First detection of the cosmic monster explosions with ground-based gamma-ray telescopes

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Gamma-ray bursts can be triggered by the explosion of a super massive star, collapsing into a black hole. From the vicinity of the black hole, powerful jets shoot in opposite directions into space, accelerating electrically charged particles, which in turn interact with magnetic fields and radiation to produce gamma rays. Credit: DESY, Science Communication Lab

The strongest explosions in the universe produce even more energetic radiation than previously known: Using specialized telescopes, two international teams have registered the highest energy gamma rays ever measured from so-called gamma-ray bursts, reaching about 100 billion times as much energy as visible light. The scientists of the H.E.S.S. and MAGIC telescopes present their observations in independent publications in the journal *Nature*. These are the first detections of gamma-ray bursts with ground-based gamma-ray telescopes. DESY plays a major role in both observatories, which are operated under the leadership of the Max Planck Society.

Gamma-ray bursts (GRB) are sudden, short bursts of gamma radiation happening about once a day somewhere in the visible universe. According to current knowledge, they originate from colliding neutron stars or from supernova explosions of giant suns collapsing into a black hole. "Gamma-ray bursts are the most powerful explosions known in the universe and typically release more energy in just a few seconds than our Sun during its entire lifetime—they can shine through almost the entire visible universe," explains David Berge, head of gamma-ray astronomy at DESY. The cosmic phenomenon was discovered by chance at the end of the 1960s by satellites used to monitor compliance with the nuclear test ban on Earth.

Since then, astronomers have been studying gamma-ray bursts with satellites, as Earth's atmosphere very effectively absorbs gamma rays. Astronomers have developed specialized telescopes that can observe a faint blue glow called Cherenkov light that cosmic gamma rays induce in the atmosphere, but these instruments are only sensitive to gamma rays with very high energies. Unfortunately, the brightness of gamma-ray bursts falls steeply with increasing energy. Cherenkov telescopes have identified many sources of cosmic gamma rays at very high energies, but no gamma-ray bursts. Satellites, on the other hand, have much too small detectors to be sensitive to the low brightness of gamma-ray bursts at very high energies. So, it was effectively unknown, if the monster explosions emit gamma rays also in the very-high-energy regime.

Scientists have tried for many years, to catch a gamma-ray burst with Cherenkov telescopes. Then suddenly, between summer 2018 and January 2019, two international teams of astronomers, both involving DESY scientists, detected gamma rays from two GRB events for the first time from the ground. On 20 July 2018, faint afterglow emission of GRB 180720B in the gamma-ray regime was observed with the 28-meter telescope of the High-Energy Stereoscopic System H.E.S.S. in Namibia. On 14 January 2019, bright early emission from GRB 190114C was detected by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes on La Palma, and immediately announced to the astronomical community.

Both observations were triggered by gamma-ray satellites of the US space agency NASA that monitor the sky for gamma-ray bursts and send automatic alerts to other gamma-ray observatories upon detection. "We were able to point to the region of origin so quickly that we could start observing only 57 seconds after the initial detection of the explosion," reports Cosimo Nigro from the MAGIC group at DESY, who was in charge of the observation shift at that time. "In the first 20 minutes of observation, we detected thousands of photons from GRB 190114C."

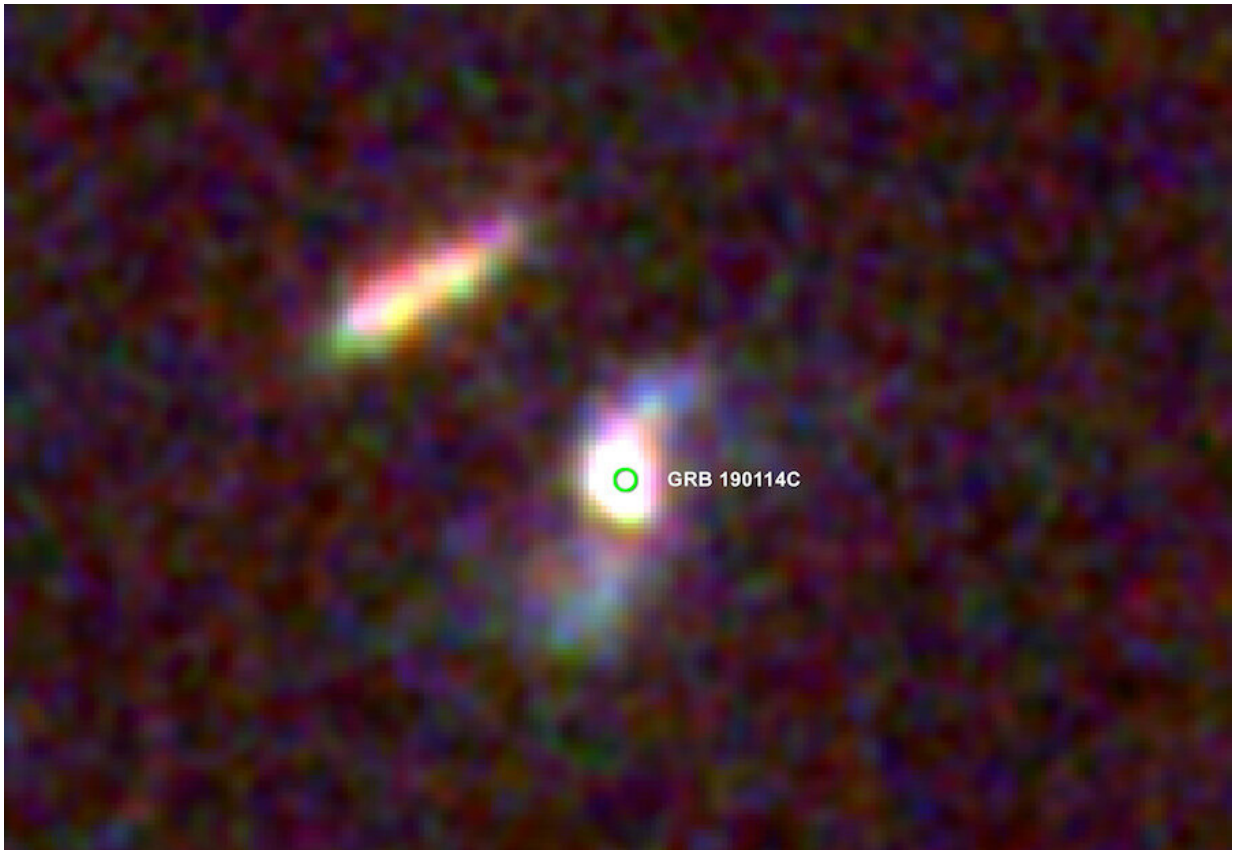
MAGIC registered gamma-rays with energies between 200 and 1000 billion electron volts (0.2 to 1 teraelectronvolts). "These are by far the highest energy photons ever discovered from a gamma-ray burst," says Elisa Bernardini, leader of the MAGIC group at DESY. For comparison: visible light is in the range of about 1 to 3 electron volts.

The rapid discovery allowed to quickly alert the entire observational community. As a result, more than twenty different telescopes had a deeper look at the target. This allowed to pinpoint the details of the physical mechanism responsible for the highest-energy emission, as described in the second paper led by the MAGIC collaboration. Follow-up observations placed GRB 190114C at a distance of more than four billion light years. This means, its light traveled more than four billion years to us, or about a third of the current age of the universe.

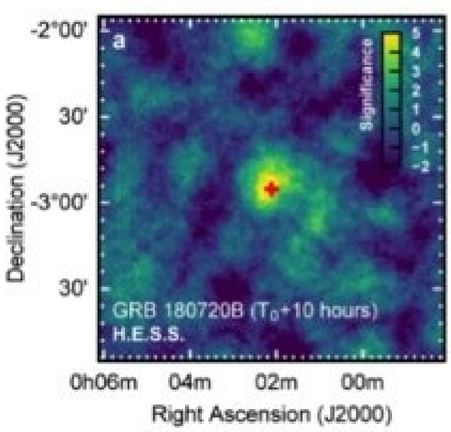
GRB 180720B, at a distance of six billion light years even further away, could still be detected in gamma rays at energies between 100 and 440 billion electron volts long after the initial blast. "Surprisingly, the H.E.S.S. telescope observed a surplus of 119 gamma quanta from the direction of the burst more than ten hours after the explosion event was first seen by satellites," says Stefan Ohm, head of the H.E.S.S. group at DESY.

"The detection came quite unexpected, as gamma-ray bursts are fading fast, leaving behind an afterglow which can be seen for hours to days across many wavelengths from radio to X-rays, but had never been detected in very-high-energy gamma rays before," adds DESY theorist Andrew Taylor, who contributed to the H.E.S.S. analysis. "This success is also due to an improved follow-up strategy in which we also concentrate on observations at later times after the actual star collapse."

The detection of gamma-ray bursts at very high energies provides important new insights into the gigantic explosions. "Having established that GRBs produce photons of energies hundreds of billion times higher than visible light, we now know that GRBs are able to efficiently accelerate particles within the explosion ejecta," says DESY researcher Konstancja Satalecka, one of the scientists coordinating GRB searches in the MAGIC collaboration. "What's more, it turns out we were missing approximately half of their energy budget until now. Our measurements show that the energy released in very-high-energy gamma-rays is comparable to the amount radiated at all lower energies taken together. That is remarkable!"



GRB 190114C, located about 4.5 billion light-years away in the constellation Fornax. Credit: NASA, ESA, and V. Acciari et al. 2019



GRB 180720B in very-high-energy gamma light, 10 to 12 hours after the burst as seen by the large H.E.S.S. telescope. The red cross indicates the position of GRB 180720B, determined from the optical emission of the GRB. Credit: H.E.S.S. collaboration

To explain how the observed very-high-energy gamma rays are generated is challenging. Both groups assume a two-stage process: First, fast electrically charged particles from the explosion cloud are deflected in the strong magnetic fields and emit so-called synchrotron radiation, which is of the same nature as the radiation that can be produced in synchrotrons or other particle accelerators on Earth, for example at DESY. However, only under fairly extreme conditions would the synchrotron photons from the explosion be able to reach the very high energies observed. Instead, the scientists consider a second step, where the synchrotron photons collide with the fast particles that generated them, which boosts them to the very high gamma-ray energies recorded. The scientists call the latter step inverse Compton scattering.

"For the first time, the two instruments have measured gamma radiation from gamma-ray bursts from the ground," concludes Berge. "These two groundbreaking observations have established gamma-ray bursts as sources for terrestrial gamma-ray telescopes. This has the potential to significantly advance our understanding of these violent phenomena." The scientists estimate that up to ten such events per year can be observed with the planned Cherenkov Telescope Array (CTA), the next generation gamma-ray observatory. The CTA will consist of more than 100 individual telescopes of three types that will be built at two locations in the northern and southern hemispheres. DESY is responsible for the construction of the medium-sized telescopes and will host CTA's Science Data Management Centre on its campus in Zeuthen. CTA observations are expected to start in 2023 at the earliest.

More information: A very-high-energy component deep in the γ-ray burst afterglow; The H.E.S.S. collaboration; *Nature*, 2019; DOI: 10.1038/s41586-019-1743-9 , nature.com/articles/s41586-019-1743-9

Teraelectronvolt emission from the γ-ray burst GRB 190114C; The MAGIC collaboration; Nature, 2019; DOI: 10.1038/s41586-019-1750-x , nature.com/articles/s41586-019-1750-x

Observation of inverse Compton emission from a long γ-ray burst; The MAGIC Collaboration; *Nature*, 2019; DOI: 10.1038/s41586-019-1754-6 , nature.com/articles/s41586-019-1754-6

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