Recent Results from the MAGIC Telescopes

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MAGIC consists of two imaging air Cherenkov telescopes located at La Palma, Spain. Since 12 years, the telescopes are performing scientific observations of gamma rays with energies between 35 GeV and 50 TeV.

Scientific highlights from MAGIC concerning both galactic and extragalactic sources in the context of multi-messenger astronomy are presented. Among these, measurements of the TeV emission from Crab observations are shown. Also, the ultra-fast variability of IC 310, which challenges jet emission models in AGNs, is discussed. Furthermore, the detection of very-high-energy gamma-ray emission from two active galaxies, B0 218+357 and PKS 1441+25, located at redshift of ∼0.94 is presented.

1 Introduction

Cosmic rays were discovered more than one hundred years ago by Victor Hess. Still, there is an increasing research field connected to their nature, their origin, and their propagation. Due to the deflection of the charged particles of the cosmic rays, e.g., by the magnetic fields of the interstellar and the intergalactic medium they reach the Earth mostly isotropic.

Interactions of cosmic rays among themselves and/or with photon fields result in the production of pions. These decay into neutral and charged muons, which themselves decay into gamma rays and neutrinos, respectively. This means that the detection of gamma rays and neutrinos from point sources can provide an unambiguous signature of the origin of the cosmic rays. While the detection of neutrinos is more challenging, a large and rising number of sources of gamma rays have already been discovered. While in the high-energy gamma-ray regime $20\,\mathrm{MeV} \lesssim E \lesssim 100\,\mathrm{GeV}$, satellite-based instruments such as the *Fermi*- LAT instrument are used, gamma-rays at higher energies ($100\,\mathrm{GeV} \lesssim E \lesssim 100\,\mathrm{TeV}$) are detected with ground-based telescopes based on the Imaging Air Cherenkov Technique.

The Major Atmospheric Gamma Imaging Cherenkov Telescope (MAGIC) is a system of two Imaging Air Cherenkov Telescopes (IACT) with a mirror dish diameter of 17 m each, separated by a distance of 85 m. It is located at the Observatorio del Roque de los Muchachos on the Canary island of La Palma, Spain, at an altitude of ∼2200 m above sea level. The construction of the first telescope, MAGIC-I, was completed in 2003 and it performs scientific observations since 2004. In 2009, the second telescope, MAGIC-II, joined in. Since then, the two telescopes are working together as a stereoscopic system which allows an improved performance in terms of sensitivity and angular resolution, among other things. The energy range covered by MAGIC overlaps with the accessible range of Fermi-LAT at low energies, starting at 50 GeV (standard trigger) and reaching up to 50 TeV. Some observations are also performed with a new digitalized trigger technique and allows for measurements even below 50 GeV [1].

The IACT technique is based on the production of air showers by highly energetic particles in the Earth's atmosphere. If a gamma-ray photon with more than 10 MeV of energy enters the atmosphere the production of an electron-positron pair dominates the absorption. Due to an interaction with molecules in the air, secondary gamma rays are produced by Bremsstrahlung. These secondaries again may produce e^+e^- pairs. The resulting electromagnetic cascade continues until the average energy reaches the value at which the losses due to ionization and Bremsstrahlung are equal. The secondary electrons in those showers, if energetic enough, i.e., when moving faster than the speed of light in the atmosphere, can activate the emission of Cherenkov photons in a cone with a small opening angle. Inside the Cherenkov light pool, mirror telescopes can be placed in order to measure the Cherenkov light. The spectrum of this light is mostly in the optical and ultra-violet range. The faint emission can be measured with photo-multipliers as also done with MAGIC. Due to a short duration of the Cherenkov pulses, a fast readout system needs to be connected with the telescope. Besides showers introduced by gamma rays, showers induced by hadrons (e.g., protons) exist. Those showers form the dominating background and hence are the limiting factor for ground-based gamma-ray astronomy. Typically, one gamma-ray event observed by an IACT telescope is hidden behind 1000 background events.

With this technique, MAGIC is able to achieve a sensitivity of 0.6% of the Crab Nebula flux for a $5\,\sigma$ detection in 50 h of observation in the best range at energies of $E \sim 400\,\mathrm{GeV}$. The angular and energy resolution, both dependent on the energy, is $0.1^\circ - 0.07^\circ$ and 15–20%, respectively. Details about the performance of MAGIC can be found in [2].

The scientific focus of MAGIC is set on the investigation of the gamma-ray emission from galactic objects of various types as well as on active galactic nuclei and gamma-ray bursts as extragalactic objects. Follow-up observations of gamma-ray bursts by MAGIC are reported in [3]. Furthermore, MAGIC concentrates on the indirect measurements of dark matter [4, 5, 6] as well as on setting constrains on the cosmic rays [7], the extragalactic background light [8], the Lorentz invariance violation [9], and the intergalactic magnetic field. In this paper, only results from galactic objects, active galactic nuclei, and follow-up observations of neutrino events are being reviewed.

2 Galactic science

MAGIC observes a variety of galactic objects which are mostly in connection with the end stages of stars, e.g., novae, supernova remnants, pulsars, and pulsar wind nebulae.

2.1 Crab Nebula and its pulsar

The Crab Nebula is the standard candle for the very-high-energy astrophysics at energies $E > 50\,\mathrm{GeV}$. Although it is known to be a TeV emitter for a long time this pulsar wind nebula is still of interest for current research. Recent MAGIC observations between October 2009 and April 2011 of 69 h revealed a spectrum ranging over the entire accessible energy range over three decades in energy [10]. Together with *Fermi*-LAT data, these yielded the most precise measurement of the inverse Compton peak of $53^{+3_\mathrm{stat}+31_\mathrm{syst}}_{-3_\mathrm{stat}-13_\mathrm{syst}}$ GeV that is dominated by systematic effects. Only a modified log-parabola function with an exponent of 2.5 instead of

2 fits the obtained spectrum. It was found that a constant magnetic field model does not reproduce the broadness of the inverse Compton peak. Most probably, this suggests that the assumption of homogeneity of the magnet field inside the nebula is wrong. Three state-of-the-art models were applied to the spectral energy distribution. A time-dependent 1D spectral model is able to match the data with a magnetic field of 80μG. However, it fails to describe the data when including the morphology of the nebula at higher frequencies.

Inside the nebula one finds the pulsar. The first detection of its pulsed gamma-ray emission above 25 GeV by a ground-based instrument was already achieved in 2008 by MAGIC [11]. After the accumulation of 320 h of observations, a spectrum between 70 GeV and 1.5 TeV was measured [12]. The pulse profile shows two narrow peaks which are synchronized with the ones measured, e.g., by *Fermi*-LAT in the lower energy gamma-ray range. The spectra of pulse I and II were found to follow different simple power-law indices, 3.2 ± 0.4 and 2.9 ± 0.2, respectively. The pulsed TeV emission can not be produced by synchrotron-curvature radiation. Instead, the inverse Compton process plays a dominating role at energies above 50 GeV. Furthermore, all current existing models fail to reproduce the observed narrowness of the peaks. The observation poses strong constrains on the Lorentz factors of the electrons. A parent population of electrons with $\gamma > 5 \times 10^6$ is needed. This suggests an inverse Compton scattering of low energy photons as the emission and that the gamma-ray production region is located near by the light cylinder.

2.2 The supernova remnant W51 C

In 2010 and 2011, MAGIC collected more than 50 h of data from the region of W51 [13]. This complex field hosts the supernova remnant W51 C which interacts with molecular clouds in the star forming region of W51 B. Observations at other frequencies suggest a possible association of a pulsar wind nebula with the remnant. Gamma rays were detected from W51 but it was not clear if this emission is originating from the pulsar wind nebula, the supernova remnant shell, and/or the molecular cloud. The spatial resolution of the measurements by MAGIC helped to pinpoint the location of the gamma-ray emission. The skymaps show an extension at high energies towards the pulsar. However, it was not possible to establish it as an independent source. The contribution from the pulsar wind nebula was estimated to be $\sim$17% of the flux, but the shocked cloud region is dominant at all energies.

Furthermore, the measured spectrum follows the high-energy points measured with *Fermi*-LAT and ranges up to $\sim$ 5 TeV with a simple-power law function. Modeling of the spectral energy distribution is consistent with a hadronic origin of the gamma-ray emission. It was found that an ongoing acceleration of ions in the interaction zone between the supernova remnant and the cloud can explain the observations.

2.3 Novae and dwarf novae

The *Fermi*-LAT telescope detected gamma-rays at GeV energies from a few novae in the last years. This emission can be interpreted in terms of the inverse Compton process of electrons which are accelerated in shocks of novae. In the same manner, protons might be accelerated to much higher energies under the same condition. This could produce a second gamma-ray emission component in the spectra possibly at TeV energies.

For this reason, MAGIC performed follow-up observations of novae and dwarf novae [14]. One example is the observation of the classical novae V339 Del in August and September 2013. These measurements were triggered by an outburst found in the optical and GeV band. MAGIC did not detect a significant signal, but upper limits to the spectral energy distribution together with the data points from *Fermi*-LAT limit the ratio of the proton-to-electron luminosity to be $L_p \lesssim 0.15\, L_e$ in theoretical models.

3 Extragalactic science

The extragalactic gamma-ray sky currently counts ~ 65 objects[1]. The parent population consists of radio-loud active galactic nuclei with jets pointing towards the earth. Those objects are called blazars and they are typically characterized by their strong variability in all wavelengths and on all time scales. The so-called Doppler boosting effect plays an important role for the interpretation of the emission of these objects. However, a handful of radio galaxies for which the angle between the jet-axis and the line-of-sight is larger were discovered as well.

3.1 Black hole lightning from IC 310

IC 310 is an active galaxy located in the outskirts of the Perseus cluster of galaxies at a cosmological redshift of $z = 0.0189$. Originally, this object was classified as a head-tail radio galaxy, where the jets of the nucleus are being bend due to the movement of the galaxy through the cluster. However, studies of the multi-wavelength emission showed several properties similar to those of blazars as well as radio galaxies.

During an extensive multi-wavelength program in late 2012, MAGIC detected an exceptionally bright TeV flare from IC 310 on one night reaching an average flux level of up to one Crab above 1 TeV with a hard spectrum over two decades in energy [15]. The intra-night light curve showed a series of strong outbursts with flux-doubling time scales as fast as a few minutes. The fast variability constrains the size of the gamma-ray emission regime to be smaller than 20% of the gravitational radius of its central black hole. Furthermore, very long baseline interferometry measurements in the radio band revealed a limit for the viewing angle of the active galactic nucleus to be $10^\circ \lesssim \theta \lesssim 20^\circ$. Thus, no strong Doppler boosting can be assumed in the explanation of the gamma-ray production mechanism. This challenges the standard model for gamma-ray emission of active galaxies being produced due to the acceleration of particles at shocks in the jets. It was found that a magnetospheric model similar to those used to interpret the gamma-ray emission from pulsars is able to explain the phenomena. Instead of having a neutron star in the center of the magnetosphere, a rotating black hole exists. In this model, the gamma rays are being produced by electromagnetic cascades, acceleration inside vacuum gaps, emission via the inverse Compton, and curvature radiation processes.

3.2 Gravitationally lensed blazar S3 0218+35

S3 0218+35 is a blazar at a redshift of $z = 0.944$, the most distant and the only gravitationally lensed gamma-ray emitting object of the very-high-energy sky today. The lensing galaxy is a spiral galaxy and is located at the redshift of $z = 0.68$. In July 2014, *Fermi*-LAT observed an outburst from this objects which triggered follow-up observations with MAGIC. This flare happened during full moon time where MAGIC interrupts observations. However, previous studies from the *Fermi* team as well as of the radio emission showed that the gravitationally lensed signals splits into two components separated by 10-12 days. MAGIC observations were

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[1] `http://tevcat2.uchicago.edu/`

scheduled around the expected time of arrival of the trailing component. Thus, MAGIC detected the object with a significance of more than $5\,\sigma$ at $\sim 12\,$d after the flare seen by *Fermi*-LAT [16].

3.3 Quasar PKS 1441+25

The second most distant active galaxy in the very-high-energy range is PKS 1441+25, a flat-spectrum radio quasar located at a redshift of $z = 0.939$. Similar to the detection of S3 0218+35, the observations of PKS 1441+25 were triggered by an outburst of the object measured with the *Fermi*-LAT telescope in April 2015. MAGIC observed the object during April and May 2015, resulting in the detection of a signal of $25.5\,\sigma$ in an energy range of 40–250 GeV and a variability time scale of $6.5 \pm 1.9\,$d [17]. In addition, many telescopes in various frequency bands performed observations, resulting in an excellent coverage of the multi-wavelength spectral energy distribution for the object at different flux states. All observations together suggest a subdivision of the high state into two distinct flux states. The theoretical interpretation of the spectral energy distribution with an external Compton model yielded that the location of the gamma-ray emitting region during the period of high activity is located in the jet but outside the broad-line region, while the emitting region during the low activity is partially inside the broad-line region.

4 Follow-up of neutrino events

As said before, the detection of neutrino emission from astronomical objects would certainly contribute to the search of the origin of the cosmic rays. However, measuring a significant neutrino excess especially from a point-source is challenging due to the much smaller cross section for neutrino interaction. The IceCube Collaboration reported on the detection of 37 neutrino events between 30 TeV and 2 PeV, spread over both hemispheres and rejecting an atmospheric origin at a $5.7\,\sigma$ level [18]. However, most of these events have a large median positional uncertainty of 10° to 20°. Thus, IACT instruments with an angular resolution of the order of $\sim 0.1°$ could provide follow-up gamma-ray observations for neutrino candidates and transient neutrino events.

For this reason, IACT instruments, e.g., MAGIC have been receiving on-line triggers from the IceCube Collaboration for a few years. A precedent case including the precursor of IceCube, AMANDA, is being reported in [19]. So far, no significant signal was found from such observations but they are still crucial as they allow for performing of real-time multi-messenger astronomy.

5 Summary

The last few years of scientific operation of the MAGIC telescopes were very successful, e.g., resulting in the detection of the most energetic pulsed emission from an astronomical object, the measurement of gamma rays from active galactic nuclei in our neighborhood or from the middle age of the universe, and ultra-fast variability giving new clues on particle acceleration.

The MAGIC team makes strong efforts in collaborating with many telescopes in all other frequency ranges as well as the Cherenkov gamma-ray instruments VERITAS, H.E.S.S., FACT, and HAWC. In addition, MAGIC performs follow-up observations of gravitational wave as well as neutrino events.

In the next years, MAGIC will continue to observe the very-high-energy gamma-ray sky bridging the gap until the future Cherenkov Telescope Array, CTA, will start its operation. The building of the first prototype of a 23 m diameter Large Size Telescope for CTA has already started in 2015 right next to the MAGIC site.

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