The only way, as with all the other black holes, is to examine the impact it exerts on its surroundings.

The first speculations about a black hole hidden in the centre of our galaxy appeared more than 40 years ago. It was predicted theoretically by several scientists, including the British astronomer Martin Rees (Crafoord Prize Laureate in 2005). He proposed that a black hole is concealed in the innermost core not only of the Milky Way but of almost every major galaxy as well.

And the American astronomer Eric Becklin discovered strong infrared emission from very many stars in a source of radio wave radiation in the midst of the Milky Way. It was named Sagittarius A* after the constellation where the Galactic Centre is located. However, our view of the Milky Way is effectively obscured by the vast interstellar dust clouds. To see into the heart of our galaxy requires wavelengths longer than those of visible light. Infrared radiation was the solution and, from his telescope on Mount Wilson in California, Becklin was able to observe that the more closely he looked at the radio source, the more stars he found clustered there. What was the source of the gravity that pulled the stars in towards the Galactic Centre?

Charles Townes, a Nobel Prize Laureate and pioneer in astronomical studies in infrared, was another of those scientists who suspected the existence of a black hole in Sagittarius A*. Townes and his group saw interstellar gas circulating in the Sagittarius A* region. Perhaps the attraction from a black hole was the cause, they thought. At the time, not many people would agree.

It was not until the 1990s that larger telescopes with better cameras permitted methodical studies of Sagittarius A*. This year's Laureates – Reinhard Genzel, who received his inspiration from collaboration with Townes, and Andrea Ghez, who joined UCLA (University of California Los Angeles) where Becklin, too, was working – each started their own projects of looking through the dust clouds straight into the heart of the Milky Way. With their research groups, they developed and refined their techniques, built suitable instruments and undertook long-term projects. Competition is an intrinsic feature of the scientific career, but it also helped that their observations matched each other. Nonetheless, it was to be many years before they succeeded in convincing the world that the black Sagittarius A* was not just a bizarre invention. These days, as we have already seen, the black hole of our own galaxy is the most convincing one found to date.

Only the world's most powerful telescope sufficed to investigate the most distant stars. 'The bigger, the better' very much applies in astronomy: with a doubling of the size of a telescope mirror, stars only a sixteenth as bright become visible. Moreover, for the first time for 100 years, Europe has succeeded in catching up with the USA in the building of large telescopes in the 21st century. This has enabled European astronomers to compete with the Americans.

Reinhard Genzel and his research team made their discoveries at the European Southern Observatory (ESO), including the Very Large Telescope (VLT), situated just over 2600 m.a.s.l. on Cerro Paranal in the Atacama Desert, Chile. The VLT consists of four giant telescopes with mirrors of 8.2 meters in diameter. These may be interconnected to the Very Large Telescope Interferometer (VLTI) which can see objects 25 times smaller than with the individual telescopes.
Andrea Ghez and her group have worked with the Keck telescopes at 4600 meters elevation on Mount Mauna Lea, Hawaii. These twin telescopes have mirrors of 10 meters in diameter and are among the largest in the world. The mirrors are composed by 36 hexagonal segments. The optical beam can be adjusted for atmospheric disturbances up to 1000 times per second!
PHOTOS: *VLT*: ESO/Y. BELETSKY. *KECK*: RICK PETERSON / W.M. KECK OBSERVATORY.

Reinhard Genzel started with the New Technology Telescope that the European Southern Observatory (ESO) built at La Silla in Chile. This was the predecessor of the Very Large Telescope (VLT), which were twice as big, at the Paranal Observatory (also in Chile), to which Genzel moved in due course. The four individual telescopes of VLT have the world's largest monolithic mirrors, molded in one piece, measuring more than 8 metres in diameter.

Andrea Ghez and her research colleagues used one of the twin telescopes of Keck Observatory on the summit of Mauna Kea in Hawaii. With their mirrors of nearly 10 metres in diameter, these are among the world's largest telescopes today. Every mirror resembles a honeycomb, comprising 36 hexagonal segments that can be adjusted separately to focus the starlight better.

But to be able to distinguish the stars from one another in the distant stellar crowd calls for more than just giant eyes gazing out into space. However large telescopes are there is always a limit to how visible the small details can be. This is a result of living, as we do, at the bottom of a sea of air nearly 100 kilometres deep. Large air bubbles above the telescope, colder or warmer than the surroundings, serve as lenses that bend the light on its way down to the telescope mirror, deforming the light wave. This is why the stars twinkle and this is why the images are blurred.

'Adaptive optics', as it is called, seek to correct for this refraction of light waves. The telescope is equipped with a thin extra mirror that is constantly reshaped as the computer senses an incoming light wave from a real or artificial reference star. Five hundred times a second, the mirror is adjusted by being deformed in different directions with a precision of one-millionth of a metre.

For decades Reinhard Genzel, Andrea Ghez and their research colleagues tracked the motions of their stars in an attempt to achieve an optimal model of their orbits. This was the only way of establishing the characteristics of the black hole that, with its gravitational attraction, steers the stars as they move around it.

In the meantime, Ghez and Genzel successively developed and refined the technology further. With ever larger digital light sensors, charge-coupled devices (CCDs), and improved adaptive optics, the accuracy increased more than thousand fold. This meant that they were now able to see stars only one-thousandth as bright. Astronomers could also determine the positions of stars with an accuracy of 30 thousandths of an arcsecond. It was like being able to see a €1 coin at a distance of 30 kilometres.

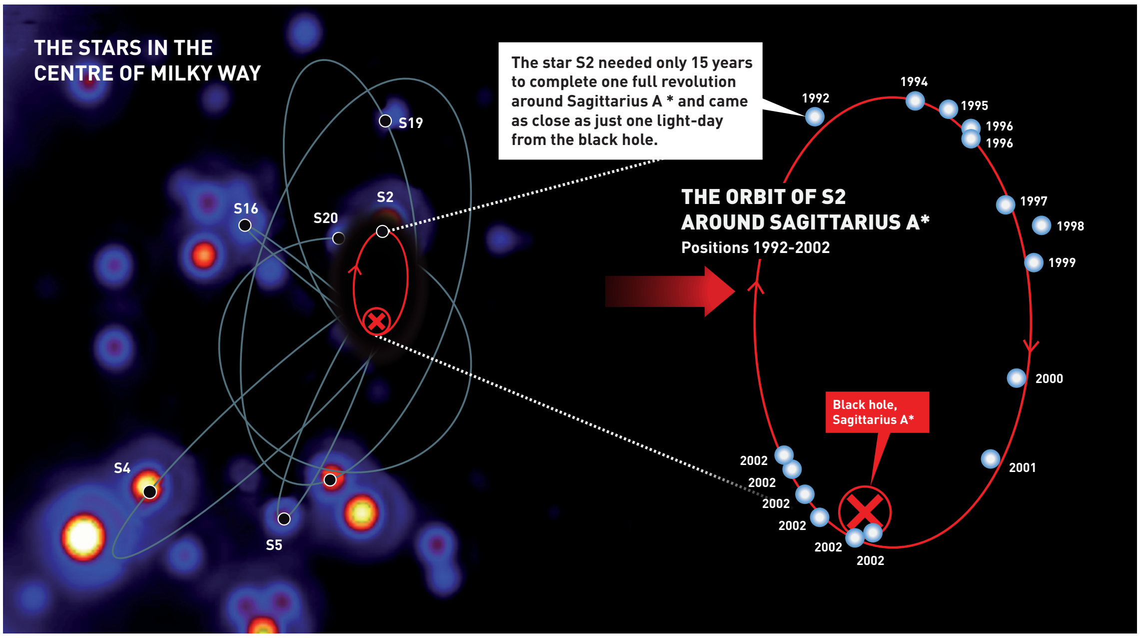
The technology is constantly improving. Now a new instrument is being built for the VLT. It will combine the light from all four telescopes. When it is finished in two to three years' time, the astronomers will be able to establish the positions of the stars a million times more accurately – down to 10 millionths of an arcsecond. These stars move ten times closer to the black hole than the stars seen today, with speeds up to 10% of the speed of light (i.e. 30,000 km/s). Since the stars come closer to the black hole it will be possible to directly study effects predicted by the theory of general relativity.

So far, applying the well established laws of motion worked out by Kepler in the 17th century was enough to map the orbits of the 28 stars that shone most brightly in the crowded innermost region of our galaxy. The stellar motions are most random within a radius of one light month from the Galactic Centre. There, like a swarm of bees, the stars perform a fairly disarrayed dance. Outside this circle, six of the stars studied were found to be orbiting in an elliptical disc around the centre, in more orderly motions.

One of the stars, S2, completed a full orbit around the Galactic Centre in 15 years. This was a record short time. Previously known stars that came close to the central point of the galaxy had 500-year long orbits. For us and the Sun, it takes roughly 230 million years to revolve all the way round the middle of the Milky Way. The last time we were here, at the same position in our Galaxy as now, dinosaurs were walking around on our planet. We are a reassuring 26,000 light years away from the black hole. This means that we see what was happening there 26,000 years ago. That is how long it has taken for the light to reach us.

With the new stellar orbits, the mass of Sagittarius A* can be calculated much better than before. But S2 is still as much as 1,000 radii outside the inner circle when it reaches the point closest to the Schwarzschild radius. And S2 is then at a distance of just one light day from the black hole – just a few times further away than the planet Neptune is from the Sun (50 billion kilometres). Never before has anyone reached so far in towards the heart of Milky Way.

How large, then, is the black hole? The radio source Sagittarius A* has been studied with several radio telescopes linked together all over the globe with so called 'very long base-line interferometry', VLBI. It seems to reach approximately as far as the average distance between the Earth and the Sun. There are reasons for assuming that the radiation from the radio source is emitted by gas located around the massive object in the centre.



Sagittarius A* – the supermassive black hole of our own galaxy, the Milky Way, forces the stars to move around it. For decades Reinhard Genzel, Andrea Ghez and their research colleagues tracked the motions of the stars in an attempt to achieve an optimal model of their orbits. One of the stars, S2, completed a full orbit around the Galactic Centre in 15 years.

Along with the stellar orbits measured, the measurements thus indicate a tentative upper limit for the size of this supermassive phenomenon. They show that the object is undoubtedly no larger than our Solar System and probably considerably smaller. This makes it highly probable that it truly is a black hole. In fact, this seems to be the most reliable evidence to date that such objects really exist. In the future it will, perhaps, even be possible to use linked radio telescopes, in short radio wavelengths, to get a glimpse of the black hole itself as it is silhouetted against the gas behind.

Several unexpected discoveries accompanied the stellar observations. One was that the stars that happened to pass close to Sagittarius A* were shot away at astonishing speeds of more than 15 million kilometres an hour.

Another unexpected discovery was that stars that came close to the black hole were not necessarily destroyed. On the contrary, some perhaps even formed there. Their hot surfaces testify to this: the hotter a star, the younger it is said to be. At the same time, the region in proximity to a black hole is a fairly unlikely environment to serve as the stars' incubator.

Another surprise was more or less regular outbursts of infrared light. These outbursts take place several times a day and last a few tens of minutes. Presumably they come from the immediate vicinity of the black hole – perhaps just 10 light minutes from it. The outbursts may be a sign that the hole is rotating. Time will tell. So, too, will it answer numerous other questions that are being asked now when the existence of the black hole has finally been established?

What is this great monster doing right inside the Milky Way? How is it affecting its surroundings and us? Has the black hole been there ever since the early days of the universe, when our galaxy began to take shape, about a billion years after the Big Bang? Or did the galaxy come first and the black hole later?

One possibility is that black holes and their host galaxies determine one another's characteristic features. In this case, these dark tools of destruction could be crucial for the emergence of something new. The Milky Way and Sagittarius A* are then helplessly tethered together, in life and in death.

One thing is now certain. Our closest supermassive black hole resides in the middle of our own galaxy, while the next presumably lies a hundred times further away in the Andromeda galaxy. So with Sagittarius A*, the astronomers can now better investigate gravity and explore the limits of the theory of general relativity. Perhaps, as some physicists have speculated, the black holes form a tunnel – an escape route towards a completely different universe on the other side of the all-devouring blackness, governed by completely different physical laws. No one knows though how this would work.

LINKS AND FURTHER READING

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

Popular-scientific articles

Closing In on the Milky Way's Central Black Hole, (2008) by John Matson, *Scientific American Magazine*, December 2008: *www.scientificamerican.com/article.cfm?id=milky-way-black-hole*

How Puzzling Stars Formed near Galactic Black Hole (2008) by JR Minkel, *Scientific American Magazine*, August 2008: *www.scientificamerican.com/article.cfm?id=how-stars-formed-near-black-hole*

Scientific articles

S. Gillessen, S. *et al.* (2012) A gas cloud on its way towards the supermassive black hole at the Galactic Centre, *Nature* 481:51–54.

Genzel, R., Eisenhauer, F. and Gillessen, S. (2010) The Galactic Centre massive black hole and nuclear star cluster, *Review of Modern Physics* 82:3121–3195.

Ghez, A.M. *et al.* (2008) Measuring distance and properties of the Milky Way's central supermassive black hole with stellar orbits, *The Astrophysical Journal* 689:1044–1062.

Genzel, R. (2007) The power of new experimental techniques in astronomy: zooming in on the black hole in the centre of the Milky Way, *Highlights of Astronomy* 14:63–76.

Schödel, R. *et al.* (2002) A star in a 15.2-year orbit around the supermassive black hole in the centre of the Milky Way, *Nature* 419: 694–696.

Ghez, A. *et al.* (2000) The acceleration of stars orbiting the Milky Way's central black hole, *Nature* 407:349–351.

Websites

TED talk by **Andrea Ghez**: *www.ted.com/talks/andrea_ghez_the_hunt_for_a_supermassive_black_hole.html*

Talk by **Reinhard Genzel**: *www.youtube.com/watch?v=ZDxFjq-scvU*

Lecture by **Andrea Ghez**: Stellar Orbits at the Galactic Center: Opportunities and Challenges: *www.cfa.harvard.edu/events/2010/dyn/videos/Ghez.mov*

Lecture by **Reinhard Genzel**: Observed Dynamics of S Stars: *www.cfa.harvard.edu/events/2010/dyn/videos/Genzel.mov*

THE LAUREATES

REINHARD GENZEL

Max-Planck-Institut für extraterrestrische Physik, Garching, Germany

German citizen. Born 1952 in Bad Homburg vor der Höhe, Germany. Ph.D. 1978 at Universität Bonn, Germany. Professor at University of California, Berkeley, CA, USA and Scientific Director of Max-Planck-Institut für extraterrestrische Physik, Garching, Germany.

www.mpg.de/463069/extraterrestrische_physik_wissM1

ANDREA GHEZ

University of California, Los Angeles, CA, USA

American citizen. Born 1965 in New York City, NY, USA. Ph.D. 1992 at the California Institute of Technology, CA, USA. Professor at the University of California, Los Angeles, CA, USA.

www.astro.ucla.edu/~ghez/

Experts of the Crafoord Prize Committee for Astronomy: Bengt Gustafsson, Claes Fransson and Arne Ardeberg (Chair)
Text: Joanna Rose
Illustrations: Johan Jarnestad/Swedish Graphics
Editor: Erik Huss