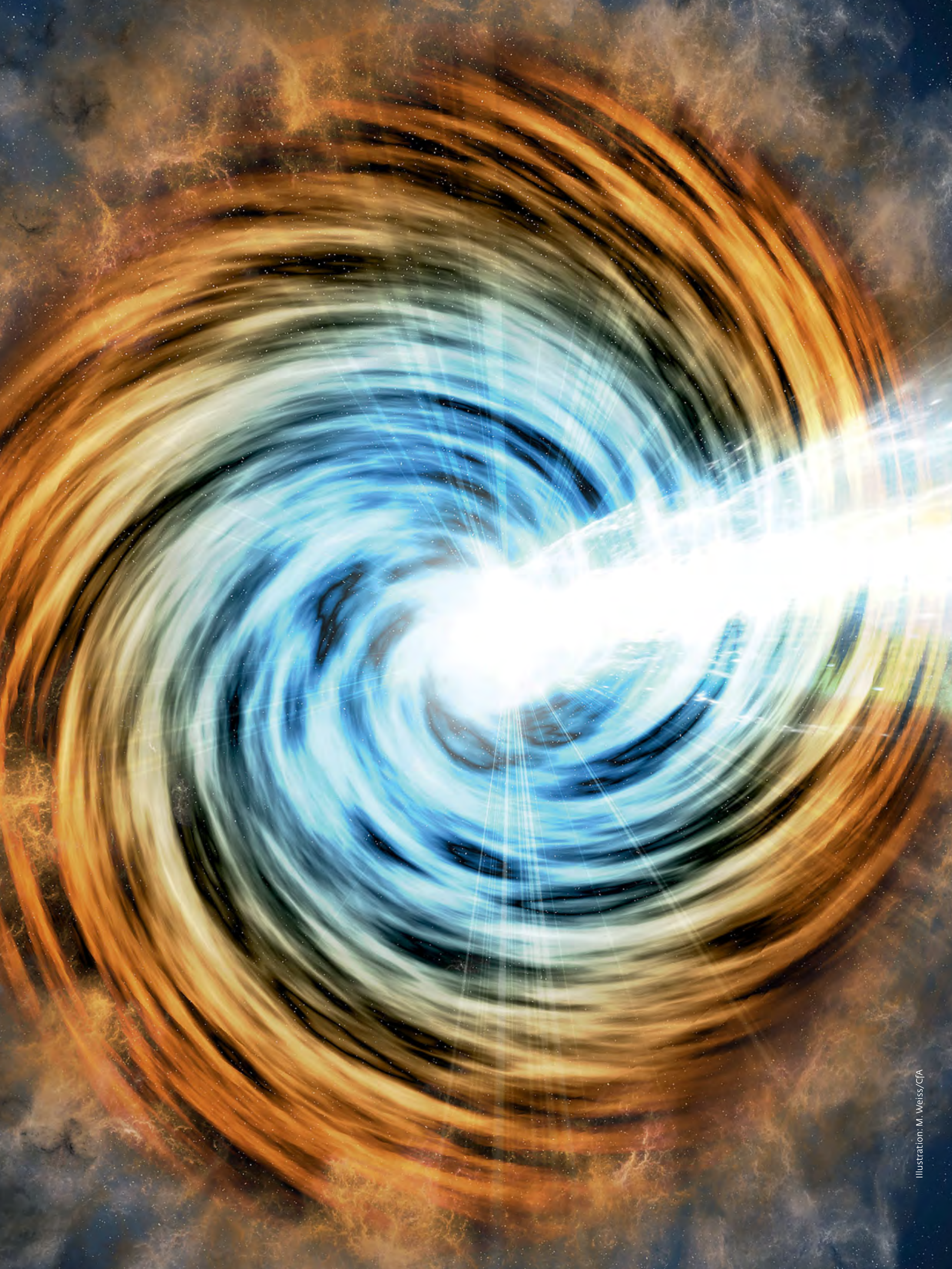


Illustration: M. Weiss/CfA

Cosmic Particle **Accelerator**

Black holes, pulsars, remnants of exploded stars – these celestial bodies accelerate particles to enormous energies and emit high-energy gamma radiation. The two observatories known as H.E.S.S. and MAGIC, whose construction was supervised by the **Max Planck Institutes for Nuclear Physics** in Heidelberg and **Physics** in Munich, make this extreme spectral region accessible.

TEXT **THOMAS BÜHRKE**

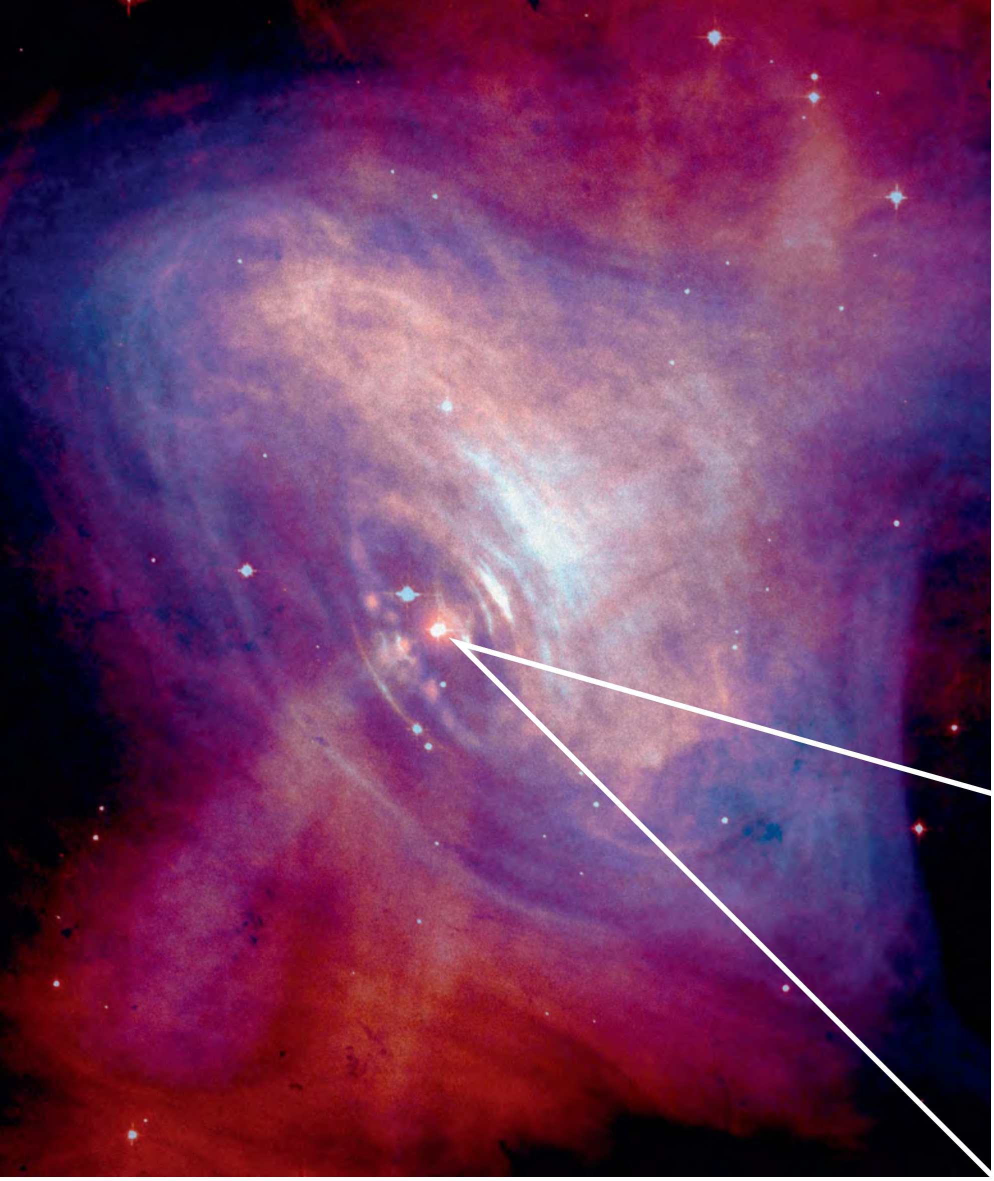
If you ask Werner Hofmann about the most recent discoveries of the H.E.S.S. observatory, he quickly starts to discuss a recently completed sky survey. “After a total of 3,000 hours of observation time, spread over ten years, we found 77 new celestial bodies that were previously unknown in this energy range,” says the Director at the Max Planck Institute for Nuclear Physics in Heidelberg. He supervised the construction of the observatory, and has been honored for this many times, most recently with the Stern-Gerlach Medal of the German Physical Society (DPG).

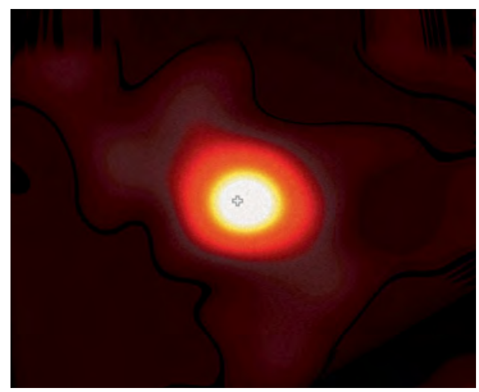
This one sentence summarizes the difficulties that astrophysics has to overcome with respect to high-energy gamma radiation: It takes a lot of time – and the largest telescopes in the world – to observe this faint radiation. Moreover, it requires a trick, which H.E.S.S. also uses: the High Energy Stereoscopic System.

The gamma radiation can’t pass through Earth’s atmosphere, but it still makes itself felt on the ground. If it penetrates into the air, it gets itself into a violent exchange of blows with the electric fields of atoms. This produces new particles that continue their journey toward Earth’s surface like an avalanche. Individual charged particles tear along faster than the speed of light.

This sounds surprising, but the speed of light in air is slightly lower than in a vacuum. It also means there is no violation of Einstein’s law, which states that a body cannot move faster than the speed of light in a vacuum. >

Mass monster shines brightly: The galaxy PKS 1441+25 belongs to the group known as quasars. A black hole at the center of the galaxy attracts matter, some of which is ejected outward at almost the speed of light in the form of two jets; the illustration shows one of these jets.





At the heart of the Crab nebula: The remnant of a supernova whose light reached Earth in the year 1054 contains a pulsar (small image). Behind this object is a neutron star that rotates about its own axis 30 times per second, emitting pulsed radiation as it does so. The MAGIC telescopes recorded gamma radiation with a record-breaking energy of 1.5 trillion electron volts.

Photos: NASA/HST/ASU/J. Hester et al. X-ray: NASA/CXC/ASU/J. Hester et al. (large image); NASA/HST/ASU/J. Hester et al. X-ray: NASA/CXC/ASU/J. Hester et al. (small image)

But in the air, these particles generate a flash of light that lasts only a few billionths of a second – a "superphotic bang," as it were.

This very weak Cherenkov radiation can be observed with large telescopes on the ground. High-energy gamma astronomy thus uses the atmosphere as an enormous fluorescent screen. The Cherenkov pool of light has a diameter of 250 to 500 meters on the ground. If this pool includes a telescope, the orientation and the intensity of the flash of light can be used to determine the energy of the gamma radiation and the direction from which it comes.

The H.E.S.S. observatory is located in the highlands of Namibia and comprises four telescopes, each with 12-meter collecting mirrors and a 28-meter-diameter reflector. Its counterpart MAGIC – Major Atmospheric Gamma-Ray Imaging Cherenkov Telescopes – is located on Roque de los Muchachos, a 2,400-meter-high mountain on La Palma in the Canary Islands. It has two telescopes, each with 17-meter collecting mirrors.

TWO OBSERVATORIES DISCOVER 139 SOURCES

"MAGIC and H.E.S.S. together can observe the whole of the northern and southern hemispheres," says Masahiro Teshima, Director at the Max Planck Institute for Physics in Munich. The two observatories complement each other slightly in their abilities, as well: "Thanks to their stereoscopic view and their large mirrors, the MAGIC telescopes can detect radiation with lower energy than H.E.S.S., but H.E.S.S. is more sensitive at very high energies and has a more detailed resolution," says Teshima's colleague David Paneque, who is responsible for coordinating the scientific work of MAGIC.

Of all 178 currently known celestial bodies that emit high-energy gamma radiation, 105 were discovered with H.E.S.S. alone, and 34 with MAGIC – a success that put H.E.S.S. among the world's top 10 observatories in 2009, together with the Hubble Space Telescope.

The gamma radiation sources are evidence of the most violent events in the universe, for instance of stellar explosions and their consequences. When a star has consumed its fuel at the end of its life, energy production comes to a halt. The center collapses within fractions of a second under the effect of gravity. The outer regions, in contrast, explode, shooting out into space and shining brightly. A supernova flares up.

If the collapsing core has less than three solar masses, a neutron star forms

» In a neutron star, matter is so strongly compressed that one teaspoon of it on Earth would weigh as much as one million long-distance trains.

– an extremely compact, rapidly rotating sphere with a diameter of 20 kilometers. Matter is so strongly compressed in such an object that one teaspoon of it on Earth would weigh as much as one million long-distance trains.

The magnetic field of the former star is also compressed in this collapse. This dipole field resembles our Earth's field with north and south poles, but is several billion times stronger and rotates several million times faster. According to the current way of thinking, electrically charged particles break loose from the star and are accelerated along the axis of the magnetic field into space at almost the speed of light.

This process generates radiation in a complex manner, predominantly in the direction of motion – like a car headlight. The swarm of particles thus generates two light cones that point into space from both the north and south poles of the neutron star.

In many cases, the axis of the magnetic field is inclined at an angle to the axis of rotation. The two light cones thus sweep through space like the beam of light from a lighthouse. If they happen to sweep across Earth, the telescopes detect radiation pulses with the rotational frequency of the celestial body. Astrophysicists call this a pulsar. These objects are deemed to be cosmic laboratories in which physical processes and theories can be tested under extreme conditions.

In 1989, astrophysicists discovered a celestial body in the high-energy gamma region for the first time. It was the Crab nebula – the remnant of a supernova explosion whose flare-up was first discovered in April 1054 by a monk in Flanders. At its center is a pulsar that rotates about its own axis 30 times per second. It can now be observed in all spectral regions, from radio waves to visible light to high-energy gamma radiation. While it is thought to be the best-investigated supernova remnant, it still throws up new mysteries time and time again.

THE MAGNETIC FIELD PLAYS THE KEY ROLE

Thanks to MAGIC, the researchers were recently able to register pulsed gamma radiation from this object with a record-breaking energy of 1.5 tera-electron volts (TeV), or 1.5 trillion electron volts. This is the most energetic pulsed radiation ever measured in a star. For comparison, visible light has an energy of two to three electron volts.

To obtain these results, which were published in early 2016, the MAGIC team had to evaluate 320 hours of observations from the period from October 2007 to April 2014. "The only thing that is clear is that the very strong magnetic field of the Crab nebula plays a key role," says Razmik Mirzoyan, spokesperson of the MAGIC collaboration and project leader at the Max Planck Institute for Physics in Munich.

In order to unravel how this cosmic accelerator works, astrophysicists and particle physicists have to work together. They conclude that electrons and their antiparticles – called positrons – are accelerated to almost the speed of light in the magnetic field and finally annihilate, but this process can likely explain only gamma radiation with energies of up to a few billion electron volts (GeV). A different mechanism must be responsible for most of the recently observed gamma pulses.

The researchers currently assume that high-energy, charged particles form a "reactive mixture" with photons of UV and X-ray radiation around 1,500 kilometers above the surface of the pulsar in that the particles transfer their energy to the photons and upgrade them to high-energy gamma quanta. This process is called the inverse Compton effect.

The gamma radiation that H.E.S.S. and MAGIC registered is therefore a secondary effect. The actual cause are particles that are accelerated under extreme cosmic conditions. Since no conversion process is perfect, the scientists think that the primary particles have more energy than the gamma radiation they produce.

Things in the surrounding explosion cloud, which expands at a speed of 1,500 kilometers per second, are very turbulent – and it is an efficient accelerator, too. This hot gaseous cloud is permeated by magnetic fields that accompany it as it moves away from the star. A game of nuclear table tennis takes place: electrically charged particles, mainly hydrogen nuclei (protons), are pushed to and fro between magnetic field fronts and continuously gain

» Computer simulations indicate that the ultrafast protons can exert a pressure and disperse interstellar clouds.

energy in the process – until they are so fast that they can escape from this ping pong. This process only works if the magnetic fields are in motion.

IN CAPTIVITY FOR SEVERAL CENTURIES

"Until recently, we expected that the particles remain trapped in the nebula for millennia before they can escape," explains Jim Hinton, who heads the Non-Thermal Astrophysics Department at the Max Planck Institute for Nuclear Physics in Heidelberg. "But according to our measurements, they escape after only several centuries."

As current models suggest, these findings are probably also relevant for the evolution of the Milky Way. The ultrafast particles break away from their accelerators at some stage and form a "gas" that is spread throughout the galaxy. "Computer simulations indicate that the ultrafast protons can exert pressure and disperse interstellar clouds," explains Hinton. This would mean that the cosmic particles suppress star formation in a galaxy. These studies are still in their infancy, but they show that the effect these particles have on the evolution of the universe is still far from being understood.

The protons and electrons whiz around all over the Milky Way and, in the process, possibly also impact on Earth. Austrian physicist Victor Franz Hess (1883 to 1964) discovered this cosmic radiation more than 100 years ago on balloon flights. The name of the telescope array in Namibia also commemorates him.

Although the currently known celestial bodies produce cosmic radiation with energies of up to 100 trillion electron volts (100 TeV), particles with much higher energies are measured. Where do they come from?

H.E.S.S. provided part of the answer at the start of 2016. An analysis of measurement data from the years 2004 to 2013 demonstrated that the gamma radiation coming from the center of our Milky Way is so energetic that an accelerator there must be speeding up protons to up to 1,000 trillion electron volts (1 peta-electron volt). The researchers therefore call it a pevatron (MaxPlanckResearch 2/2016, page 42).

Current findings indicate that this radiation is caused by a gigantic black hole because, over the past 20 years, large numbers of astronomical observa-

Photo: Axel Griesch

Good view from here: Razmik Mirzoyan (left) and David Paneque from the Max Planck Institute for Physics observe the universe with the two MAGIC telescopes on La Palma. The picture shows the researchers standing on a construction model for a new gamma radiation telescope that is also set to be built on La Palma.

Cosmic accelerator: A source of intense radiation sits at the center of the Milky Way. This artist's impression (small image) shows processes that contribute to the generation of high-energy gamma radiation. Protons (blue spheres), which are accelerated by the black hole Sagittarius A* at the center, interact with clouds of molecules in the vicinity. This produces pions, among other things, which decay almost immediately into gamma radiation photons (yellow waves).

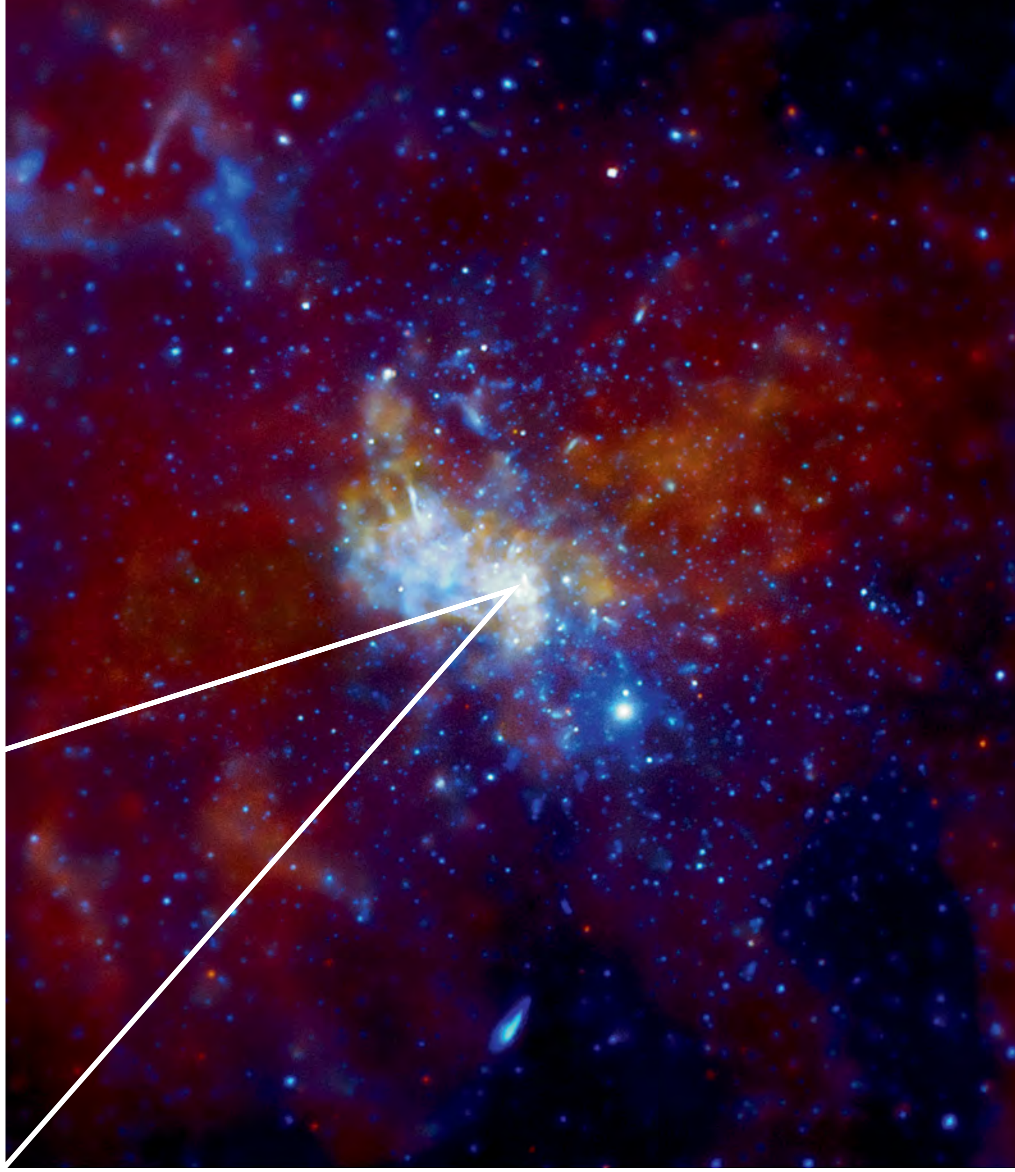


Photo: X-ray: NASA/CXC/MIT/F. Baganoff et al. (large image); graphic: Dr. Mark A. Garlick/H.E.S.S. Collaboration (small image)

tions have shown with increasing accuracy that our Milky Way rotates about a black hole concealing a mass of around 4.5 million Suns. This object, called Sagittarius A*, is surrounded by a hot disk of gas from which it draws in and then swallows matter.

The H.E.S.S. researchers conclude from the data that the cosmic accelerator in the galactic center has been in continuous operation for tens of thousands of years. However, the exact details of how and where the particles are brought up to speed are not clear. It takes place either in the immediate vicinity of the black hole or in the surrounding disk, where some of the matter that falls toward the mass monster is ejected again and accelerated in magnetic fields.

The mystery of the most energetic particles of cosmic radiation thus remains unsolved. Particles with up to 100,000 PeV have been detected by the international Pierre Auger Observatory in Argentina. Their origin is completely unclear. The main candidates are thought to be centers of galaxies that accommodate black holes but are much more massive and considerably more active than the center of our Milky Way.

GRAVITATIONAL TRAPS COLLECT SCORES OF GAS AND DUST

Astronomers know of types of galaxies that could be responsible: quasars, radio galaxies and blazars. The supermassive black holes at their centers can be as heavy as several billion solar masses and collect vast amounts of gas and dust – sometimes even entire stars – from their surroundings. This releases significantly more radiation – including high-energy gamma radiation – than is emitted by all the stars in the surrounding galaxy.

However, the large distances involved make it very difficult to detect it. Of the 13 most distant objects currently known, eight were discovered by MAGIC, two by H.E.S.S., one by the two of them together and two further ones with VERITAS, the **V**ery **E**nergetic **R**adiation **I**maging **T**elescope **A**rray **S**ystem with four 12-meter telescopes located in the US state of Arizona. The objects emitted the radiation registered when the universe was at most only two thirds of its present size.

MAGIC currently holds the distance record with its detection of the two active galaxies PKS 1441+25 and B0218+357. "We were able to track down these objects because we have used various technical measures to increase the sensitivity of MAGIC tenfold for low-energy gamma radiation since it was commissioned," says Max Planck researcher David Paneque. "This shortened the observation time needed for

Top Specialist for high energies: Werner Hofmann, Director at the Max Planck Institute for Nuclear Physics in Heidelberg, supervised the construction of the H.E.S.S. observatory in Namibia.

Bottom Intense source: The galaxy IC 310, which is 260 million light-years away, experiences violent outbursts of radiation. These are presumably connected to the magnetic field that surrounds a central, supermassive black hole. The inset shows the inner region of IC 310 in high resolution in the radio wave region.

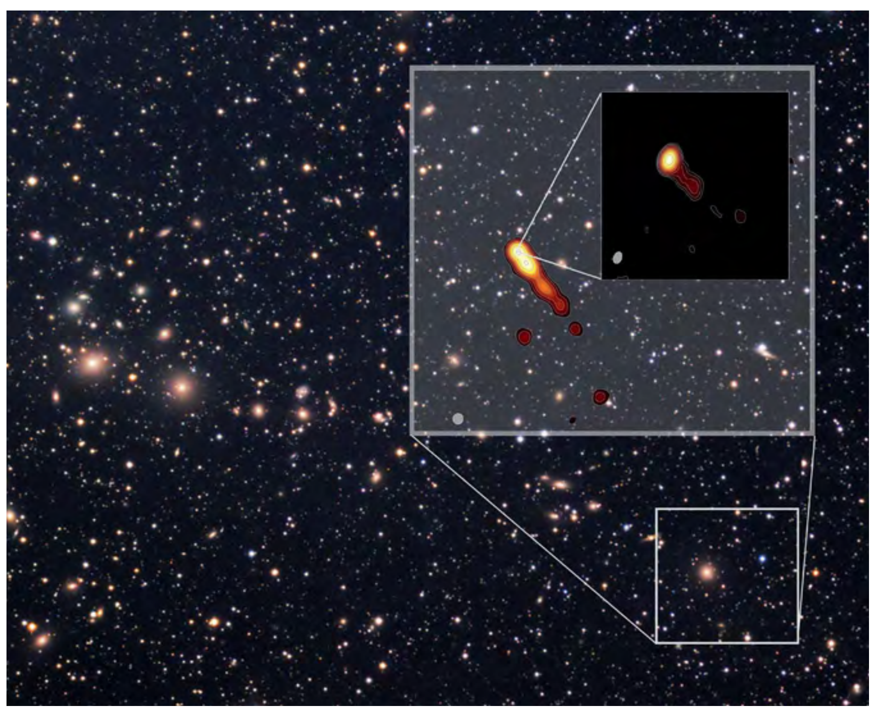


Photo: Christian Föhr/MPI for Nuclear Physics (top); photo and graphic: MPI, based on original material from H. Wilson (bottom)

very distant objects to one hundredth of the original value."

PKS 1441+25 is an example of a so-called blazar, a celestial body that often exhibits very powerful radiation bursts. The Fermi space telescope detected one of these eruptions in April 2015. A global alarm was immediately triggered at selected observatories, and when MAGIC directed its sights toward this object, the gamma radiation was up to 100 times more powerful than normal. This outburst was also observed by other telescopes, for example in the visible and X-ray ranges (MaxPlanckResearch 1/2016, page 44).

LIKE LOOKING INTO A BRIGHT HEADLIGHT

This is where the special characteristic of blazars comes into play. The central supermassive black hole accretes matter from the surrounding gaseous disk, and in doing so, diverts some of it – probably as a result of magnetic fields – into two beams or jets that shoot out into space in opposite directions at right angles to the disk. In the case of a blazar, one of the two jets is coincidentally directed toward Earth, meaning that the astronomers and their instruments look into it as if into a bright headlight.

"We believe that the outburst took place far away from the black hole in a compact region inside this jet," says David Paneque. Compact here means roughly as big as our planetary system, but not filling the whole diameter of the jet. "The mixture of particles and magnetic fields gives rise to turbulence and shocks in which the particles experience strong acceleration and thus produce radiation," says the researcher.

A further highlight is the observation of the radio galaxy IC 310, whose separation of 260 million light-years puts it more in the galactic neighborhood. On November 13, 2012, MAGIC recorded radiation outbursts of previously unknown intensity.

What was surprising about this outburst was that it lasted less than five

» Exactly what happens in the immediate vicinity of the black holes and further out in the jets is still nowhere near final clarification.

minutes. This allows conclusions to be drawn about the size of the region that flared up, because no object can illuminate faster than light takes to travel across it. The region from which the gamma radiation originated must therefore be significantly smaller than the black hole with a mass of 300 million solar masses whose diameter measures around 23 light-minutes.

"We assume that the black hole rotates rapidly and is surrounded by a magnetic field," says Paneque. As a result, strong electric fields occur in the polar regions, which accelerate electrons and their antiparticles (positrons) to almost the speed of light. These then generate the gamma radiation when they interact with their surroundings.

This can be imagined to be something like flashes of lightning that discharge every few minutes. The lightning in space releases its energy over a region the size of our planetary system. All of this takes place very close to the black hole. "With these observations, we are trying to look directly into the machinery at the center of the galaxy, as it were," says Razmik Mirzoyan.

LOCATIONS ON LA PALMA AND IN THE CHILEAN ANDES

Exactly what happens in the immediate vicinity of the black holes and further out in the jets is still nowhere near final clarification. The researchers are also puzzling over the question of whether active galaxies produce those cosmic radiation particles detected with the Pierre Auger Observatory, that plunge into the terrestrial atmosphere with extreme energies.

The successes of H.E.S.S. and MAGIC have led to the decision to create an international successor project: the Cherenkov Telescope Array (CTA). This observatory will be established at two locations: in the Chilean Andes and on La Palma, the current location of MAGIC. With 19 telescopes on La Palma and 99 in Chile, the researchers again have the whole sky in their sights.

"If everything goes according to plan, we can start with the construction as early as 2017," says Masahiro Teshima. And his colleague Werner Hofmann from Heidelberg adds: "With the CTA, the observation times needed will be a hundred times shorter than those of H.E.S.S. or MAGIC." So things are looking good for astroparticle physics. ◂

TO THE POINT

- **Astronomers currently know of 178 celestial bodies that emit high-energy gamma radiation. It can be observed indirectly from the ground with telescopes such as H.E.S.S. and MAGIC.**
- **The Crab nebula, a supernova remnant, is among the best-investigated objects. Researchers registered pulsed gamma radiation with a record-breaking energy of 1.5 trillion electron volts from the center of the pulsar.**
- **At the heart of the Milky Way sits a cosmic accelerator that accelerates protons to energies of up to 1,000 trillion electron volts (1 peta-electron volt).**
- **The Pierre Auger Observatory in Argentina has even detected particles of up to 100,000 PeV from the cosmos. Their origin is completely unclear. The main candidates are thought to be centers of galaxies with black holes that are much more massive and considerably more active than that in the Milky Way.**

GLOSSARY

Electron volt: A unit of energy, abbreviated eV. If an electron is accelerated in an electric field, its kinetic energy changes by one electron volt when the accelerating voltage is one volt. In the largest accelerator on Earth, the LHC, protons are accelerated to approximately 7 TeV (7×10^{12} eV). The most energetic particles in the cosmic radiation have energies of more than 10^{20} eV. The energy of radiation can also be stated in the unit eV.

Jets: Bundled beams of matter in which particles fly into space in a specific direction at almost the speed of light. They are produced when a black hole accretes gas from a rotating disk. As this happens, only a portion of the gas in the disk plunges into the gravitational trap – the other portion streams away at right angles to the plane of rotation in the form of jets.