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Astroparticle Physics with Very-High-Energy Photons

When in 1912 the Austrian physicist and Nobel Prize winner Victor Francis Hess discovered the cosmic rays, an intensive radiation from the universe, consisting mainly of high energy protons and heavier atomic nuclei, he couldn't know that this was the beginning of a long and exciting story. Not only was modern elementary particle physics born in the research on cosmic rays. But also the quest for the origin of this radiation and the astrophysics of its sources developed into a fascinating field of research with plenty of unanswered questions and phenomena not fully understood. The sources of cosmic rays are probably violent energy transformers like supernovae, neutron stars and black holes. The Humboldt-Universität groups for experimental particle physics are participating in a coordinated international effort to solve this almost 100 year old puzzle. Two observatories for highest energy gamma-rays have been constructed to identify the sources of high energy radiation in the northern and the southern sky. They open a new frequency window for astronomy which allows studying the laws of nature under extreme conditions far from anything realizable in earth-bound laboratories.

Only a tiny fraction of the light reaching us from the universe is in the visible range which covers about one octave from red to blue. The full electromagnetic spectrum observed today ranges over about 70 decades in frequency, from radio to gamma rays. Using the detection techniques developed in elementary particle physics experiments at earth-bound particle accelerators, astronomy at photon energies in the TeV range became possible. A TeV is the energy an electron reaches when running through a voltage difference of 10^{12} Volts. The field was pioneered by the Whipple Telescope [1] which detected first sources towards the end of the eighties. Important refinements in the nineties by the HEGRA Observatory [2], especially the introduction of stereoscopy by using several telescopes in parallel, brought the field to maturity. The time had come for the next generation of experiments with more sensitive instruments in order to fill the still scarcely populated sky in TeV-light.

Fig. 1
The High Energy Stereoscopic System (H.E.S.S.) in Namibia.

It was at that time that the Humboldt-Universität (working group Lohse) started to participate in the design and construction of a large telescope array in Namibia, the H.E.S.S. (High Energy Stereoscopic System) observatory (Fig. 1). End of 2003, four telescopes (called the phase 1 of the project) were completed and fully commissioned. H.E.S.S. is exploring the southern sky, particularly interesting because of the excellent observability of the center of our galaxy which is known to house a giant black hole of 2.6 million solar masses.

In 2003 the Humboldt-Universität (working group Pavel) also joined the MAGIC observatory (Fig. 2) on La Palma, which is currently in the commissioning phase. H.E.S.S. and MAGIC are in many ways complementary. Together, they cover both the northern and the southern sky. H.E.S.S. uses the stereoscopic technique with moderate size telescopes for largest sensitivities up to highest energies and for precise characterization of the morphology of extended sources. MAGIC employs a single but very large telescope in order to push the energy threshold for gamma rays as low as possible, maximizing the number of detectable sources, and is optimized for swift movements to promptly react on satellite-alerts for sudden gamma ray outbreaks (so-called bursts).

At the same time, our partner institute DESY Zeuthen pursues an alternative approach for high energy astrophysics using TeV neutrinos as electrically neutral messenger particles from cosmic ray sources. Two observatories, BAIKAL at the Lake Baikal and AMANDA at the South Pole are currently in operation. A cubic kilometer size detector, ICECUBE, is under construction at the South Pole. Recently the Humboldt-Universität (working group Kolanoski) also joined this project.

Cosmic Accelerators and Fundamental Questions

Although the origin of cosmic rays is still open, the last decade has taught us much about the possible candidates. The enormous advances in experimental techniques were accompanied by similarly impressive

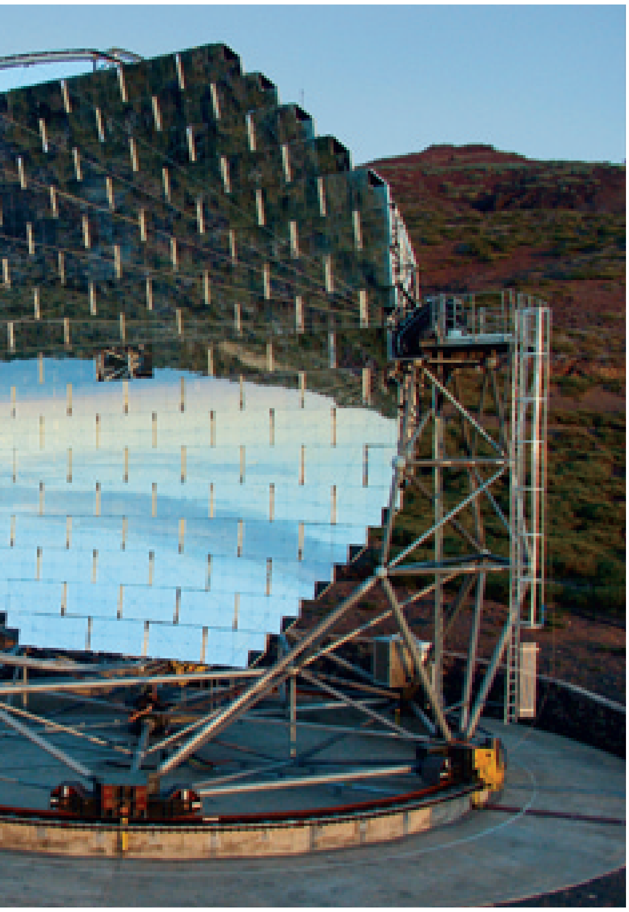


Fig. 2
The MAGIC telescope on La Palma.

Fig. 3
Optical image of the Crab supernova remnant. (Image: ESO – European Southern Observatory)

progress in theoretical understanding. Very basic considerations show that no material body can be hot enough to be the source of TeV-photons. Therefore the radiation must be of non-thermal, dynamical origin. Only violent processes are able to produce the high energies of the photons, which are in turn fingerprints of acceleration of charged particles like electrons or protons, the latter being the prime component of the cosmic rays discovered by Victor Hess.

The most important class of such processes consists of star explosions, so-called supernovae, in which a collapse of the core of a star converts enormous amounts of gravitational energy into kinetic energy of the out blown material. This kinetic energy is typically comparable to the total amount of radiation energy our sun emits during its whole life cycle of 9 billion years. Given the rate of supernova explosions in our galaxy (roughly three per century), an efficient acceleration mechanism, converting about 10 percent of the kinetic energy of the explosion into energy of cosmic rays, would be needed to explain the power consumption of the galactic cosmic ray acceleration from supernova explosions alone. The prime candidate for such a mechanism is the so-called shock wave accelerator as explained below.

Fig. 3 shows a picture (in visible light) of the Crab Nebula, a remnant of a supernova explosion in the year 1054 AD. It was the first strong source of TeV-gamma rays discovered by the Whipple telescope in 1989 and serves today as a standard candle for gamma rays. The explosion cloud is filled by plasma heated by a high-energy wind of electrons. These are emitted from the remainder of the collapsed core of the exploded star, a rapidly rotating, highly magnetized neutron star (a so-called pulsar) in the center of the cloud. The electrons reveal themselves by the bluish light from the interior of the cloud which can be interpreted as synchrotron radiation. The gamma rays from this kind of supernova remnants are hence strongly linked to accelerated electrons.

Astroteilchenphysik mit hochenergetischen Photonen

Als der österreichische Physiker und Nobelpreisträger Victor Francis Hess 1912 die kosmische Strahlung – die im Wesentlichen aus hochenergetischen Protonen und schwereren Atomkernen besteht – entdeckte, konnte er nicht wissen, dass dies der Beginn einer langen und aufregenden Geschichte sein würde. Nicht nur war die Erforschung der kosmischen Strahlung die Geburtsstunde der Elementarteilchenphysik, sondern die Suche nach deren Ursprung und Quellen entwickelte sich auch zu einem faszinierenden Forschungsfeld mit einer Fülle offener Fragen und Phänomenen, die bis heute nicht völlig verstanden sind. Die Quellen der kosmischen Strahlung sind wahrscheinlich gewaltige Energiewandler wie Supernovae, Neutronensterne und schwarze Löcher. Forschergruppen der Humboldt-Universität beteiligen sich an den international koordinierten Bemühungen, dieses beinahe 100 Jahre alte Puzzle zu lösen. Zwei Observatorien für hochenergetische Gamma-Strahlen wurden aufgebaut, um die Quellen der hochenergetischen Strahlung im nördlichen und südlichen Sternenhimmel zu identifizieren. Sie eröffnen ein neues »Frequenzfenster« für die Astronomie, das die Erforschung der Naturgesetze unter extremen Bedingungen ermöglicht, die in keinem Labor der Erde simuliert werden könnten.

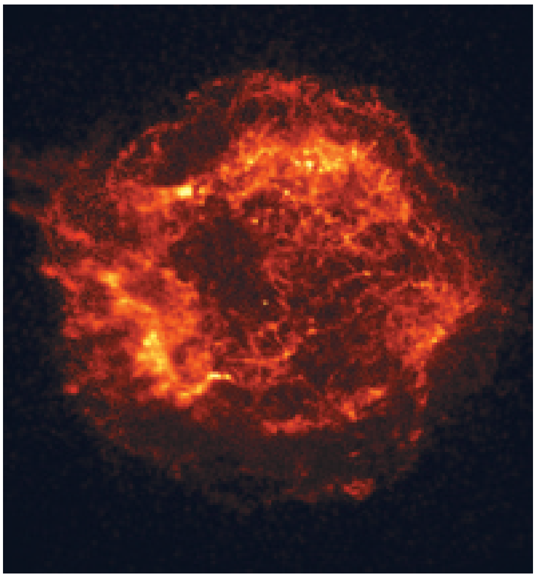


Fig. 4
X-ray image of the supernova remnant Cassiopeia A. (Image: NASA and Chandra Science Center)

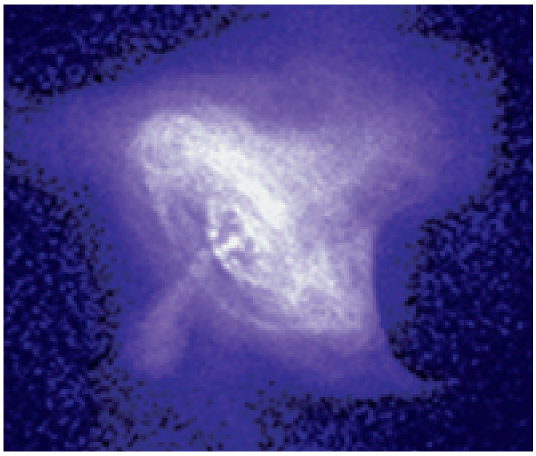


Fig. 5
X-ray image of the neighborhood of the Crab pulsar. (Image: NASA/CXC/SAO)

In order to find signatures of accelerated protons and hence the cosmic radiation, it is most promising to search for gamma radiation from a second class of supernova remnants which are not heated by an electron wind from a central pulsar. An example for such a hollow, shell-type supernova remnant is shown in Fig. 4 (picture taken in X-rays). Theory predicts that the expanding shell, a plasma shock front, is a very

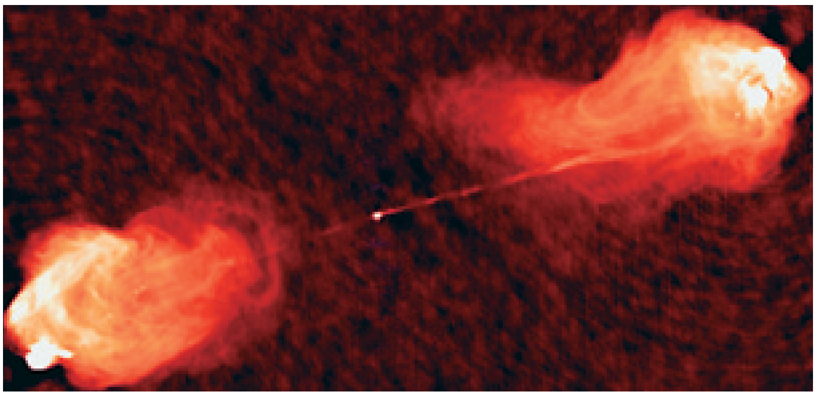


Fig. 6
Radio image of the active galaxy Cygnus A. (Image: NRAO – National Radio Astronomy Observatory, USA)

efficient accelerator for charged particles reflected by magnetic fields and meandering back and fourth along the shock front. These accelerated particles will consist both of electrons and protons and both components will give rise to TeV gamma radiation. The spectral features of the latter allow disentangling the two components and clarifying whether protons are really accelerated in supernova explosions or not.

The pulsars, remnants of collapsed stars, are themselves possible sources of high energy radiation. In a simplified picture they are giant atomic nuclei consisting mostly of neutrons (neutron stars) and being held together by gravity. They typically have radii of only 10 km while being as massive as our sun, and they are spinning around an axis up to hundreds of times per second. Frozen into the neutron stars and the surrounding plasma are unimaginably large magnetic fields of up to 10^9 Tesla. The neighborhood of the pulsar in the Crab nebula, as seen in X-rays, is shown in Fig. 5 for illustration. One sees rings of material thrown out from the center and jet-like emission features perpendicular to the rings. What happens in the vicinity of such extreme objects, where gravitational and electromagnetic forces are orders of magnitude beyond anything we can test in the laboratory? We are far from a complete understanding. A way to shed light on the physics of pulsars is to systematically analyze the time structure and spectroscopic features of light flashes at all energy bands. Up to now, no pulsed signal has ever been observed in the energy range accessible to gamma ray telescopes, but with higher sensitivities and new detection strategies both H.E.S.S. and MAGIC have a chance to achieve a break-through. As a promising first step, in March 2004, the H.E.S.S. collaboration discovered a new source type [3], a pulsar accompanying a large star and interacting with its solar wind. The object is being continuously monitored since then and analysis is ongoing at the Humboldt-Universität.

A promising class of extragalactic sources for high energy radiation consists of giant black holes of a billion solar masses, suspected to be at the cores of so-called active galaxies. These black holes are continuously fed by stellar material from the surrounding galaxy spiraling in a so-called accretion disk into the center. Perpendicular to this accretion disk, tightly collimated plasma beams (jets) are emitted at relativistic energies across many thousands of light years, finally stopped in large lobes of turbulent flow. As an example, the galaxy Cygnus A is shown (in the radio waveband) in Fig. 6. The small spot at the center of the picture represents the galaxy which is tiny compared to the length of the jets. It is believed that particle acceleration takes place in shock waves within the jets. Again, TeV photons are the fingerprints of such acceleration processes. These photons have been observed for a number of active galaxies where the jets are almost aligned with the line of sight (so-called blazars), in which case both the photon energy and the flux are boosted due to the relativistic motion of the source material towards the earth. Many other source classes exist and we now even know TeV gamma ray sources which have not been seen at any other wavelength.

However, gamma ray astronomy also sheds light on other fundamental physics questions which are not connected to pure astrophysics but to neighboring fields like cosmology and elementary particle physics. One important example is the question of the nature of the mysterious dark matter, an unknown form of matter which we only detect indirectly via its gravitational effect, and which is twenty times more abundant in the universe than the matter we know today. Particle physicists speculate whether this dark matter could consist of a new type of particles, so-called supersymmetric particles which are heavy, electrically neutral, and stable and which interact extremely weakly with other particles. How would one see these directly? One way is to try to produce them in giant particle accelerators, like the Large Hadron Collider LHC, currently being built at CERN in Geneva. A second possibility, the only one to show that such new particles really constitute the dark matter, is offered by the fact that these particles occasionally annihilate. This should especially happen in places of higher densities like in the center of our galaxy or in large globular clusters where the dark matter particles gradually accumulate. In the annihilation process normal particles are produced, amongst them high energy gamma rays which are detected by our observatories and are identifiable by characteristic features in the measured spectra. And even more exotic question can be addressed. What is the structure of space time at very small scales, tested by the short wavelength TeV photons? Is the speed of light an energy independent constant of nature, or is there energy dispersion due to the hypothesized foamy structure of the quantum vacuum? What is the nature of the recently established dark energy which acts like an anti-gravitational force blowing up the universe at ever increasing speeds? Can we use the absorption of the gamma rays on the long way from distant galaxies to the earth to measure the cosmological infrared radiation field which is connected to fundamental parameters of the evolution of the universe since the big bang?

Detection Technique: Blue Flashes from Black Holes

How then are TeV gamma rays observed? This is not easy since cosmic gamma rays interact with the atoms in the atmosphere before they reach the ground. One therefore often studies cosmic rays using particle detectors installed on satellites orbiting the earth. However, the TeV gamma rays are so rare that the satellite detectors are much too small to achieve any useful detection rate.

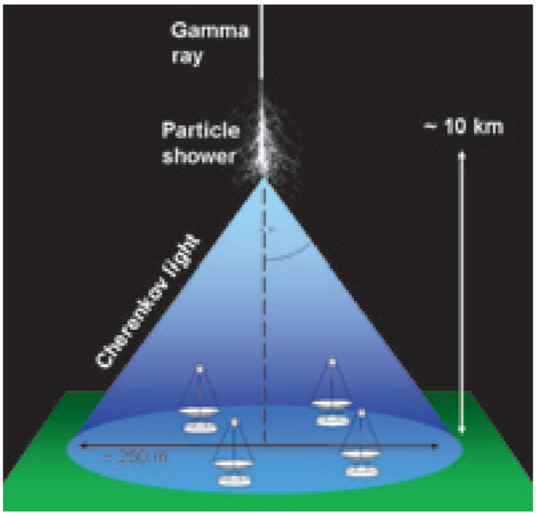


Fig. 7
Detection of TeV gamma rays via Cherenkov light produced in air showers.

The Cherenkov technique utilized by MAGIC and H.E.S.S. is illustrated in Fig. 7. Imaging telescopes equipped with ultra-fast photomultiplier pixel cameras are installed on the surface, typically in high altitude like 2000 m above sea level. When cosmic gamma rays interact in the atmosphere, they produce a cascade of particles, a so-called shower, which has a length of a few kilometers and has its maximum in an altitude of roughly 10 km. The shower particles don't reach the ground either, but they emit so-called Cherenkov light in a cone of around 1° opening angle, illuminating a circle of a few hundred meters diameter on the ground. The Cherenkov light has bluish color and can be in principle detected by classical photo-sensors. However, it is very faint and arrives on the ground in a short flash of few nanoseconds length. A telescope

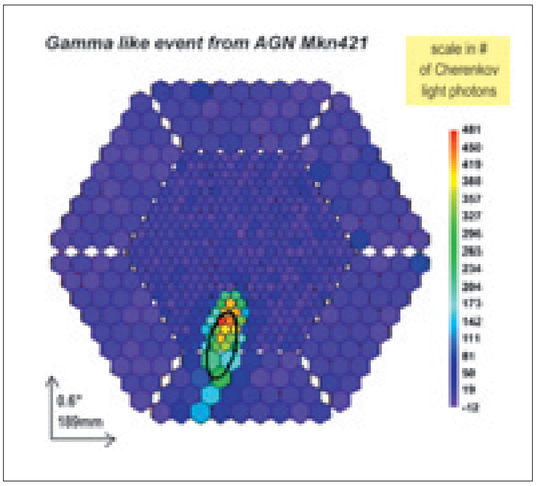
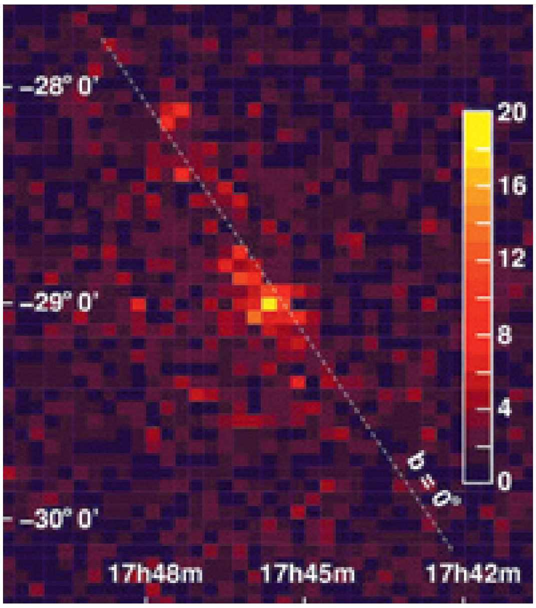


Fig. 8
Cherenkov image of a gamma ray shower in the photomultiplier pixel camera of the MAGIC telescope during the observation of the active galaxy Mkn421 in April 2004.

illuminated by the Cherenkov light therefore has to have sensitive detectors like photomultiplier tubes and ultra-fast electronics to allow for triggering and for short exposure times of a few nanoseconds. Longer exposure times would lead to hopeless overexposures of the images because of night-sky background, mostly from scattered starlight.

A typical image seen by the photomultiplier matrix of the MAGIC telescope is shown in Fig. 8. The brightness of the image allows reconstructing the energy of the original cosmic gamma ray within about 20%. The orientation of the image allows reconstructing one projection of the flight direction of the cosmic gamma ray. In the case of H.E.S.S., each shower illuminates several telescopes which are looking at the shower from different directions. This stereoscopic method allows to reconstruct the full flight direction of the cosmic gamma ray (and therefore the source position) event-by-event with a precision of 0.1°.

Fig. 9
TeV gamma ray image of the center of our galaxy.



Discoveries from Early Data Demonstrate the Potential of the Observatories

We are just in the start-up phase of the two observatories but already now a multitude of important physics insights have been achieved, some of them highly exciting, and even first rank discoveries have been made. Two examples may serve as illustration.

From the observation of our galactic center, the H.E.S.S. collaboration has discovered a strong TeV gamma ray signal with a hard spectrum [4]. Fig. 9 shows an intensity plot which locates the source with unprecedented angular resolution. It is found that the source position is compatible with the location of the dynamic galactic center Sgr A* which is known to house a black hole of 2.6 million solar masses. In addition signs of gamma ray emission are also seen along a band coinciding with the galactic plane. The observation of the galactic center is ongoing and theoretical implications of the data are being worked on.

With its excellent angular resolution, H.E.S.S. has been able for the first time to resolve the morphology of an extended source and to correlate it with that seen in a different frequency range (X-rays) [5]. This source, the shell type supernova remnant RX J1713.7-3946, shows strong emission of X-rays and gamma rays from the shock wave region of the expanding remnant of the exploded star, as expected from the shock wave acceleration theory. This is an important step in identifying the acceleration sites of cosmic rays. This discovery, first presented on the summer conferences 2004, created a lot of excitement in the community and is subject of intense discussion.

The Future: Higher, Larger, Faster

After many years of challenging research and development the time of harvest in TeV gamma astronomy has clearly come. With both H.E.S.S. and MAGIC up to speed and similar observatories in Australia and the U.S.A. under construction, our view of the gamma ray sky will change completely in the coming years. Of course, all observatories have planned upgrade steps right from the beginning to further improve their performances. MAGIC will build a second telescope to profit from stereoscopy. H.E.S.S. will add one or two larger telescopes to increase the sensitivity and at the same time to reduce the energy threshold. In general all collaborations are already involved in research and development for the next steps. New fast photon detection devices, robotic telescope operation and the possibility to operate a large telescope array in high altitudes of 5000 m above sea level are topics very high on the priority list. The working groups at the Humboldt-Universität will actively participate in this program and continue to offer students the chance to be trained in a broad variety of fields, ranging from real time computing and networking over electronics development to data analysis, and also to gain experience with working in international teams.

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