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THE HEART OF DARKNESS

THE SUPERMASSIVE BLACK HOLES THAT LIE AT THE CENTRE OF EVERY LARGE GALAXY ARE FULL OF MYSTERIES. BUT ASTRONOMERS ARE FINALLY GETTING A CLEAR LOOK.

Many of the astronomers and physicists invited to the meeting feared for their safety. Others felt that the event should be cancelled outright. To hold a conference in Dallas, Texas, only weeks after US President John F. Kennedy had been assassinated there — it just seemed disrespectful.

In the end, the first Texas Symposium on Relativistic Astrophysics went ahead as scheduled, starting on 16 December 1963, and most of the invited scientists did go — after the mayor of Dallas sent them a telegram urging their attendance. But the shadow cast by Kennedy's death added to the already surreal mood as they grappled with a phenomenon that seemed unfathomable.

That year, observers had discovered that a collection of mysterious 'quasi-stellar' objects, dubbed quasars, were not just oddball versions of ordinary stars. They were cosmically distant, glowing with radiation that had travelled for billions of years to reach Earth. They were prodigiously bright, able to outshine 100 galaxies containing billions of normal stars. And they were astonishingly small for such bright objects — no bigger than our own Solar System. The presence of so much energy in so small a volume would bend space-time, as described by Albert Einstein's general theory of relativity, and might even cause the matter there to collapse into a gigantic black hole: an exotic possibility that at the time seemed like pure science fiction.

"Quasars really changed everything," says Michael Turner, a cosmologist at the University of Chicago, Illinois, who gave a speech commemorating the 50th anniversary of that inaugural meeting last month at the 27th Texas symposium, again in Dallas. Einstein's theory, which until the 1960s had been considered a niche idea with little to do with practical astronomy, was pushed to the fore. "The floodgates had opened," says Turner: observations soon proved that the Universe was stranger and more violent than astronomers had ever imagined. Explosions and eruptions were commonplace. And Solar System-sized black holes with masses measured in millions or billions of Suns turned out to lie not just inside quasars, but at the centre of every large galaxy in the cosmos — including our own.

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As last month's symposium made clear, giant black holes still pose many puzzles, ranging from how they produce and release enormous amounts of energy to how they grew rapidly in the early Universe. Researchers are now starting to glean important clues from instruments including NASA's Nuclear Spectroscopic Telescope Array (NuSTAR), which was launched in mid-2012 as the first spacecraft dedicated to studying these objects. And this year astronomers will get a rare chance to study the eating habits of the black hole at the centre of our own Galaxy, when it feasts on a cloud of gas set to stray too close to its gravitational trap.

The basics of black holes' energy production are now well established (see 'Accretion power'). Stars, gas and dust moving through the core of a galaxy get pulled in and compressed by the black hole's gravity, growing hotter and hotter as they spiral inwards, forming an accretion disk. By the time the superheated material approaches a spinning black hole's event horizon — the point of no return, beyond which even light cannot escape — up to 42% of its mass has been converted to energy.

That energy emerges in the form of heat, light and, often, jets of high-speed particles that rocket in opposite directions perpendicular to the accretion disk. These jets can extend for thousands or even millions of parsecs. If one happens to be aimed directly at Earth, astronomers see the object as a quasar. If the jets point sideways instead, astronomers see the object as a galaxy with a very bright 'active galactic nucleus'. And if the black hole's food supply is somehow restricted, so that it accretes very little gas and dust, the object is effectively invisible.

Within that general picture, however, the details can be perplexing. Starting in 2006, for example, several sky surveys began to indicate that jets were emerging from their parent black holes with three times more energy than was contained in the original fuel, producing what seemed to be a gross violation of the conservation of energy.

MAGNETIC BOOST

At last month's conference, physicist Roger Blandford of Stanford University in California described a possible solution based on simulations of jet formation[1,2]. He and his colleagues imagine a rapidly spinning black hole with a strong magnetic field, properties that are difficult to detect directly but are theoretically plausible. The lines of the magnetic field are assumed to go out to great distances, threading through the accretion disk like stiff wires and dragging the disk's gas along with them as they rotate. The simulations show that under the right circumstances, the magnetic field can transfer enough of the black hole's rotational energy into the disk to power the anomalously strong jets.

NuSTAR recently made the first definitive measurement of a supermassive black hole, revealing that it is spinning very fast indeed. This work was prompted by simulations that suggested a way to gauge the rotation of a black hole using X-rays emitted from near the event horizon. Rapidly spinning black holes should pull material closer to that horizon and subject it to intense gravity that would shift escaping X-rays to redder, less energetic wavelengths.

Although astronomers had seen hints of this gravitational imprint with earlier X-ray telescopes, they could not rule out the possibility that gas clouds were blanketing the accretion disk and confounding the result. But NuSTAR is sensitive to X-rays that have ten times higher energies than its predecessors could measure, and that punch through any such clouds. At the December meeting, NuSTAR chief scientist Fiona Harrison, an astronomer at the California Institute of Technology in Pasadena, reported seeing a clear signal of red-shifted X-rays from a relatively nearby spiral galaxy known as NGC 1365. Taken together with measurements at lower X-ray energies made by the European Space Agency's XMM-Newton satellite, the observations showed that NGC 1365's central black hole was spinning at nearly the maximum rate allowed by Einstein's theory[3]. It had enough rotational energy to tear apart its entire home galaxy, if that energy could somehow be unleashed.

NGC 1365 may not be typical. But as NuSTAR and future spacecraft begin to measure black-hole spins further back in time, Harrison says,

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ACCRETION POWER

At the centre of every large galaxy lives a giant black hole that swallows gas or dust clouds that stray too close. As matter spirals inwards, it is compressed into an accretion disk. By the time it falls into the black hole, the matter is so hot that much of its mass is converted to energy, which emerges as heat, light and jets of high-energy particles.

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the data may shed light on another conundrum. Astronomers have found quasars that are powered by billion-solar-mass black holes dating back to some 750 million years after the Big Bang, when the Universe was less than 6% of its current age. How did they get so big so fast?

A black hole's spin rate may be a kind of fossil trace of its formation, Harrison explains. Supermassive black holes are too big to have been formed by a star collapsing under its own gravity, like stellar-mass black holes. If the giant black holes were built from many smaller ones, each merger would have brought together black holes spinning in random directions. After millions or billions of years of such collisions, the full-grown beast would have a net spin close to zero. But if the giant black hole had been built by the merger of just a few medium-sized objects, the growth could have been quicker, the spins would not necessarily have cancelled one another out, and the net rotation could be quite high.

The near-maximum spin of the black hole in NGC 1365 suggests that at least some supermassive black holes grew through rapid mergers — although that still leaves the question of where the original medium-sized black holes came from.

FAST SPIN, SLOW GROWTH

Yet high spin could be a problem for black-hole growth in the early Universe, says Avi Loeb of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts. A rapidly rotating black hole tends to drag the inner edge of the accretion disk along with it, pulling it inwards, so the infalling matter has to trace out a longer, slower spiral to reach the event horizon than it would if the black hole were spinning slowly. And that provides more time for its mass to be converted into radiation instead of adding to the hole's mass.

It is conceivable that strong magnetic fields came to the rescue, says Loeb. By transferring the black hole's rotational energy to the outer disk, they could quickly slow its spin, allow more matter to dive inwards and help the earliest black holes to pack on mass. If that is so, then future measurements will show that supermassive black holes have relatively modest spins.

But Loeb's favourite model for how black holes could grow in a hurry involves episodes in which the monster gorges itself on a stream of material so dense and opaque that photons do not have enough time to leak out before the gas makes its final plunge. The radiation is carried inwards instead of escaping, and the black hole swallows its energy as extra mass[4].

Sometimes, a strong magnetic field can stunt a black hole, rather than helping it to grow. That could be what is happening to Earth's closest giant black hole, Sagittarius A*, which lies just 8,300 parsecs from Earth at the heart of the Milky Way. As such objects go, our local specimen is on the small side, with a mass of only four million Suns. And its emissions are minimal.

The question is, why? It may simply be that there is not much gas and dust in the Milky Way's centre for the black hole to swallow. Or maybe something else is at work, says Mitchell Begelman, an astrophysicist at the University of Colorado Boulder. "There is a lot of interesting speculation that some accretion flows are 'magnetically arrested,'" he says.

Last year, for example, NuSTAR discovered a magnetar — a highly magnetized neutron star — in an orbit close enough to Sagittarius A* for astronomers to use it to probe the black hole's magnetic field. A close examination of the magnetar's radio emissions shows that the magnetic field surrounding Sagittarius A* is both sizable and highly ordered[5] — perhaps enough to block the black hole's food supply and put it on a near-starvation diet.

Our black hole does occasionally get a little nourishment. Observers are hoping to watch what happens this March, when a distended object called G2 is predicted to come dangerously close to Sagittarius A*. The object, either a gas cloud or a star with a distended gaseous envelope, will be torn apart by the black hole's gravitational tidal forces. If it is gas, the resulting fireworks could be spectacular. But if G2 is a star, the chances of fireworks will be slimmer: it will keep a firmer grip on the gas and less material will fall in, says Andrea Ghez, an astronomer at the University of California, Los Angeles (see *Nature* **495,** 296–298; 2013).

AS SUPERMASSIVE BLACK HOLES GO, THE ONE IN THE MILKY WAY IS ON THE SMALL SIDE.

Either way, astronomers should get a better understanding of what really happens when something falls into a giant black hole. And they may well have a preview in the next few months. In observations unveiled at the Texas meeting, NuSTAR showed that the neighbourhood of Sagittarius A* contains an assortment of small, stellar-sized black holes and neutron stars.

"It's a rare treat that we've been given," says astrophysicist Zoltán Haiman of Columbia University in New York City, who has helped to carry out simulations which suggest that G2's fateful journey may lead to a collision with one of the small black holes[6].

Sagittarius A* promises even more excitement as astronomers gain new observational tools. Over the next few years, all 64 of the radio dishes from the Atacama Large Millimeter/submillimeter Array in northern Chile are expected to join other radio telescopes around the world to create an Earth-sized network. This combination could get an ultra-high-resolution snapshot of how the black hole bends radiation from objects on its far side into a thin ring, or shadow, around Sagittarius A*. Everyone expects the shape of the shadow to conform to the predictions of Einstein's theory. But if it doesn't — if general relativity does not correctly describe space-time around a black hole — the network could offer crucial clues about what theory should replace it.

"That's the big-picture question," says Jonathan McKinney, a physicist at the University of Maryland in College Park. Fifty years after the first Texas symposium, "everyone wants to know if Einstein was right". ■

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