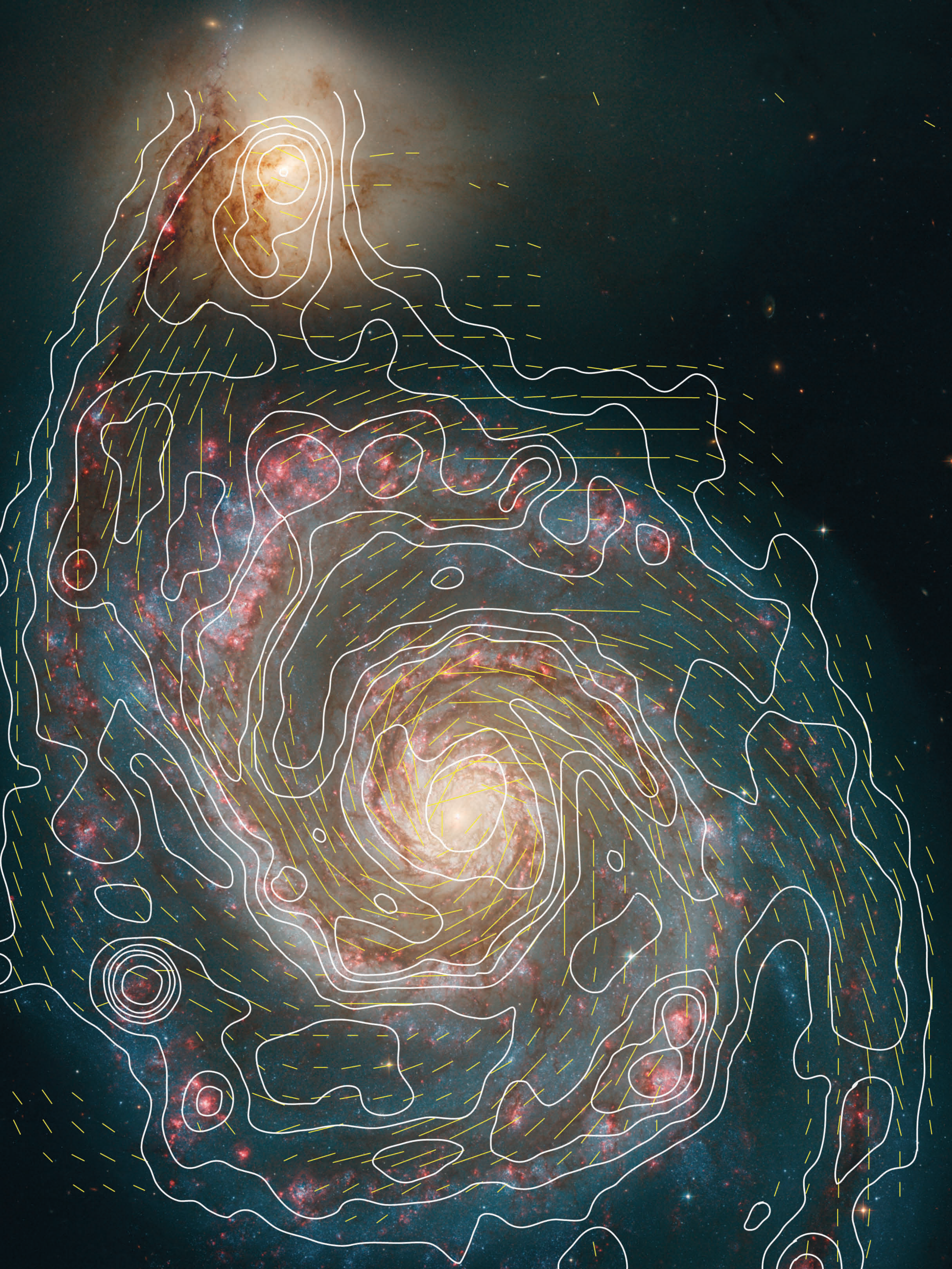


Forces that **Rule in Galaxies**

Magnetic fields spanning 100,000 light-years permeate entire galaxies and envelop their central black holes. Researchers working together with **Rainer Beck**, **Silke Britzen** and **Sui Ann Mao** at the **Max Planck Institute for Radio Astronomy** in Bonn are teasing the secrets out of these invisible force fields.

TEXT **THOMAS BÜHRKE**

Hardly anyone can resist the fascination of the huge radio telescope in Effelsberg. Its 100-meter diameter makes it the second largest, fully steerable observation instrument of its kind in the world. Even while still a student, Rainer Beck wanted to listen in on the universe with this gigantic ear. That was the beginning of a career in research. Today, almost 40 years later, the scientist is long established. And only very few know as much about magnetic fields in galaxies as he does. In the beginning, though, there was a setback.

In 1973, his doctoral supervisor, Richard Wielebinski, then Director at the institute, together with his colleague Elly Berkhuijsen, had discovered surprisingly intense radio emissions in the neighboring Andromeda Galaxy around two and a half million light-years away. These had to have originated from fast electrons that were moving in relatively strong magnetic fields. "No one had expected this back then," recalls Beck. And this was what made the result spectacular. Since then, Beck and his students confirmed and improved it several times. In 1999, it even received an unexpected honor when it was chosen to adorn a special stamp issued by the German postal service.

Magnetic whirlpool galaxy: In this image of the M 51 galactic system, white contour lines indicate the intensity of the radio emission, yellow dashes the magnetic field orientation.

Rainer Beck, as part of his doctoral research, was to then also search for radio emissions in a different spiral galaxy, called Messier 51. "This was a complete waste of time, because the stellar system was too far away for the detector technology of the time," says the scientist. But he didn't let this deter him.

FIELD LINES FOLLOW THE SPIRAL ARMS

To date, the group working with Beck and Marita Krause has studied many galaxies in the radio range – now including M 51, as well. Magnetic maps show that the lines of the ordered field follow the course of the spiral arms, snuggling up to their curves, as it were. On the most accurate maps, it's possible to see that the magnetic field strength is often strongest at the inner edges of the arms, but ordered fields also exist between them.

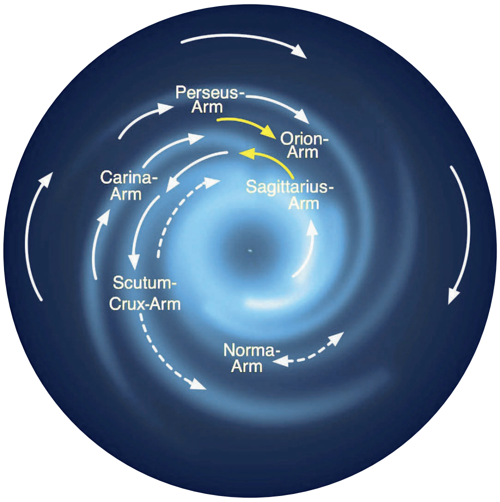
Moreover, M 51 – also called the Whirlpool Galaxy – is a very good example of how magnetic fields are influenced by external effects. The gravity of a close companion galaxy produces strong density waves in the gas of M 51, with the consequence that the spiral arms are particularly pronounced and stand out clearly. At the same time, the waves also compress the magnetic field at the inner edges of the spiral arms.

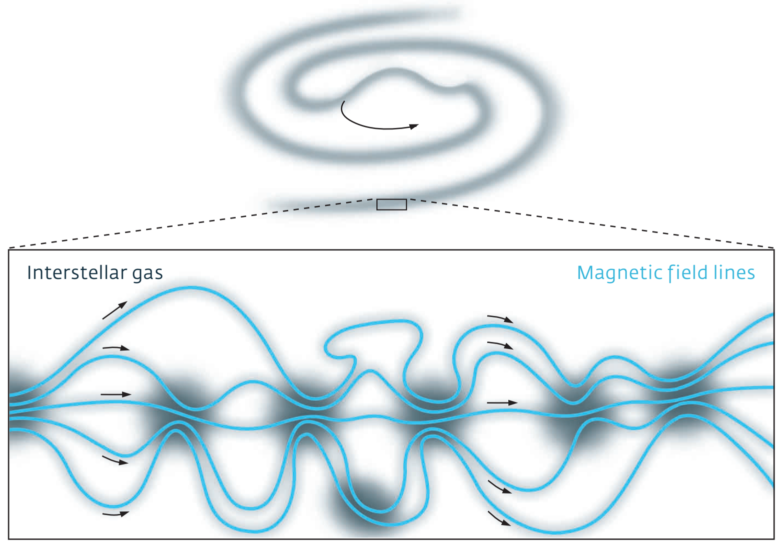
"Here we see a clear connection between the gas density and the strength of the magnetic field," explains Beck. This is also interesting because new stars can form in these compacted regions. For decades, astronomers have been discussing what effect the magnetic fields have on the gas clouds and star formation.

New stars form in the interior of dense rotating clouds, which slowly contract under the influence of their own gravity. As such a cloud becomes smaller, it rotates faster and faster. This leads to an increase in the centrifugal force, which is an outward force, and counteracts the collapse, possibly stopping it completely.

In this process, the gas heats up and becomes partially ionized: a plasma in

Photo and graphic: Rainer Beck/MPI for Radio Astronomy, A. Fletcher/University of Newcastle, Hubble Space Telescope / Graphic: "Sterne und Weltraum" magazine





This page | Model of the Milky Way: The diagram on the left shows the structure of the ordered magnetic field in the spiral arms of the galaxy. Yellow and white arrows indicate verified structures, and dashed arrows structures that are as yet unverified. The two yellow arrows mark a reversal of the direction of the magnetic field. The arrows at the outer edge indicate the rotation direction of the Milky Way. Our solar system is roughly in the center of the Orion arm. The diagram on the right shows ordered and chaotic magnetic fields and their relationship with gas clouds in a spiral arm.

Right-hand page | Experts for the radio universe: Sui Ann Mao, Silke Britzen and Rainer Beck (from left) in the control room of the 100-meter telescope in Effelsberg.

which electrically charged particles – primarily protons and electrons – whiz about. These react to the magnetic field, pull at it like dough in a mixer, and decelerate the rotational motion of the whole cloud. The centrifugal force decreases and the cloud can contract further. In this manner, magnetic field brakes could assist in star formation.

"Despite many decades of research, we still know relatively little about the effect of magnetic fields on the events in the interior of galaxies, such as the formation of spiral arms or active galactic centers," says the Max Planck researcher. They absolutely can't be neglected, as most astronomers believed when Beck first started his research.

While the gas and the stars in a galaxy can be seen, magnetic fields remain invisible. So how can we detect them at all? "They have to be illuminated," says Rainer Beck, "and this is what the electrons do."

These particles, which exist in the space between the stars, are forced onto helical trajectories in a magnetic field and thus emit radio waves in their direction of motion, like minute headlights. Furthermore, the radio waves are linearly polarized: they have a tendency to oscillate in one plane, namely the one vertical to the magnetic field orientation. The strength and structure of the magnetic field can be derived from the intensity and polarization of the radio emissions.

ASTRONOMERS USE AN EFFECT FROM NATURE

The Effelsberg radio telescope is uniquely suited to accomplish this: Despite having reached the ripe old age of 43, continual technical improvements mean it is still the most sensitive instrument in the world for detecting polarized radio waves.

Our Milky Way, too, is a disk-like spiral galaxy. Since our solar system is within the disk, radio telescopes receive the radiation from all directions. This makes the detection of the spatial structure more difficult. Then again, the Milky Way is the nearest spiral galaxy to us, and thus reveals a great many details.

In order to find out about the spatial structure of the magnetic field, astronomers use a further method here. They observe pulsars and distant galaxies that emit radio waves. When this radiation passes through a magnetic field, the plane of polarization rotates. This effect is named after Michael Faraday, who discovered it in laboratory experiments even back in 1845.

The researchers derive the strength and direction of the magnetic field traversed from the value of the Faraday rotation. Furthermore, the average strength of the field found in between is given by the distance of a pulsar. "For us, the Faraday rotation is like a cosmic compass," says Beck. But it doesn't work quite as simply as its counterpart on Earth.

One problem is that, although a specific polarization plane of the radio waves is measured, the plane in which the radio source originally emitted the waves is unknown. Here, astronomers are assisted by the fact that the wave rotates to a greater degree the greater the wavelength of the radio emissions and the field strength are. Observations at several wavelengths therefore provide the strength and direction of the field.

Graphics: van Eck et al., Astrophys. J. Vol. 728, p. 97 (2011), J.-A. Brown, Univ. Calgary, Canada (left)/Designergold based on original material by E. Parker, Univ. of Chicago, USA, Scientific American Vol. 249, August 1983, p. 44 (right)

» The further one moves away from the center of the Milky Way, the more the magnetic field changes. In the outer region, for example, the field lines are nearly circular.

Sui Ann Mao has collaborated on what is so far the most precise magnetic field chart of the Milky Way. The radio astronomer, who was born in Hong Kong, spent several years as a researcher at Harvard University in Cambridge (USA); since the beginning of 2014, she has been working at the Max Planck Institute in Bonn. Here, she was awarded a five-year fixed-term position within the framework of the Minerva program.

For Mao, this program, which promotes the careers of female scientists, was one of the key reasons for moving to Germany. "In addition, the scientific environment here in Bonn is very good, and I can set up my own research group," she says.

Together with colleagues, Mao measured the Faraday rotation of the radio waves with the help of pulsars and distant radio galaxies. To do this, she used the *Very Large Array* (*VLA*), a system consisting of 27 radio dishes in New Mexico.

The result of the magnetic field survey isn't easy to interpret. Nevertheless, the data best fits a model in which the magnetic fields in the interior of the Milky Way – as with Messier 51 – follow the spiral arms and are symmetric about the disk plane. Here, they have a strength of up to two microgauss. For comparison, the Earth's magnetic field is around one hundred thousand times stronger at middle latitudes.

The further one moves away from the center of the Milky Way, the more the field changes. In the outer region, it is nearly azimuthal, meaning the field lines are almost circular. Astronomers had long been in the dark about how such a structure, which can be found in a very similar configuration in almost every spiral galaxy, can form.

"We now assume that this takes place in a multi-step process," says Rainer Beck. In an electromagnet, a wire carrying a current generates a magnetic field. In space, this role is assumed by turbulent plasmas, which are formed, for example, when stars explode. The stars then shed hot gaseous envelopes that propagate at high speeds. Initially, chaotic magnetic fields form inside these envelopes, and then the envelopes get caught up in the rotation of the galaxy and dragged along.

As this happens, the field lines gradually rearrange until they produce the pattern observed today, following the spiral arms. "This galactic dynamo creates order from chaos," is how Beck's colleague Mao summarizes this process, which takes place on scales of tens of thousands of light-years. "Dynamo" because kinetic energy is converted into magnetic energy here – remotely comparable to a bicycle dynamo.

Most of the galaxies investigated are undisturbed lone wolves, but astronomers know that the stellar systems can also come dangerously close to each

Photo: Frank Vinken

other or even collide. Gas and dust clouds then swirl around, densify locally and become the birthplaces of large numbers of new stars. What happens to the magnetic fields in these cases?

Beck and his colleagues have used the *VLA* to investigate the most prominent example of two merging stellar systems, the Antennae Galaxy, 90 million light-years away. A special property of this array came to their aid here: its overall size can be varied by moving the 27 telescopes mounted on tracks backwards and forwards. "In this way, we can realize a kind of zoom lens for the radio range," explains Beck.

In fact, this is how he determined that the magnetic fields are stronger than in normal spiral galaxies, especially in the "crumple zone" of the cosmic crash. The causes are probably the increased turbulence in the gas and intensive star formation. The ordered magnetic field structure is destroyed there and makes way for a chaotic one. Sui Ann Mao recently used the now considerably improved *VLA* to carry out new measurements that will hopefully explain the magnetic chaos.

An ear to space: The 100-meter diameter dish of the Effelsberg radio telescope (top) also strains its ears for signals from quasars. A jet emanates from the object 3C 279 (diagram below). Two densifications (C5 and C10) move away from the quasar. They apparently have different birthplaces (red squares). Modeling (red solid line) these different trajectories makes it possible to determine the parameters of a binary system of two supermassive black holes.

Cosmic collisions: Magnetic fields play a key role in the formation and focusing of jets (right-hand page, left). In the merging stellar system – known as the Antennae Galaxy – the ordered magnetic field structure is destroyed (right-hand page, right).

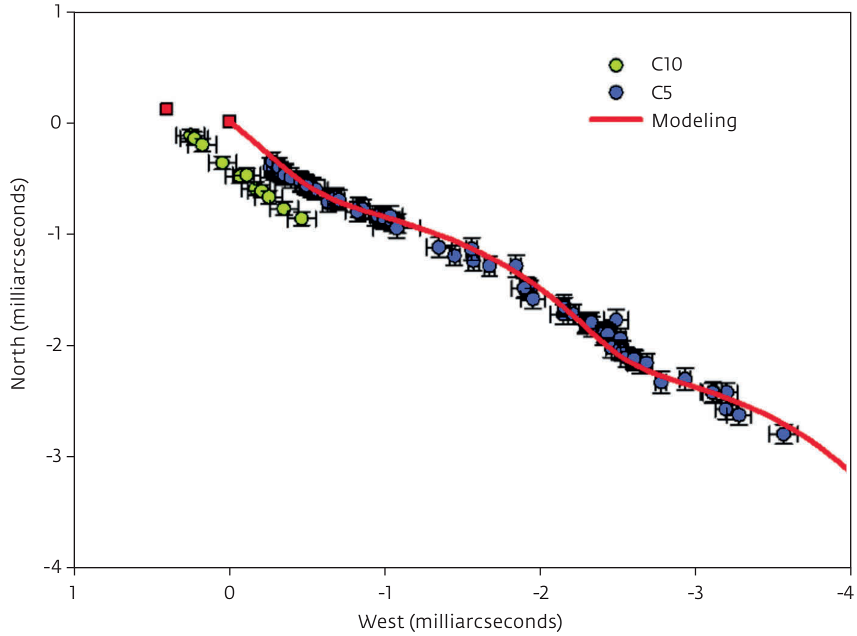


Photo: Frank Vinken, graphic: Roland, Britzen et. al. 2013, Astronomy & Astrophysics, Vol. 557

» For the *SKA*, thousands of radio dishes with a total collection area of one square kilometer will be installed in Australia and South Africa.

It would be exciting to investigate these fields locally with greater resolution of detail, but today's telescopes come up against their limits here. The radio astronomers place great hope in the future *Square Kilometre Array* (*SKA*). This is an international project in which thousands of radio antennas with a total collection area of one square kilometer will be installed in Australia and South Africa. This gigantic installation is expected to be completed during the coming decade, and to dominate this research for a long time to come.

BLACK HOLES AT THE HEARTS OF THE GALAXIES

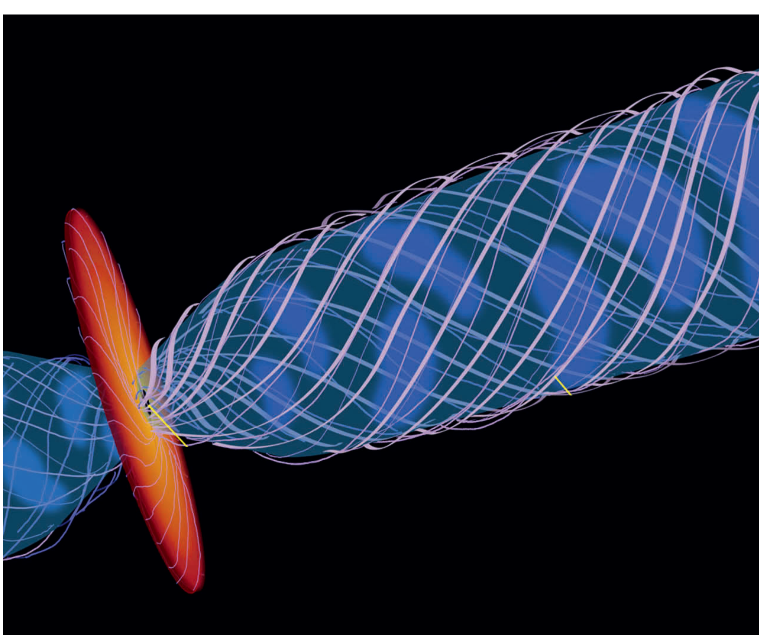
"With the *SKA*, the number of pulsars that we use for the magnetic field survey of the Milky Way would increase to 10,000," enthuses Mao. But to the great surprise and dismay of all German radio astronomers, the German Federal Minister for Education and Research, Johanna Wanka, announced Germany's exit from this pioneering project in June 2014.

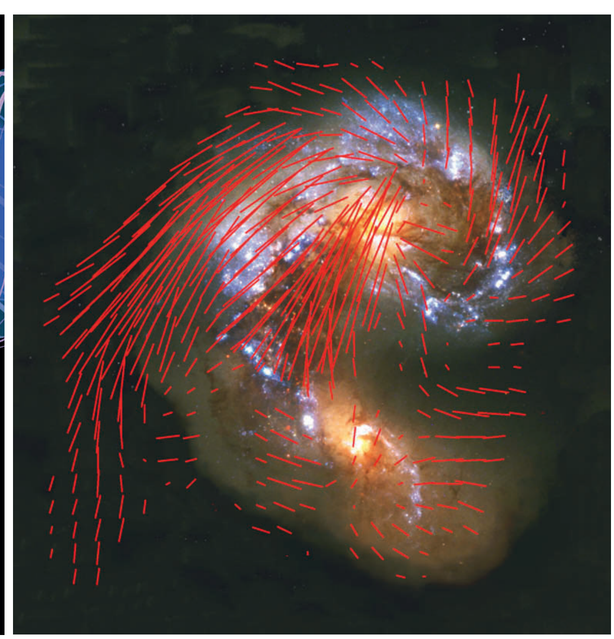
The *SKA* would also be ideal to study a further aspect of galaxies: the activity of supermassive black holes at their centers. According to what is known today, at the heart of almost every galaxy is a black hole that contains matter amounting to several million to billions of solar masses. It is likely that each of these invisible bodies is surrounded by a hot, rotating gas disk that can shine very brightly depending on the conditions.

In some cases, matter breaks away from the disk and flows toward the black hole. While a large part of it disappears into the cosmic maelstrom never to be seen again, another part is redirected and shoots into space in two opposite directions perpendicular to the plane of the disk at almost the speed of light. Such a jet can extend over a distance of several million light-years; it is presumably held together by magnetic fields. Silke Britzen is trying to discover how these plasma flows form.

"There is now hardly any doubt that magnetic fields play an important – maybe even the key – role in this," says the astrophysicist. They could decelerate the gas in the disk – a process that is crucially important in order to allow the gas to approach the black hole on a spiral trajectory and ultimately plunge into the massive monster. However, what really happens in its immediate vicinity is still largely unclear.

The researchers don't know, for example, whether a dynamo similar to the one in the spiral galaxy is at work in the gas disk on much smaller scales. It would also be conceivable that mag-





Photos and graphic: NASA/ESA and Ann Feild (Space Telescope Science Institute) (left), Hubble Space Telescope, Chris Chyzy/University of Cracow

netic field lines with opposite polarity suddenly connect and release energy that goes into accelerating the jet particles. Researchers are familiar with these magnetic short-circuits from the Sun, where they trigger outbursts of radiation and gas.

Einstein's theory of general relativity should also have an impact on the formation of jets. This theory predicts that space is entrained by a rapidly rotating black hole, and whirls around the central body like a whirlpool in the drain of a wash basin. This rotation of space carries everything along with it, including the inner region of the gas disk.

What causes the jet to accelerate? The rotation of the black hole or the rotation of the disk? "This question can be addressed using computer models only by solving the physics of the theory of general relativity and magnetohydrodynamics together," explains Silke Britzen. An extremely complicated undertaking – and actually a problem that science hasn't yet been able to solve.

"Naturally, we would prefer to observe the region in the immediate vicinity of the black hole directly using radio telescopes," says the Bonn-based researcher. Perhaps this will be possible one day with very long baseline inter-

Antennas on the field: The *Low-Frequency Array* (*LOFAR*) station in Effelsberg. Some of the 96 dipole antennas for low frequencies can be seen in the lower half of the image, while the upper half shows panels that conceal dipoles for higher frequencies. *LOFAR* is an array of many radio telescopes, spread all over Europe, whose signals are combined into a single signal. The system currently consists of 46 stations.

Photo: Frank Vinken

» The "wobble" at the bottom of the gas jet could be caused by two black holes orbiting each other at close proximity, causing the gas disk of one partner to oscillate at the bottom of the jet.

ferometry (VLBI) at short wavelengths. In this technique, a celestial body is observed simultaneously by several radio telescopes around the world, and the data is combined in a specific way. This produces a resolution that a single telescope as big as the Earth would have.

MOST JETS AREN'T STRAIGHT

VLBI is a long-established technique for radio wavelengths of a few millimeters to centimeters. If it could be expanded into the sub-millimeter range, the spatial resolution would increase as well. This next large project, in which the Max Planck Institute in Bonn is playing a leading role, is known under the project name *Event Horizon Telescope*.

Silke Britzen has recently been tracking down a further phenomenon that could be more important than previously assumed: binary black holes. When two galaxies collide and ultimately merge together, the newly formed galaxy must actually have at its center two black holes that orbit each other. Such binary systems have indeed been detected in a very small number of cases. "There are probably many more pairs than is assumed," says Britzen. She sees indications of this in some jets. "We've been observing some jets for decades now, so we also notice changes in them," says the astrophysicist. Most jets aren't quite straight, but wind like snakes, having kinks and bends.

This could be caused by conditions varying during the formation of the gas jet: "Something at the base of the jet wobbles," believes Silke Britzen. This "wobble" could be caused by two black holes orbiting each other in close proximity, causing the gas disk of one partner to oscillate at the bottom of the jet. In order to be able to explain her observation data with the aid of models, Britzen is collaborating with theoreticians. Recently, they were able to explain the jet structures of two galaxies. In one case, two black holes could orbit each other at a separation of one and a half light-years; in the other, of nine light-years. For two giants – estimated to have a mass of one billion solar masses each – this distance is downright tiny.

The enormous distances of several billion light-years will make it impossible to observe the central regions of these two galaxies directly, but according to the model, the bright base of the jets should also wobble to and fro. Silke Britzen wants to look for these variations. She puts her faith not only in increasingly precise radio telescopes, but also in the European Space Agency's (ESA) recently launched astrometry satellite *Gaia*. The researcher in Bonn will have to wait a few more years yet for its results, though. But astronomers need a lot of patience anyway. ◂

TO THE POINT

- **In spiral galaxies, magnetic fields are presumably generated in turbulent gases, as are produced by the energy of exploding stars.**
- **The rotation of the galaxies provides these locally chaotic fields with an ordered structure that follows the spiral arms.**
- **Pulsars are ideal for measuring the ordered magnetic fields of our Milky Way.**
- **Magnetic fields also exist in the central region of a galaxy, where a supermassive black hole resides in nearly all cases. They feed the invisible central body and are the reason why jets form.**

GLOSSARY

Charles Messier: The French astronomer (1730 to 1817) compiled a catalog with more than 100 celestial objects such as galaxies, gas nebulae and star clusters. The numbers from this Messier catalog are still used today.

Gaia: The *Gaia* space probe of the European Space Agency (ESA) was launched on December 19, 2013. It is expected to produce a survey of the complete sky in the visible range and chart around one billion stars astronomically, photometrically and spectroscopically.

Ionization: A process whereby an atom or molecule loses one or more electrons. This leaves a positively charged ion behind.

Michael Faraday: The English natural scientist (1791 to 1867) was one of the most important experimental physicists of the 19th century. His discoveries include electromagnetic induction. The farad, the unit of electrical capacitance, is named after him.

Polarization: Light or radio waves usually oscillate along all possible directions. A wave is polarized when it oscillates along one particular direction only.