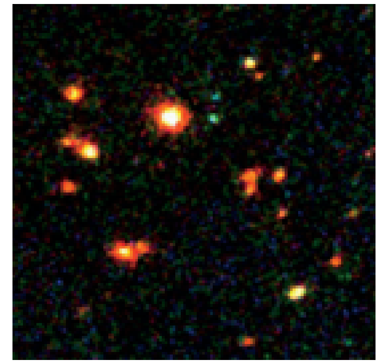
Black Holes as Intergalactic Gas Heaters



Black holes, with a mass millions to billions times greater than that of the sun, probably exist at the centres of most galaxies. Over the years, astronomers have collected a wealth of scientific data on these cosmic phenomena. But it is only in recent years that it has become obvious that black holes played an important part in the development of galaxies. With the help of the European X-ray Observatory XMM-NEWTON, *Max Planck scientists have been able to shed more light on this dark side of the universe.*

XMM image of the environment around the galaxy M 87. The surrounding gas has an essentially smooth distribution and is significantly hotter than ten million degrees.

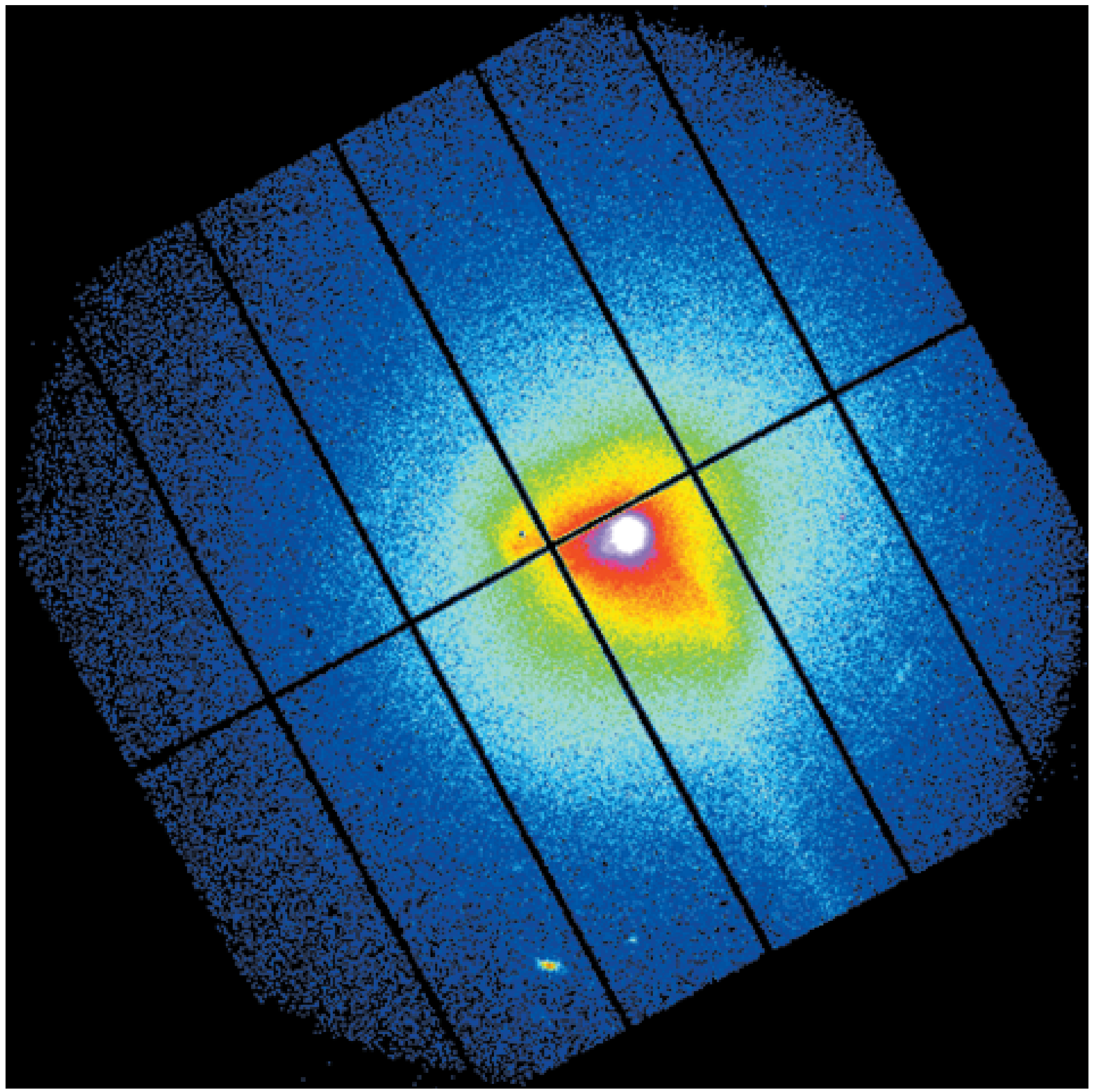


Photo: MPE/ESA

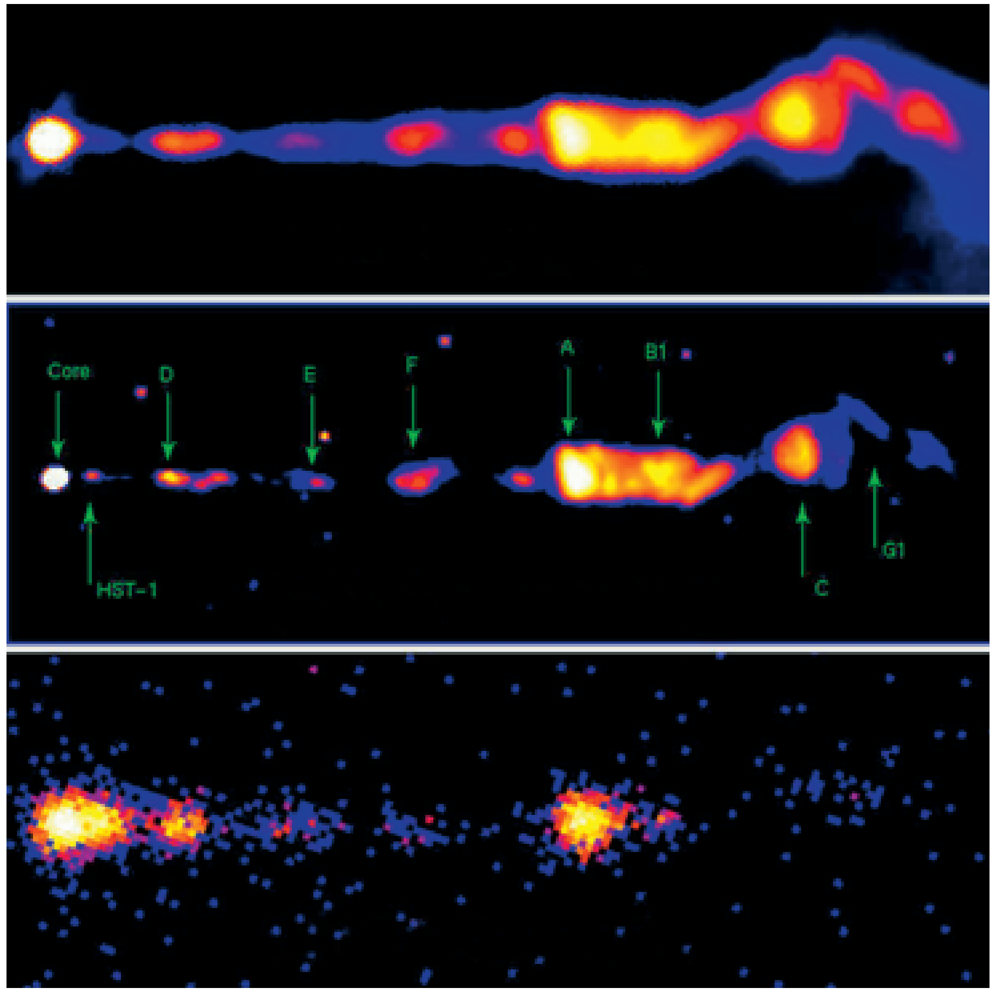
Galaxies such as our Milky Way are certainly not unique. They have merged to form large groups, which, in the case of a rich cluster, may contain as many as several thousand members. Close to the centre of virtually every large cluster is a giant galaxy. The space between galaxies is not completely empty, as appears to be the case in pictures of the visible spectrum. To the contrary, this space is filled with a tenuous gas. However, as it has a temperature of many million degrees, it only radiates in X-ray light - something which is difficult to observe, as the earth's atmosphere absorbs this high-energy radiation. The discovery of this intergalactic gas in the seventies led ten years later to a theory which, to this day, remains hotly disputed: at that time, British astrophysicists came to the conclusion that the gas first flows into the central area of the cluster, where the massive galaxy with its strong gravitational field dominates its surroundings. Here it cools down over a period of about a billion years and "condenses" into new stars. The specialists used the term "cooling flows". From the data available at the time, the scientists estimated that in this way, in extreme cases, more than a thousand new stars might form in the cooling flows every year. An unbelievably high rate in comparison to the average spiral galaxy like the Milky Way in which roughly one new star lights up annually. So this hypothetical process would contribute significantly to the formation of galaxy clusters.

However, this sensational theory had a snag: neither the cool gas itself nor the young stars formed within it could be observed. So advocates of the theory were keen to invent new hypotheses to explain the discrepancy between theory and observation. For example, it was believed that the formation of stars in the cooling flows happens differently from the process with which we are familiar in our Milky Way and other galaxies. It was believed in particular that it was essentially only low-mass stars that form, which, from a great distance, cannot be distinguished from an old star population, such as that existing in the central galaxy. This was, however, in contrast to all previous experience.

Paradox Between Hot and Cold

The paradox remained: there was absolutely no doubt that the hot gas existed, and according to all the rules of physics it also had to cool down. But apparently it does not. Why? All previous observations suffered from the fact that the X-ray telescopes did not have a high enough angular resolution, and so did not show any details in the centre of the galaxy cluster. There were also no sensitive spectrographs. However, an instrument like this is needed to measure gas temperatures, for example. The European X-ray Observatory XMM-Newton, launched at the end of 1999, has both of these capabilities. In 2000, Hans Böhringer and colleagues from the Max Planck Institute for Extraterrestrial Physics in Garching used XMM-Newton to observe the central galaxies of a total of three galaxy clusters, looking for their cooling flows. The researchers obtained their best data from the Virgo galaxy cluster and its central galaxy Messier 87 (M 87 in short), approximately 50 million light years away. It is one of the largest known galaxies. The peculiarity of this galaxy is a collimated gas jet, emerging from the centre and shooting out into space over a distance of approximately 5,000 light years.

The astronomers had to direct the telescope onto the galaxy for over eleven hours, until they had an excellent spectrum, in which they identified the signatures of various chemical elements in the form of emission lines. These occur when matter is located within hot and radiation-rich surroundings and they themselves are excited to light up. The emission line of



The jet of the M 87 galaxy, observed in radio waves, with the Hubble Space Telescope and the Chandra X-ray Telescope (from above).

PHOTOS: NRAO / NASA

iron was particularly clear and to a certain extent served the astronomers as a thermometer for the gas in the centre of the Virgo galaxy cluster. If the model of the cooling flows was correct, there would have to be regions of greatly intermingled gases with very different temperatures in the environment of M 87. However, nothing of this kind could be identified in the spectra. They could be most easily explained with an essentially uniform high temperature of more than ten million degrees, clearly in conflict with the cooling flow model. Just to be absolutely certain, the Max Planck scientists also examined very special models which could explain these observations in the framework of the cooling flow model, for example, strong absorption of the X-ray light, which only occurred very selectively in the cool areas. "But in our opinion, we can even rule out this possibility", says Hans Böhringer.

The Garching astronomers are supported by their colleagues in the United States. With the Chandra X-ray telescope, they have obtained pictures of very high resolution from the M 87 galaxy environment and likewise find no indications at all of large cool clouds. Just in the central areas of some clusters, they were able to identify small areas containing somewhat cooler gas. However, they are ten to one hundred times lower in mass than the advocates of the cooling flow model would expect. However, if the hot gas - which clearly exists - does not cool down, it must be constantly heated. This "heat" must moreover be very finely tuned to its task: if it were too strong, it would drive the intergalactic gas away from the centres of the galaxy clusters - something which has not been observed. If it were too weak, the huge masses of gas would still cool down over a protracted period of time. In the view of the Garching scientists, there is only one possibility: black holes in the centres of active galaxies.

Nowadays the astronomers are fairly certain that black holes lurk at the centre of almost every galaxy. These objects can be several million to billion times more massive than the sun. They are surrounded by hot gas discs, from which matter slowly swirls into the central black hole and disappears for eternity. Presumably these cosmic particle streams rotate and twist magnetic field lines which wind along their rotational axes - perpendicular to the disc plane - into space. According to the theory, electrically charged particles, presumably electrons and their antiparticles (positrons) are shot into space along these field lines. This scenario is supported by astronomers from Tübingen, who have used XMM-Newton to study the area in the immediate environment of a black hole.

Jets Act as Energy Carriers

These rays of matter (or jets) can extend far into space up to a distance of one million light years. Here they meet with the cluster gas and swirl around in large, continuously expanding clouds. The jets constitute a significant flow of energy. This makes it conceivable that the expanding gas bubbles convey this energy, in part, to the intergalactic gas, thereby heating it. Astronomers were now able to use Chandra to prove this kind of interaction.

Eugene Churazov from the Max Planck Institute for Astrophysics in Garching is currently developing a computer model to simulate the release of energy from the jets into the hot gas. However, just some simple estimates already show that the scientists from Garching are on the right track. For example, the jet from M 87 supplies approximately twice as much energy as that radiated by all the stars in our Milky Way. In fact, the jets in the central galaxies in the Perseus and Hydra A galaxy clusters are ten times more powerful in energy. A comparison with the theoretical cooling rate of the gas shows that the jets supply energy in precisely the right strength to keep the gas from cooling - a surprising degree of fine-tuning.

A self-regulating mechanism could explain how this works. Let us assume that the intergalactic gas streams into the centre of gravity, the black hole. The dark giant will consume one part of this gas; the other part will be shot

The XMM image shows an array of active galaxies and quasars. The colours indicate the energy areas: from red to green to blue the energy of the X-ray light emitted increases.

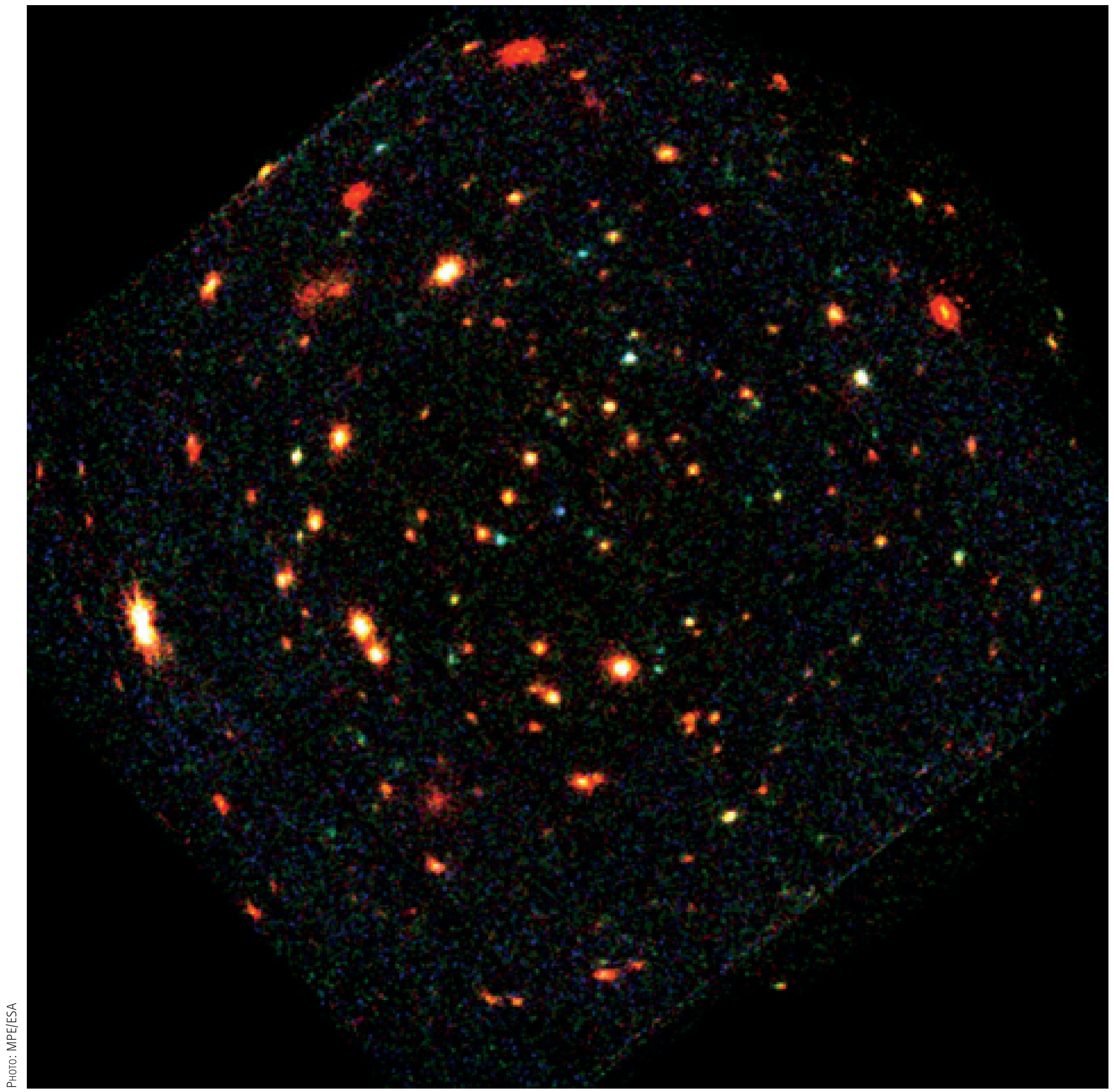


PHOTO: MPE/ESA

The double helix in 3C273

Jets emanating from the centres of radio galaxies have already been known for decades. How they originate and the way in which their particles are accelerated remains as yet largely unanswered. Andrei Lobanov and Anton Zensus of the Max Planck Institute for Radioastronomy in Bonn have recently discovered a wave-like structure in the jet of the quasar 3C272, which is reminiscent of the double helix of DNA – admittedly on a wholly different scale of several hundred light years.

Presumably this phenomenon arises from the jet drilling through a surrounding gas which compresses it from the outside. Similar to a water jet, periodic instabilities then form in the gas jet. Using a theoretical model, the Bonn astronomers managed to explain the internal structure of the jets on scales of up to several hundred parsecs, corresponding to approximately 1,000 light years. The model also provided important physical dimensions. The jet was thus shown to possess only one quarter of the density of the surrounding gas. The helix model moves from the centre of the galaxy at a speed of approximately 20 per cent of the speed of light. The model's predictions will be tested by future observations.

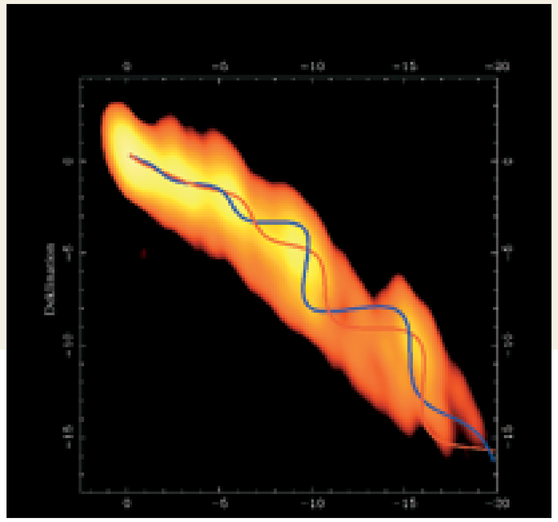


Photo: MPI for Radioastronomy

The observations were made possible by technology used only once up until now. In 1997, Japanese researchers had shot an eight-metre high radio telescope named HALCA into an earth orbit. For the first time, this allowed the use of Very Long Baseline Interferometry (VLBI), which had been used terrestrially for a long time, to be extended into space. This involves a celestial object being observed simultaneously by several radio telescopes located worldwide. Finally, the researchers combined the data in a specially designed computer centre. This "Space VLBI" provides four times better resolution than that achieved with ground telescopes. Ten American antennae and the Effelsberg 100 metre radio telescope were used for the observation of the 3C273 jets. Thomas Bührke

into the jets along the magnetic fields. The more gas available in the surroundings, the more matter streams into the black hole, and the more energy is supplied by the jets. At the same time this is also necessary because the heat requirement increases with the mass of the surrounding gas. If less gas is available, the black hole receives less nourishment and heats its surroundings to a lesser degree. This mechanism explains not just the heating of the intergalactic gas. It also results in the growth of the Black Holes. For example, M 87 is supposed to swallow matter approximately equal to one hundredth of a solar mass annually. Over a period of ten billion years this would result in one hundred million solar masses. However, this process cannot be the sole cause of the Black Hole's size in M 87, as it has approximately three billion solar masses.

An Observation Period of 16 Days

The question as to how these cosmic giants formed and the role they played in the creation and development of the galaxies is one of the most exciting chapters in astrophysics today. This is an area to which XMM-Newton has also made quite a significant contribution. Already at the beginning of the sixties, when rocket-borne detectors first detected X-ray photons from the universe, diffuse background emission had been observed. It could not be attributed to any individual source. It was only in the nineties that the German-US-UK ROSAT X-ray satellite shed light on the matter due to its greatly increased sensitivity and resolution: it showed that approximately three-quarters of this radiation field originates from very distant active galaxies and quasars, i.e. galaxies which - similar to M 87 - conceal a black hole at their centres. Astronomers had to direct the telescope onto a particular area of the sky for 16 days in order to make this observation. This is certainly one of the longest astronomical exposures of all time.

Not long after that, it was mooted that the remaining unidentified sources were active galaxies. The background of this conjecture was a new model of active galaxies which had resulted from other observations. The theory was that the black holes in the centres of the galaxies are surrounded not just by a hot disc but at a greater distance also by a ring of dust. This then obscures the view into the centre if the galaxy happens to be observed laterally. While the dust can effectively block low-energy X-ray radiation, high-energy X-ray radiation can supposedly penetrate this curtain.

ROSAT was not sensitive in this energy region, but XMM-Newton was. So an international team led by Günther Hasinger, the new Director at MPE, pointed the instrument to the same area which ROSAT had observed. The result of this approximately 28-hour observation was incredible. The whole image field was studded with galaxies. On a surface measuring a quarter of a square degree, corresponding to the surface of the full moon, the astronomers counted approximately 500 X-ray sources. Due to the energy resolution of the X-ray CCD detectors developed at MPE, it could be established that, as expected, approximately a quarter of all sources can only be recognised in the high-energy X-ray light. Many of the new sources could indeed be identified as distant, obscured active galaxies, as proven with spectroscopic observations in visible light.

This makes it clear: the whole X-ray background originates from active galaxies, many of which are only revealed in high-energy X-ray light. If one extends the number of objects found on a small surface with XMM-Newton over the whole celestial sphere, one reaches a total figure of approximately one hundred million. So a rough estimate leads to the surprising discovery that at least a fifth of all radiation in the whole universe is generated by black holes – by those very same celestial bodies which are renowned for swallowing light. This new discovery already shows that Black Holes must have had a significant influence on the development of the universe. However, the thread can be followed yet further. Hence astronomers from the Max Planck Institute for Astronomy in Heidelberg and colleagues from the USA found the most distant quasar to date (see the article on Page 22 ff. in this magazine). It radiated the light received from it at a time when the universe was only about 700 million years old.

Astronomers Observe "Premature Births"

The researchers start from the assumption that the majority of the huge black holes already existed within the first billion years after the Big Bang. And a further finding provides food for thought: it has been discovered that the more massive the surrounding stellar system, the larger the black holes. Therefore there must be an evolutionary link between black holes and galaxies.

So everything points to the fact that black holes can no longer be regarded merely as fascinating, exotic forms of matter. In fact, they must have co-evolved with the galaxies. To a certain extent, they may even have acted as condensation nuclei of the galaxies. At the moment we are really experiencing a paradigmatic change in our understanding of the formation of galaxies.

"The black holes have obviously played a far greater role in this than we previously thought", sums up Günther Hasinger.

Further research must now tackle the question as to how the black holes were formed. Was it the case, as today's theories lead us to believe, that in the beginning they only had approximately ten solar masses, and did they just grow with a continuous flow of matter? Or did something else unknown happen which meant that black holes with approximately one million solar masses were able to form spontaneously? These questions will keep the astrophysicists occupied for a long time yet. Thomas Bührke

XMM-Newton – Europe's X-ray observatory

Photo: ESA

In December 1999, the European Space Agency (ESA) launched its largest scientific satellite to date: the eleven-metre long XMM-Newton (X-ray Multi Mirror) X-ray Observatory weighing four tons. The satellite has three parallel telescopes, each measuring 60 centimetres. Each consists of 58 concentric gold-plated tubes with diameters ranging from 70 to 30 centimetres. The mirror systems mean that three different detectors can be worked with on the focal plane at the same time: one camera and two spectrometers.

XMM-Newton enabled X-ray sensitive Charge Coupled Devices (CCD) - developed and built at the Max Planck Institute for Extraterrestrial Physics in Garching - to be used for the first time. These allow the energy carried by the X-ray photons to be established, thereby making it possible to take "coloured pictures" in the X-ray region. The spectrometers are indispensable for modern astrophysics. In the X-ray light dispersed according to wavelength, "finger prints" of individual chemical elements can be found. They give clues about important physical quantities such as temperature, density, or chemical composition of the matter. Using XMM-Newton, the astronomers hope to discover more than one million previously unknown X-ray sources and to take spectra of more than 30,000 celestial bodies within ten years.

Germany was significantly involved in XMM-Newton. The 460 million Mark high-tech instrument was built under the direction of the Dornier Satellite System (today Astrium) in Friedrichshafen. The Carl Zeiss corporation was involved to a great extent in the construction of the mirror. The most sensitive X-ray detector in the focal plane was developed in Garching's Max Planck Institute for Extraterrestrial Physics. Thomas Bührke