Black Holes: 
The Shapers of the Galaxies

Until a few years ago, black holes were considered more as fascinating curiosities or the stuff of science fiction. Researchers at three Max Planck Institutes – of Astrophysics and of Extraterrestrial Physics in Garching, and of Astronomy in Heidelberg – have shed some light on these dark singularities in the fabric of space-time. According to their findings, black holes evidently play an important role during the formation and development of galaxies.

TEXT THOMAS BÜHRKE
In the 1960s, astronomers discovered star-like celestial bodies that were substantially more luminous than any other previously known objects. Within a region no larger than our solar system, these bodies, known as quasars (from quasi-stellar radio source), emitted up to ten thousand times more energy than the hundred billion stars in our Milky Way combined. The quasars were later found to be unusually bright and compact central regions of galaxies that, due to their unrivaled luminosity, can be observed billions of light-years away.

It was not long before a theory was formulated to explain this tremendous energy discharge – a theory that largely holds true today. It states that at the center of the quasar is a giant black hole. The black hole attracts surrounding matter, which first collects in a disk and orbits the black hole. As a result of friction, the gas heats up, loses energy, and approaches the black hole on spiral trajectories before finally vanishing into it like water down a drain. This hot gas disk is the reason why the quasar shines; it “feeds” the black hole, causing it to grow.

In the decades that followed, it became increasingly clear that black holes can be found not only at the centers of quasars, but probably in any galaxy. Our own galaxy, too, contains such a black hole (see also page 43 of this issue and MaxPlanckResearch 1/2003, page 56 ff.). The central black holes of galaxies have masses of between about one and several billion solar masses. The gas disks surrounding them shine at different intensities. Their brightness at a given point in time is determined by their instantaneous rate of growth: the more matter falling into the black hole, the brighter the disk.

A STRICT RELATIONSHIP BETWEEN THE MASSES

The discovery that each galaxy possesses a black hole was remarkable. The realization that these giants could have influenced the development or even the formation of galaxies was even more puzzling to astronomers. Black holes remained more or less a curiosity, albeit a fascinating one, until a discovery made about a decade ago. Several research teams had detected a striking relationship between the masses of central black holes and the galaxy surrounding them. According to this relationship, the surrounding stellar bulges possess approximately a thousand times the mass of the black hole. This holds true for different types of galaxies and for a range of masses spanning some three orders of magnitude. "This
Black holes that are currently very bright – in other words, that are absorbing large quantities of matter and are growing – are found primarily in galaxies in which many new stars have formed in the recent past.

discovery hit like a bombshell,” remembers Fabian Walter of the Max Planck Institute of Astronomy in Heidelberg.

At first glance, it seems completely logical that massive black holes should gather more stars around them than their low-mass counterparts. However, the situation is more complicated than that. In a spiral galaxy, the central collections of stars – also known as a bulge – have radii measuring several thousands of light-years. The gravitational effect of a black hole, however, is felt only within a radius of a few light-years. It is thus much too weak to be able to act on all members of the star cluster that surrounds it. Put simply, the vast majority of stars in the bulge do not “sense” the giant in their midst. How, then, does this mass relationship come about?

“We regard it as a sign that the black holes and the parent galaxies in which they are located share a common development,” says Guinevere Kauffmann of the Max Planck Institute of Astrophysics. This raised a number of questions: Does the black hole control the growth of the galaxy? Or does the galaxy somehow limit the mass of the object at its center? Do black holes and galaxies develop together in some form of symbiotic relationship? “To answer these questions, we needed to carefully study the growth process of black holes and galaxies,” says Kauffmann.

A COMPLICATED MODEL WITH MANY UNKNOWNS

Initially, theoretical models were the instrument of choice for the young Max Planck researcher, who obtained her Ph.D. in astronomy at the University of Cambridge (UK). And she did, in fact, succeed in creating computer simulations of the growth of black holes and their parent galaxies in the young universe. “But then I realized that not everything can be fully described in purely theoretical terms,” she explains. The complicated model contained too many unknowns. That is why she then turned to observations.

Together with a colleague at Johns Hopkins University in Baltimore (USA), Kauffmann developed a new method by which information on the growth rate of a black hole and the age of the stars in the galaxy could be determined from galaxy spectra. The data to which she applied her method was already available – it had been obtained in one of the most comprehensive surveys of the sky ever been performed: the Sloan Digital Sky Survey (SDSS).

Guinevere Kauffmann examined around 33,000 galaxies and reached an astonishing conclusion: black holes that are currently very bright – that is, are absorbing large quantities of matter and are growing – exist primarily in galaxies in which many new stars have been formed in the recent past. “The faster the growth rate, the higher the rate at which stars were created,” she says. In extreme cases, the black hole develops as rapidly as in bright quasars. And the galaxy consists largely of young stars.

Stars are continually being formed in spiral galaxies such as the Milky Way. However, the rate is low, at around three solar masses per year. In contrast, the galaxies that Kauffmann and her colleagues discovered, and that contain a rapidly growing black hole, must have experienced a veritable boom of star births in the past. This is probably triggered by two galaxies coming into close proximity with each other, or merging with each other.

A MARKED BABY BOOM FOLLOWING A COSMIC UNION

When this happens, the gas within the galaxies swirls about and great clouds crash into each other and condense to form stars. Such a cosmic marriage is then essentially followed by a baby boom of young stars. In a crash, large quantities of matter may also flow into the central regions of the galaxy and cause the black hole there to grow rapidly. Ultimately, the two central black holes of the two colliding galaxies may even merge with each other.

In this context, an exciting discovery was recently made by an international group of researchers led by Max Planck scientist Fabian Walter. The researchers observed the most distant known quasar, J1148+5251. The light that we receive from it today was transmitted when the universe was only 870 million years old, or about 1/16 of its current age. In the central region of this object, the astronomers identified an area with a diameter of approximately 5,000 light-years in which stars with a mass totaling over a thousand solar masses are created each year.

Such a large figure has never been observed anywhere else in such a small volume. “What we have found corresponds to an accumulation of a hundred
Black holes can be found at the centers of the majority of star systems. These mass monsters attract matter, which initially accumulates in a disk. As a result of friction, the gas heats up, loses energy, and approaches the black hole on spiral trajectories before finally vanishing into it like water down a drain. This activity is often hidden behind a dust torus, but the rays of matter that shoot outward into space perpendicular to the disk are visible.
But this has not been the only interesting discovery in recent years. On the whole, only black holes with a relatively low mass of less than 30 million solar masses are growing in the universe today. These black holes are found in galaxies similar to our own Milky Way. The growth rates calculated from them suggest that these low-mass black holes have formed on a timescale that is comparable to the age of the universe – in other words, they have grown slowly and steadily. In contrast, black holes of billions of solar masses are currently exhibiting very little growth. The researchers are thus faced with the apparently paradoxical finding that the largest black holes had grown to full size very shortly after the Big Bang, while the smaller black holes are still growing. In accordance with this concept of cosmic downsizing, the active formation of stars and the growth of black holes have shifted over time to smaller and less massive galaxies. Our Milky Way belongs to the latter group.

One of Kauffmann’s colleagues at the institute, Volker Springel, believes there is only one explanation for the existence of black holes with both rapid and slow growth: we must assume that, in the early universe, which was smaller than our current universe and in which the galaxies were closer together, collisions were frequent. Springel has conducted theoretical research into...
the development of the black holes and their galaxies in the “Millennium Simulation” (see MaxPlanckResearch 4/2006, page 46 ff.).

This cosmological simulation – the most detailed ever conducted – originally had the purpose of studying the formation and evolution of galaxies under the influence of dark matter in a region of two billion light-years in size. Springel also simulated individual galaxy collisions in detail on a computer in order to understand the effect of active quasars on the gas in a galaxy.

He found that when two galaxies merge, the mass of the black hole may grow by a factor of between ten and one hundred within approximately 200 million years. Such rapid growth is necessary if the black hole is to attain a mass of several billion solar masses in a relatively short time. In the galaxies that are spared such cosmic mergers, however, the central black holes grow more slowly – and continue to do so today.

The relation between central black holes and the surrounding bulge, and the resulting common development of these two components, can be traced back quite reliably over the past several billion years. (Telescopes act as time machines here since, due to the finite speed of light, observing distant galaxies also involves looking back into the history of the universe.) But did this relationship always exist?

Today, some ten quasars are known that existed and shone very brightly within the first billion years after the Big Bang. Determining the masses of the central black holes and of the stars in these extremely distant objects requires exceptional observational skill, the best telescopes on Earth, and good ideas.

27 ANTENNAS – COUPLED TO FORM A SINGLE TELESCOPE

This was achieved in two cases by the group led by Fabian Walter and his colleague Dominik Riechers, who is currently continuing the studies he began in Heidelberg with a Hubble Fellowship at the renowned California Institute of Technology in Pasadena (USA). The scientists observed the quasars using the Very Large Telescope of the European Southern Observatory in Chile, and the Very Large Array, a facility in New Mexico (USA) in which 27 radio telescopes are coupled together for simultaneous observation of the celestial bodies.

The results are inherently substantially less accurate than those for less distant galaxies, but they point in the same direction: the black holes in these two quasars possess between ten and one hundred times the mass anticipated in accordance with the known relationship. Two other research groups obtained a very similar result.

Should these findings be confirmed, it must be concluded that, in the young universe, the black holes grew more rapidly than their respective parent galaxies. Then the chicken-and-egg question must be asked: which came first, the black hole or the galaxy? Might black holes even have served as condensation nuclei for the later galaxies? Black holes as midwives of sorts?

It’s a fascinating idea, but Guinevere Kauffmann is cautious: “Black holes and stars can form only where a large quantity of matter is concentrated,” she says. They are thus unlikely to have formed at different times. But just how this birth took place, no one is able to say. “We are observing the youngest quasars at a time when the universe was 870 million years old,” explains Walter. Compared to the universe’s current age of 13.7 billion years, comparatively little time was available for a black hole to grow to a size of several billion solar masses.

THE INEXORABLE COLLAPSE OF A HEAVYWEIGHT

According to current knowledge, a black hole is created when a very massive star has consumed its fuel and the central body inexorably collapses. A stellar black hole of this kind, however, has a mass of perhaps ten solar masses. Is it really able to become so massive
The spiral galaxy with the name M 51 presents a sea of stars. It is similar in form to our own Milky Way. Galaxies are the largest building blocks in the universe.

The largest known black holes, some of which have masses of more than a billion solar masses, are located at the heart of so-called elliptical galaxies. These gravitational traps exert a particularly strong pull on stars. The stellar density in their vicinity could thus be expected to be very high. In fact, however, astronomers observe the opposite: the elliptical galaxies with the highest mass, which were probably formed by a cosmic "pile-up" involving several small systems, exhibit the lowest stellar densities.

According to the theory, the merging of two galaxies is accompanied by the formation of a pair of black holes. The latter dance around each other, with an effect similar to that of a kitchen mixer. Should a star approach the pair too closely, it will be catapulted out of the galaxy. Generally speaking, the greater the mass of the black holes, the stronger the thrust. In physical terms, the process is similar to the "slingshot method" used to accelerate space probes by exploiting the gravitational field of a planet as the probe passes close by it.

Together with their colleagues Mark Cornell and David Fisher, John Kormendy and Ralf Bender recently published measurements of unprecedented precision of the density profiles of elliptical galaxies (Astrophysical Journal Supplement 2009, at press). In an accompanying article in The Astrophysical Journal Letters (February 2, 2009), Bender and Kormendy succeeded in precisely calculating the total mass of the stars missing from the centers of the largest elliptical galaxies – and in confirming the theory in practice. A further result: the missing mass increases in strict proportion to the measured mass of the central black hole. "These two values were known to be connected," says Bender. "But we were surprised at how closely they correlated."

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 Zombie Hornung

PHOTOS: NASA/ESA and the Hubble Heritage Team (STScI/AURA) (left), NASA/AURA/STScI and WikiSky/SDSS (right)

On a large scale, the two elliptical galaxies NGC 4621 and NGC 4472 in the Virgo cluster are very similar. If their core regions are enlarged, however, it can be seen that the stellar density in the center of NGC 4472 is much lower than that in the center of NGC 4621. In the case of NGC 4472, the stars were catapulted outward by interaction with a pair of black holes revolving around each other.

STAR SLINGSHOTS

The astronomers now have proof of what they had long suspected: when galaxies collide, pairs of black holes are formed that act as gravitational catapults and that very effectively fling stars outward from their centers. While the two black holes merge over time to form one, the core region of the new galaxy thins out. This interaction was recently observed by Ralf Bender from the Max Planck Institute of Extraterrestrial Physics and the University Observatory Munich, and by John Kormendy from the University of Texas in Austin. This relationship applies only to the immediate vicinity of the black hole, and has no bearing on the wider correlation between the masses of the central black holes and the stars surrounding them.
The heart of the Sloan Digital Sky Survey (SDSS) is the automatic 2.5-meter telescope of the Apache Point Observatory in New Mexico (USA). Within such a short time? Volker Springel’s simulations offer no answer: they employed black holes with an initial mass of a hundred thousand solar masses.

Theoreticians all over the world are puzzling over the question of whether black holes were also able to form in the early universe by some other means. One possibility would be for massive stars to be born in dense clus-
ters, and to develop into black holes within these in a comparatively short time. They could then merge to form a single, supermassive black hole. A further theory is that a large gas cloud may also have collapsed to form a body of such enormous mass, without first forming a star.

Astrophysicists do not know the answer. They are placing their hopes in more powerful computers and in a new generation of telescopes that is set to become available in the coming decade. These include the international Atacama Large Millimeter/Submillimeter Array (ALMA), an installation comprising approximately 50 radio telescopes in the Chilean Andes. These arrays will probably be accompanied by two large optical telescopes with mirror diameters of 30 to 40 meters.

New scouts will also soon go to work in space: the European infrared Herschel telescope is set for launch in spring of this year. It will be followed in the next decade by the successor to the Hubble Observatory, the James Webb Space Telescope. These instruments will provide astronomers with completely new views of the distant galaxies – and of the role of black holes.

GLOSSARY

**Dark matter**
Some 23 percent of the universe consists of a substance that cannot be observed, but that can be detected due to its gravitational interaction with visible matter. The composition of this dark matter is unknown.

**Milky Way**
Popular term for the galaxy to which our Sun and its planets belong. The galaxy resembles a disk, has a diameter of approximately 100,000 light-years, and encompasses around 200 billion stars, in addition to dust and gas clouds.

**Supernova**
The spectacular end of a massive star. As the star is destroyed by a tremendous explosion, its brightness increases by up to a billion times its former luminosity.

**Big Bang**
According to the Standard Model of Cosmology, the beginning of the universe approximately 13.7 billion years ago. The Big Bang, also known as singularity, gave rise to space, time and matter.