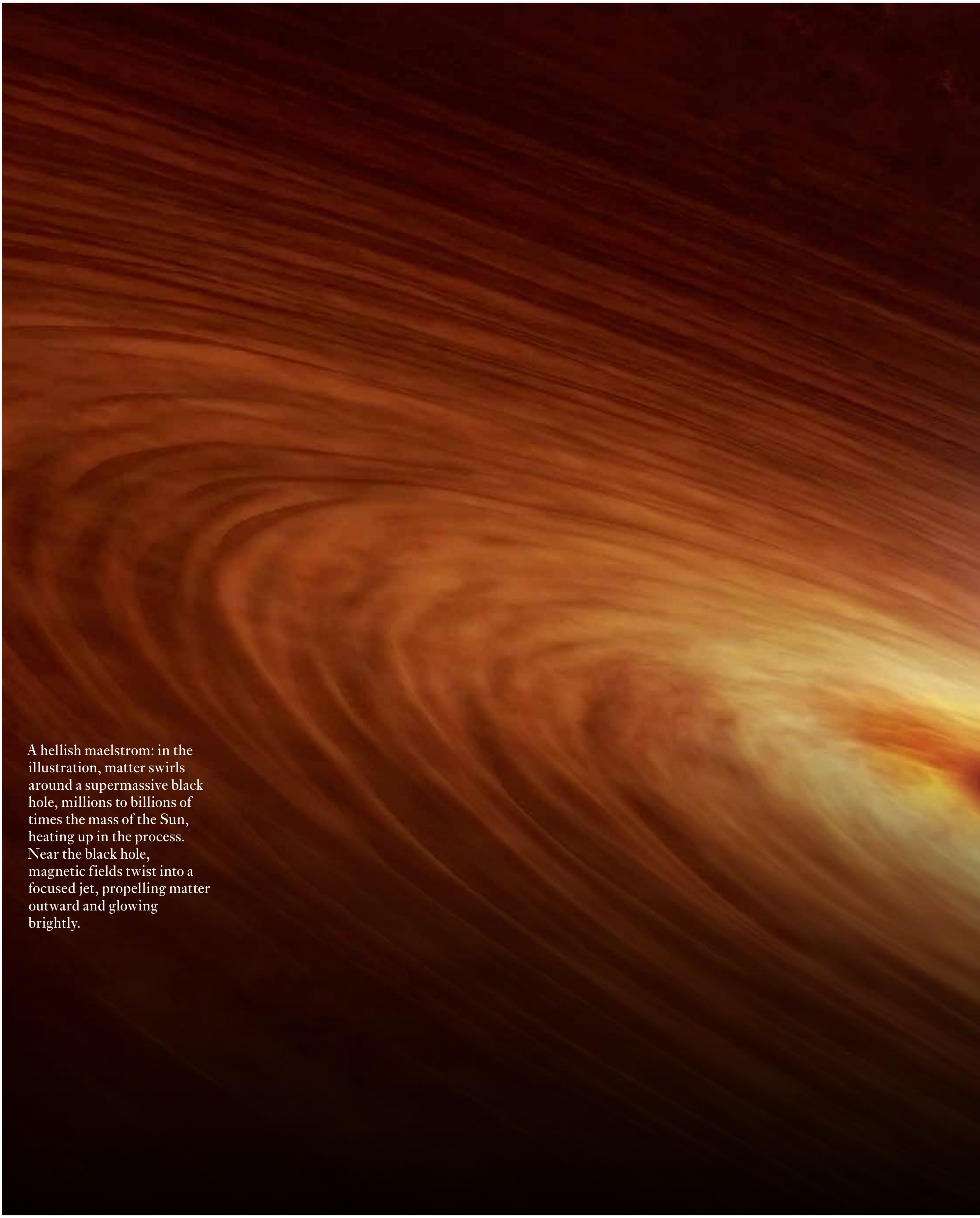
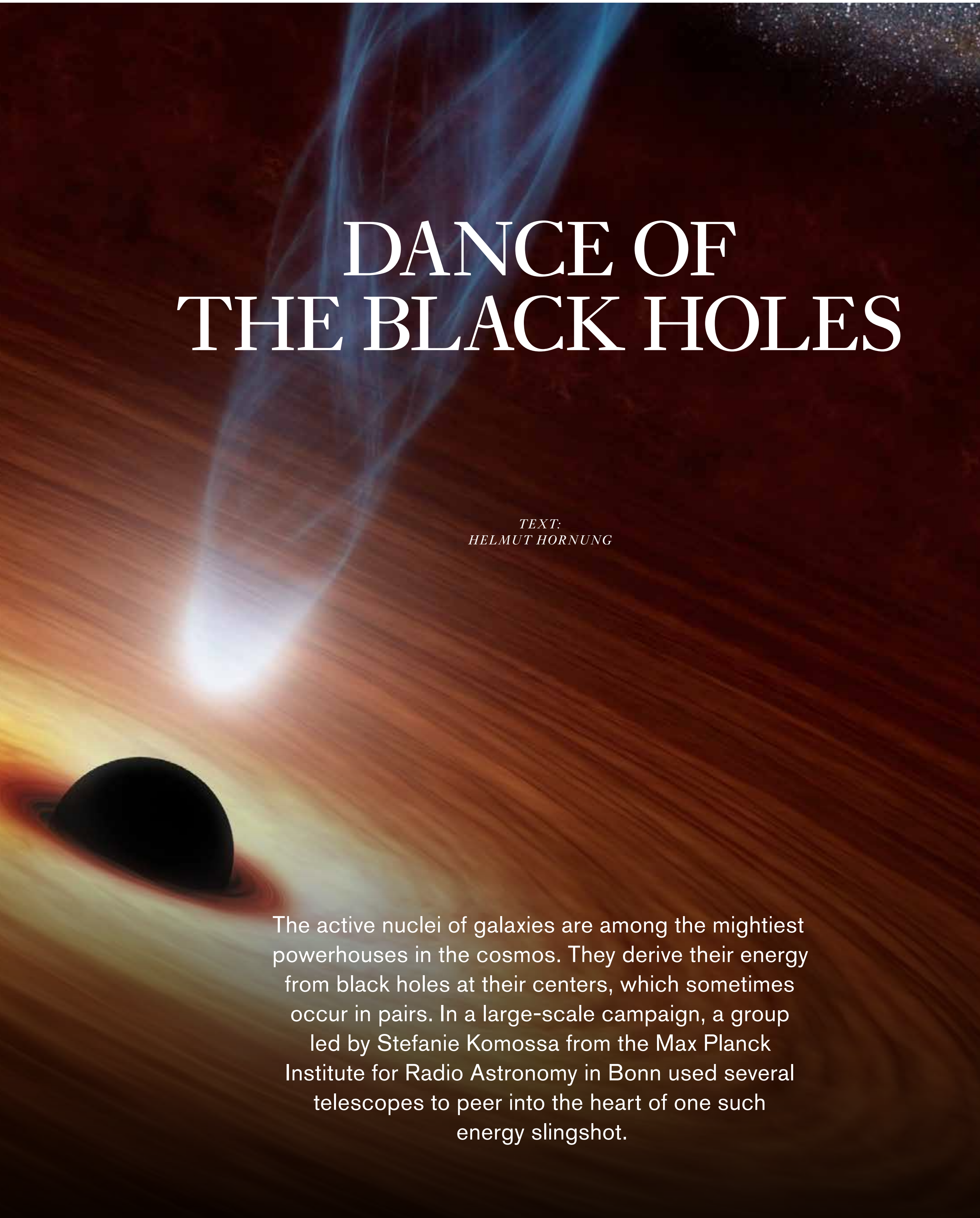


A hellish maelstrom: in the illustration, matter swirls around a supermassive black hole, millions to billions of times the mass of the Sun, heating up in the process. Near the black hole, magnetic fields twist into a focused jet, propelling matter outward and glowing brightly.

PHOTO: NASA/JPL-CALTECH



DANCE OF THE BLACK HOLES

TEXT: HELMUT HORNUNG

The active nuclei of galaxies are among the mightiest powerhouses in the cosmos. They derive their energy from black holes at their centers, which sometimes occur in pairs. In a large-scale campaign, a group led by Stefanie Komossa from the Max Planck Institute for Radio Astronomy in Bonn used several telescopes to peer into the heart of one such energy slingshot.

Lacerta is an inconspicuous constellation in the northern sky that few people ever get to see. It was in this constellation that Cuno Hoffmeister discovered a faintly glowing dot on a photographic plate in 1929, flickering with no discernible rhythm. The astronomer at the Sonneberg Observatory in Thuringia specialized in such variables, i.e., stars whose brightness varies more or less periodically. Thus, the object became known as BL Lacertae (Latin for lizard) in Hoffmeister's catalog and remained unnoticed for decades.

Mysterious Torches in the Sky

The story of BL Lacertae – BL Lac for short – is closely linked to the rise of a new technique: radio astronomy. Prior to 1940, researchers had only observed in the optical spectral range. In the 1940s they began to scan the universe with large antennas. Over time, they discovered a great number of cosmic radio sources. Some of them had the same position in the sky as previously unexplored points of light recorded in star catalogs. One such point of light was object 3C 273. Photographed with conventional telescopes in visible light, it appeared as a star-like point with an elongated appendage. What was behind it? The surprise grew when the light from this "radio star" was split into a small rainbow. Such astronomical spectra usually contain characteristic lines that indicate chemical elements. These fingerprints were also present in the spectrum of 3C 273, but they could not be attributed to any known substances.

The mystery was solved in 1963 by the Dutch astronomer Maarten Schmidt: the lines do belong to a chemical element, namely, hydrogen. However, they are not in the usual position, but shifted towards the red range of the spectrum, indicating longer wavelengths. That means the object must be moving away from Earth. For 3C 273, an impressive escape velocity of 45,000 kilometers per second was calculated – far too fast for a star to be moving within our galaxy. The observed effect can be explained by cosmological redshift. As the entire universe expands, galaxies move like raisins in rising dough. In other words, it is space itself that is expanding. This elongates the waves of a distant source, shifting its light into the red range. Maarten Schmidt calculated a distance of no less than two and a half billion light-years for the mysterious light point 3C 273. This means that the object cannot be a normal star, because to shine so brightly at such a distance, its luminosity would have to be equivalent to that of an entire galaxy with its billions of suns. Somewhat presciently, objects like 3C 273 and similar radio stars were already called "quasi-stellar objects" before Schmidt's discovery, from which the term "quasar" was derived.

Through further observations, an increasing number of radio stars were identified as quasars. In 1968 it was shown that the BL Lacertae light point discovered by Cuno Hoffmeister was identical to the radio source VRO 42.22.01. Photographs eventually revealed a faint nebular patch surrounding the "star." Spectra were recorded, allowing conclusions to be drawn about the nature of the nebula. It had to be a massive Milky Way system, with BL Lacertae at its center. Such an active galactic nucleus emits an enormous amount of energy in a relatively small space. But BL Lac shines even brighter than most quasars and also shows more pronounced variations in brightness. From a neologism combining the words BL Lacertae and quasar, such galactic nuclei are called blazars.

But what is the driving force behind these cosmic powerhouses? Astronomers are convinced that massive black holes reside at the cores of most galaxies. "These gravity traps are particularly active in the hearts of quasars and blazars," says Stefanie Komossa of the Max Planck Institute for Radio Astronomy in Bonn. Because of their strong gravitational pull, a considerable amount of matter accumulates around them. This gaseous ma-

Not a star, but a galaxy: the Hubble Space Telescope captured the quasar 3C 273, along with a jet that appears as a faint line above the central bright spot.

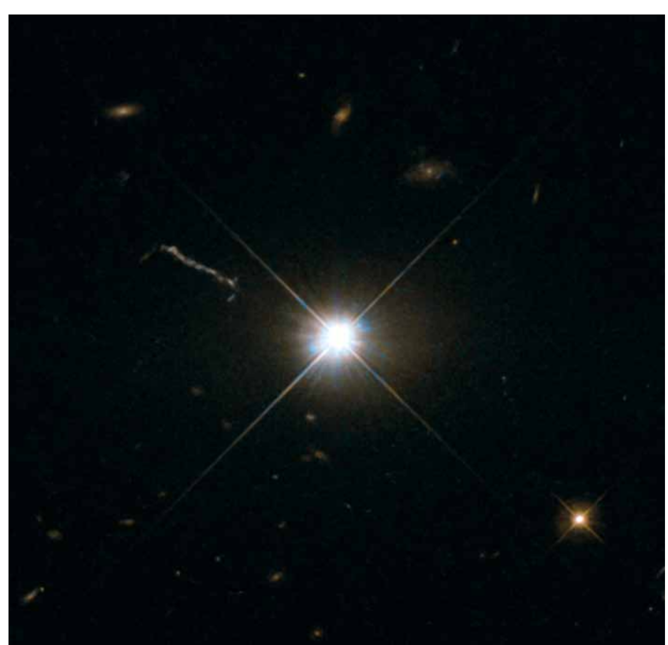


PHOTO: ESA/HUBBLE

terial swirls around the black hole in spiral orbits, its particles colliding with each other. The gas heats up and gradually moves closer to the black hole. The closer it gets, the more turbulent it becomes. Such an infernal maelstrom is called an accretion disk

In the inner region of the flat disk, friction makes the material so hot that it emits high-energy ultraviolet and X-ray radiation. In a wild dance, the gas hurtles at high speed around the cosmic abyss, eventually disappearing into it. However, some of the gas expands, becomes collimated, and flows out into space parallel to the axis of rotation of the disk. This occurs in two opposing jets, which in some galaxies can reach lengths of thousands of light-years. They are therefore millions of times larger than the black hole and its accretion disk.

The jet is also the source of the radio emissions of such quasars. The central engine accelerates particles to nearly the speed of light along tangled magnetic fields that resemble a strand of DNA. This produces synchrotron radiation, among other things. Other processes cause the jets to emit light across the electromagnetic spectrum, releasing unimaginable amounts of energy on the order of trillions of electron volts, similar to terrestrial particle accelerators. Jets are the key to distinguishing quasars from blazars: the latter are a subset of quasars that have one of these powerful headlights pointed directly at Earth. If we look directly into the engine room of a quasar, we see a blazar. So whether an object is classified as one or the other depends on the angle from which we observe it.

The Turbulent Years of the Universe

These cosmic energy slingshots are billions of light-years away from Earth, so their light travels for billions of years before it reaches terrestrial telescopes. We are looking back at a turbulent early era of the universe, when these energy monsters flourished. "At that time, collisions between galaxies were particularly common," explains Komossa. The wild dance of two galaxies flushes large amounts of gas toward the center, feeding the developing heart of the Milky Way system. A quasar, or blazar, is born. But that is not all. Most galaxies have central black holes, which can form a pair when two Milky Way systems collide. The resulting galactic core is exceptionally bright and therefore visible over a wide area. But how realistic is this scenario? To investigate this question in practice, for several years researchers have been observing the blazar OJ 287, located about →

A glimpse of an active galactic nucleus: this image from the Swift space-based telescope shows the blazar OJ 287 in ultraviolet light (left). Further observations suggest that it is a system of two black holes, as shown in the illustration (right). In addition, a jet is forming near the central black hole.

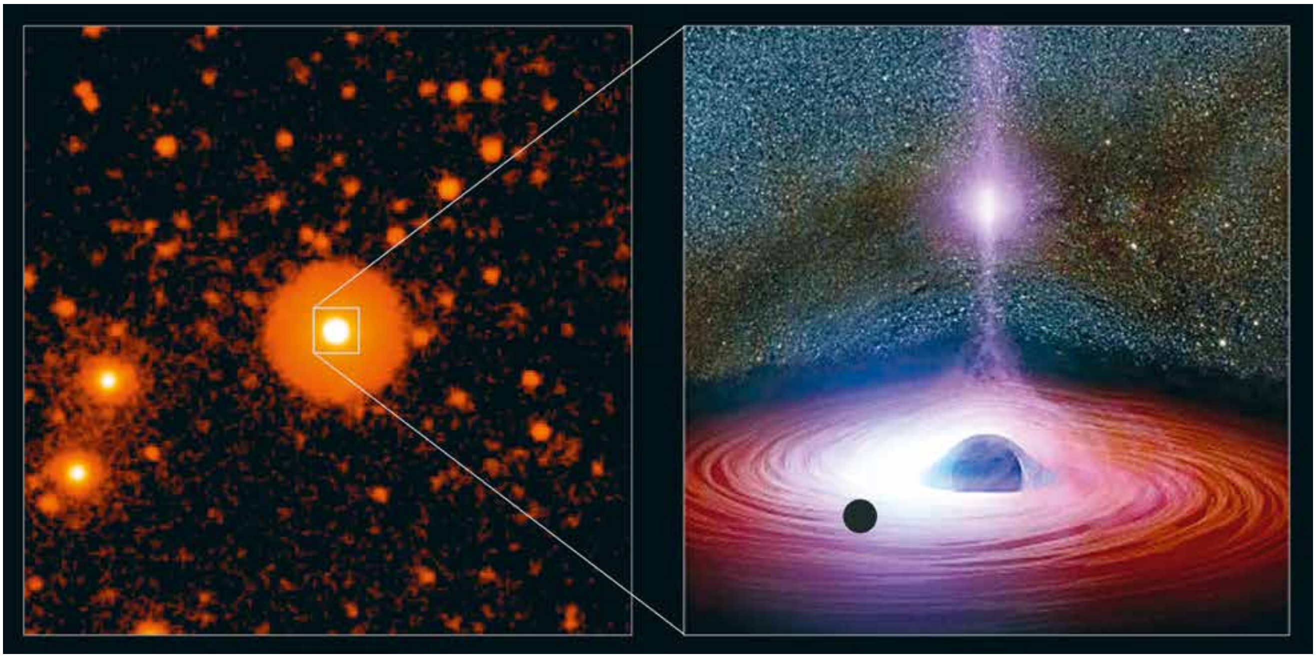
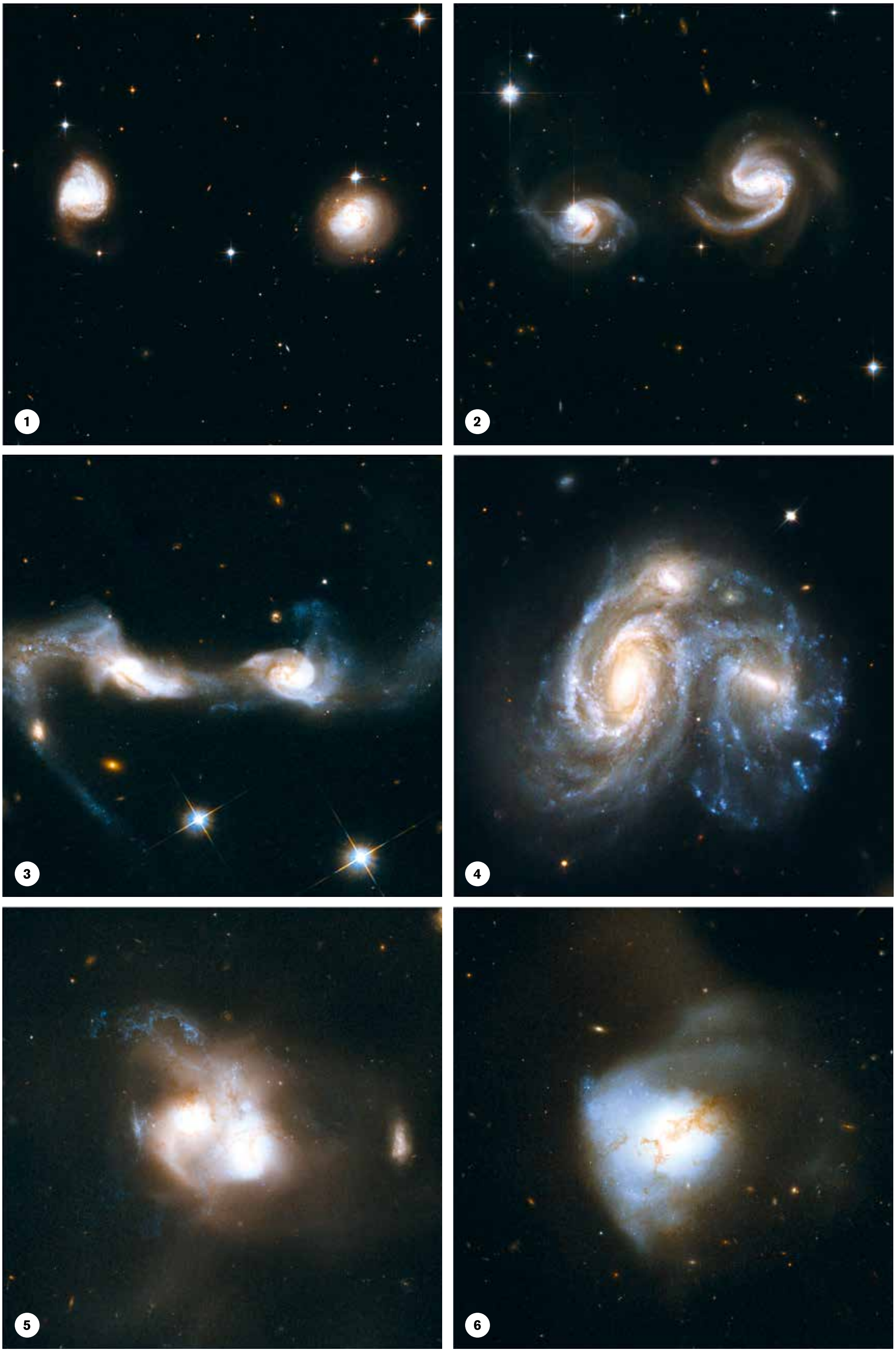


IMAGE: S. KOMOSSA ET AL. (LEFT); NASA/JPL-CALTECH (RIGHT)

IMAGE: S. KOMOSSA ET AL.



Cosmic choreography: the Hubble images show six different pairs of galaxies in visible light. Each image illustrates a stage in the merging of galaxies, from the initial approach (photo 1) to the merger (photo 6).

five billion light-years away in the constellation Cancer. This object is considered a strong candidate for the existence of a binary black hole system. An international team has studied OJ 287 using a technique called Very Long Baseline Interferometry (VLBI). This technique combines the signals from 12 radio antennas, including one aboard the Russian Spektr-R satellite. The resulting virtual telescope spans 193,000 kilometers and provides a resolution of 12 microarcseconds, which would allow us to see a 20 euro cent coin on the moon.

The goal of the campaign was to trace the jets back to their origin in the blazar's engine room. The interferometric images show a jet with several bright nodes and a curvature that increases toward the origin. This supports the idea that the jets are influenced by the two central black holes. In addition, the team studied the oscillation direction of the radio waves. This suggests the presence of a helical magnetic field passing through the jets, consistent with astrophysical models of jet collimation.

The observed properties of OJ 287 are indeed consistent with the presence of two supermassive black holes orbiting each other. In this scenario, the lighter black hole, on a very tight elliptical orbit, punctures the accretion disk of the heavier black hole about twice every 12 years, one year apart, stirring up the matter in the disk. Each puncture produces a flare. These intense bursts of radiation make OJ 287 temporarily the brightest blazar in the sky.

But what does the binary system actually look like? Until recently, the heavier (primary) of the two black holes was thought to have a mass of about ten billion solar masses. In the literature, values as high as 18 billion solar masses have been found. But then Momo came into play. Momo stands for Multiwavelength Observations and Modeling of OJ 287. As part of this international project, the blazar has been monitored continuously over many years using several powerful ground-based and space-based telescopes. Researchers are observing the object from radio to X-ray wavelengths, gaining insights into the heart of the blazar. They can address questions such as which theoretical scenario best describes the conditions inside. The models differ, for example, in the mass of the black holes involved.

SUMMARY

Blazars are active galactic nuclei and are true energy slingshots. They host active black holes at their centers.

A black hole of at least ten billion solar masses was long thought to be at the heart of blazar OJ 287.

New observations with a project called Momo show that OJ 287 probably harbors a pair of black holes, the heavier of which has a mass on the order of 100 million solar masses, a hundredth of the previously supposed mass.

Observations with the Event Horizon Telescope and the Square Kilometre Array are expected to provide further insights into the inner workings of OJ 287.

In the context of Momo, the 100-meter antenna of the Effelsberg Observatory and the Swift satellite mission play a central role. "We determined the mass of the primary black hole and estimated the amount of matter in the surrounding accretion disk," says Komossa. However: "Even with Momo, the supposed system of two black holes cannot be spatially resolved." So the astronomers had to look for indirect clues. And they found them, by studying the brightness variations of the light curve with unprecedented precision. "This allowed us to discriminate between different models of binary systems – we disproved the leading model, which assumed a high mass for the primary black hole," says Komossa.

The electromagnetic radiation reaching us from OJ 287 is usually dominated by the jet, which effectively drowns out the light from the accretion disk. This is similar to a flashlight: when we look directly into its bright beam, the light blinds us and we cannot see the immediate surroundings of the lamp. Because the Momo telescopes followed the light curve almost continuously, they discovered "deep fades" – times when the light from the jet becomes darker. In our example, this corresponds to a brief flicker of the flashlight. This allowed the researchers to constrain the contribution from the surrounding radiation, i.e., the accretion disk. The result of the measurements was surprising: the matter around the primary black hole shines at least ten times fainter than previously thought, but still corresponds to five trillion times the luminosity of our sun.

Mass Monsters – Lighter than Expected

From the lower brightness, the researchers concluded that the mass of the associated black hole is significantly lower. "The most extensively studied binary model to date showed that a mass of ten billion solar masses is required," says Stefanie Komossa. "Based on our new observations, we can definitely rule out this model." Instead, Momo indicates a mass on the order of 100 million solar masses, which is one hundredth of the previously assumed value.

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This result is supported by another measurement of the light curve. According to the old model, a bright outburst should have been observed in OJ 287 in October 2022. However, no such outburst was observed during this period. Instead, researchers using Momo found that the last two flares occurred in 2016/2017. In addition, radio observations with the 100-meter telescope in Effelsberg show that these bursts are not caused by heated matter. This means that other processes in the jets, such as synchrotron radiation, are involved as an energy source. Thomas Krichbaum, Komossa's colleague at the Max Planck Institute in Bonn, summarizes it like this: "All our results indicate that ten billion solar masses are not required for the primary black hole. Nor is an extraordinarily luminous accretion disk required."

New Insights from Gravitational Waves

But what is the center of the blazar really like? The members of the Momo team do not want to commit themselves to a definitive model, since it is still a "work in progress," as Komossa puts it. In any case, the scientist is certain that only models with a much lower mass for the primary black hole are feasible. In addition, the smaller gravitational trap weighs only one hundredth of the primary black hole at the center. Accordingly, the secondary black hole would have only one million solar masses. In addition, OJ 287 is likely a very close pair of black holes that have been moving closer together since the original galaxies collided. The distance between the black holes may now be well under three light-years. This is supported by the relatively fast flickering of the blazar.

The close proximity of the two mass monsters is also the basis for the conclusions drawn by Stefanie Komossa's group from their observations. And these have nothing to do with the electromagnetic spectrum and are a relatively new branch of astrophysics: the measurement of gravitational waves. These are generated, for example, when black holes dance around each other and eventually merge. There are currently two ways to measure this: high-tech detectors on Earth or pulsars in the universe. Pulsars are rapidly rotating neutron stars that emit beams of radiation into space. When these beams pass over Earth, the star appears to flash like a lighthouse. The pulses reach Earth with amazing precision. But when gravitational waves distort spacetime, these high-precision clocks go out of sync. The signals change. Such a "pulsar timing array" can be used to detect the cosmic tremors of merging black holes. "Now we have found that this method does not work for OJ 287 because the mass of the primary black hole is too low," explains Stefanie Komossa. "And that brings the blazar into the sensitivity range of detectors like Lisa." This laser interferometer, consisting of three satellites that form a triangle with sides measuring two and a half million kilometers, is designed to search for gravitational waves from space with a higher sensitivity than ground-based detectors in about 15 years. However, Lisa may only be able to detect the final merger of the black holes. And in the case of OJ 287, that will probably not happen for several hundred thousand years.

But in the foreseeable future, astronomers may gain new insights. They have pointed a mighty instrument at the cosmic powerhouse: the Event Horizon Telescope, which has so far captured spectacular images of black holes in the distant galaxy M87 and at the center of our Milky Way. In addition, the blazar OJ 287 is on the list of the Square Kilometre Array, a network of hundreds of radio telescopes and hundreds of thousands of antennas that will one day span South Africa and Australia. "These observations will be a big step in understanding binary black holes and their evolution," says Komossa. The radio star in the constellation Cancer, discovered as a blazar in 1968, has certainly lost none of its research appeal 55 years later.

www.mpg.de/podcasts/universum (in German)

GLOSSARY

GRAVITATIONAL WAVES
They occur in space whenever large masses move with acceleration, such as when two black holes dance around each other and eventually merge. Gravitational waves arise from the theory of relativity, were predicted over a century ago, and were first measured in September 2015.

COSMOLOGICAL REDSHIFT
This phenomenon occurs when light from a distant source is stretched and shifted into the long-wavelength (red) range of the spectrum due to the expansion of the universe and thus the entire space, so to speak.

SYNCHROTRON RADIATION
This is emitted by charged particles, such as electrons, accelerated in a magnetic field. In astronomical objects, the particles reach speeds close to the speed of light.