Mem. S.A.It. Vol. 81, 204

Memorie della

MAGIC highlights

Josep M. Paredes[1] and Massimo Persic[2] on behalf of the MAGIC Collaboration

[1] Departament d'Astronomia i Meteorologia and Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (UB/IEEC), Barcelona, Spain, e-mail: `jmparedes@ub.edu`
[2] INAF and INFN, Trieste, Italy,v e-mail: `persic@oats.inaf.it`

Abstract. The single-dish configuration of the MAGIC Cherenkov telescope has been in operation since 2004 , with an operational window of 0.03–30 TeV. The stereo configuration, made possible by the recently completed second dish, is due to start a second phase of MAGIC operation soon. In this paper we offer a review of MAGIC phase-1 (mono) results.

Key words. Gamma rays: observations, supernova remnants, pulsars, pulsar wind nebulae, active galactic nuclei; γ-ray bursts; cosmic rays; dark matter

1. Introduction

The Imaging Air Cherenkov (IAC) technique (e.g., De Angelis et al. 2008 for a review) uses the atmosphere as a calorimeter to detect the extensive air shower produced after the interaction of a VHE γ-ray. The charged particles (mainly electrons and positrons) in the air shower produce Cherenkov light that can be easily detected with photomultipliers on the ground. An IAC telescope (IACT) uses a large reflector area to concentrate as much as possible of these photons and focus them to a camera where an image of the atmospheric cascade is formed. By analysing this image it is possible to reconstruct the incoming direction and the energy of the γ-ray. The analysis of the images is also used to reject the much higher background of cosmic rays initiated showers.

The ground-breaking work of the Whipple IACT led to the earliest detections of sources in the photon VHE (i.e., ~0.1-100 TeV) band, the Crab nebula (Weekes et al. 1989) and the blazar Mkn 421 (Punch et al. 1992). These pioneering attempts started VHE astrophysics. Following on, the first generation of major IACTs – that included CAT (1996-2003), CANGAROO (1992-2001) and HEGRA (1993-2002), in addition to Whipple (1969-....) itself – broadened the discovery potential of the new field by detecting several more active galactic nuclei and Galactic sources. Thanks to reduced low-energy thresholds, improved sensitivities, wider-field cameras, and lighter mechanical structures, the current second-generation IACTs – i.e., H.E.S.S. (2003-), MAGIC (2004-), CANGAROO-III (2004-), and VERITAS (2006-) – have taken VHE astrophysics into maturity. In this paper we highlight some recent progress in VHE astrophysics obtained with MAGIC.

2. The MAGIC telescope

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope is a last-generation instrument for very high energy (VHE, $E \gtrsim 50\,\mathrm{GeV}$) γ-ray observation exploiting the IAC technique. It is located on the Roque de los Muchachos Observatory

(28°45′30″N, 17° 52′ 48″W, 2250 m above see level) in the North-Atlantic Canary island of La Palma, Spain.

Due to its large collection area (17 m diameter) and uniquely designed camera, MAGIC has reached the lowest energy threshold ('standard' trigger threshold 50–60 GeV at small zenith angles, 'sum' trigger for pulsar observations ~25 GeV) among IACTs.

Since February 2007, MAGIC signal digitization has been upgraded to 2 GSample/s Flash Analog-to-Digital Converters (FADCs), and timing parameters are used during the data analysis (Aliu et al. 2009a). This results in an improvement of the flux sensitivity from 2.5% to 1.6% (at a flux peak energy of 280 GeV) of the Crab Nebula flux in 50 hours of observations. Its energy resolution is about 30% above 100 GeV and about 25% from 200 GeV onwards. The angular resolution is $\sim 0.1°$, while source localization in the sky is provided with a precision of $\sim 2'$. The MAGIC standard analysis chain is described, e.g., in Albert et al. (2008a).

Observations during moderate moonshine enable to increase MAGIC's duty cycle by a factor ~1.5 w.r.t. using only dark time, and a better sampling of variable sources.

MAGIC has been operating in single-dish configuration since fall 2004, carrying out a physics program which includes both, topics of fundamental physics and astrophysics. A recently completed second telescope will soon allow MAGIC to start stereoscopic observations with improved sensitivity (~ 0.8 Crab units in 50-hour observation).

3. Galactic sources

In a break-through VHE survey of the Galactic plane, the southern-located H.E.S.S. telescope discovered a plethora of sources previously unknown in other wavebands (Aharonian et al. 2006a). Further Galactic sources, accessible from the northern hemisphere, were subsequently observed with MAGIC.

Proposed counterparts of such Galactic VHE sources include supernova remnants (SNRs), pulsar wind nebulae (PWNe), and accreting binaries. Whatever their detailed nature, it is expected that Galactic VHE sources are related to evolutionary endproducts of massive, bright, short-lived, stellar progenitors. Hence, these Galactic VHE sources are immediate tracers of the current star formation.

In this section we highlight the MAGIC contributions to Galactic astrophysics.

3.1. The unidentified γ-ray source TeV J2032+4130

The TeV source TeV J2032+4130 was the first unidentified VHE γ-ray source, and also the first discovered extended TeV source, likely to be Galactic (Aharonian et al. 2002a). The field of view of TeV J2032+4130 was observed with MAGIC for 93.7 hours of good-quality data, between 2005 and 2007 (Albert et al. 2008b). The source appears extended w.r.t. the MAGIC psf, its intrinsic size being (for a Gaussian profile) $\sigma_{\rm src} = 5.0 \pm 1.7_{\rm stat} \pm 0.6_{\rm sys}$ arcmin. The energy spectrum is well fitted ($\chi^2_\nu = 0.3$) by $\frac{{\rm d}^3 N}{{\rm d}E\,{\rm d}A\,{\rm d}t} = (4.5 \pm 0.3_{\rm stat} \pm 1.5_{\rm sys}) \times 10^{-13} (E/1\,{\rm TeV})^{-2.0\pm0.3_{\rm stat}\pm0.2_{\rm sys}}\,{\rm TeV}^{-1}{\rm cm}^{-2}{\rm s}^{-1}$. The energy spectrum measured by MAGIC is compatible both in flux level and photon index with the one measured by HEGRA, and extends it down to 400 GeV. The MAGIC data show no spectral break nor any flux variability over the 3 years of observations.

3.2. Shell-type supernova remnants: Cassiopeia A and IC 433

Galactic cosmic rays have long been suspected to be produced at supernova (SN) shock fronts via diffusive acceleration. If the observed VHE γ-rays were found to be generated through the hadronic channel, then the acceleration by SNe of nuclei to energies of the order of the knee in the CR spectrum would be virtually proven (e.g., Torres et al. 2003). However, it is difficult to disentangle the hadronic VHE component from the leptonic one, produced by inverse-Compton (IC) scattering, by measuring γ-rays over only a decade or so in energy. The VHE data of RX J1713.7-3946 can be explained in terms of either channel, leptonic/hadronic if the relevant magnetic field is low/high ($B{\sim}10/100\,\mu$G: Aharonian et al. 2006b and Berezhko & Völk 2006). Data in the ~0.1–100 GeV band, such as those to be provided by *AGILE* and *Fermi Gamma-ray Space Telescope*, are clearly needed to discriminate between the two channels.

Whatever the details, the detection of photons with energy $\gtrsim$ 100 TeV from RX J1713.7-3946 is a proof of the acceleration of primary particles in SN shocks to energies well above 10^{14} eV. The differential VHE spectral index is ~2.1 all across this SNR, suggesting that the emitting particles are ubiquitously strong-shock accelerated, up to energies ~200/100 TeV for primary CR protons/electrons if the hadronic/leptonic channel is at work (Aharonian et al. 2007). This is getting close to the knee of the CR spectrum, $\sim 10^{15.5}$ eV, that signals the high-energy end of the Galactic CR distribution (e.g., Blasi 2005).

Circumstantial evidence supports a hadronic origin of the VHE emission. In several expanding SNRs the X-ray brightness profile behind the forward shock is best explained as synchrotron emission from energetic electrons in high magnetic fields, $B{\sim}\mathrm{O}(10^2)\,\mu$G, i.e. ~100 times larger than typical interstellar medium (ISM) values. Such a large amplified magnetic field disfavors the IC interpretation of the VHE data. Furthermore, in the remnant HESS J1834–087 the maximum of the extended VHE emission correlates with a maximum in the density of a nearby molecular cloud (Albert et al. 2006a) – which suggests hadronic illumination of the target molecular cloud.

MAGIC observed the shell-type supernova remnant (SNR) Cassiopeia A during 47 good-quality hours, and detected a point-like source of VHE γ-rays above ~250 GeV (Albert et al. 2007a). The measured spectrum is consistent with a power law with a differential flux at 1 TeV of $(1.0{\pm}0.1_{\rm stat}{\pm}0.3_{\rm sys}) \times 10^{-12}$ TeV^{-1}cm^{-2}s^{-1} and a photon index of $\Gamma = 2.4 \pm 0.2_{\rm stat} \pm 0.2_{\rm sys}$. The spectrum measured by MAGIC is consistent with that measured by HEGRA about 8 years before (Aharonian et al. 2001) where they overlap, i.e. at $E \gtrsim 1$ TeV. VHE data seem to favor a hadronic scenario for the γ-ray production, since a leptonic origin of the TeV emission would require low magnetic field intensities, which is in principle difficult to reconcile with the high values required to explain the rest of the broad-band spectrum. However, current hadronic models (Berezhko et al. 2003) predict for the 0.1–1 TeV region a harder spectrum than then measured one.

MAGIC detected a new source of VHE γ-rays located close to the Galactic Plane, namely MAGIC J0616+225 (Albert et al. 2007b), which is spatially coincident with the SNR IC 443. The measured energy spectrum is well fitted ($\chi^2_\nu = 1.1$) by the following power law: $\frac{d^3N}{dE\,dA\,dt} = (1.0 \pm 0.2_{\rm stat} \pm 0.3_{\rm sys}) \times 10^{-11}(E/0.4\,{\rm TeV})^{-3.1\pm0.3_{\rm stat}\pm0.2_{\rm sys}}\,{\rm TeV}^{-1}{\rm cm}^{-2}{\rm s}^{-1}$. MAGIC J0616+225 is point-like for MAGIC's spatial resolution, and appears displaced to the south of the center of the SNR shell, and correlated with a nearby molecular cloud and with the location of maser emission. An EGRET source, too, is centered on the SNR shell. The observed VHE γ-rays may be due to π^0-decays from interactions of cosmic rays accelerated in IC 443 and the dense molecular cloud. The distance of this cloud from IC 443 could explain the steepness of the measured VHE γ-ray spectrum.

3.3. Wolf-Rayet binaries

WR stars display some of the strongest sustained winds among galactic objects with terminal velocities reaching up to $v_\infty > 1000 - 5000\,{\rm km\,s}^{-1}$ and also one of the highest known mass loss rate $\dot{M} \sim 10^{-4} - 10^{-5}\,{\rm M}_\odot{\rm yr}^{-1}$. Colliding winds of binary systems containing a WR star are considered as potential sites of non-thermal high-energy photon production, via leptonic and/or hadronic process after acceleration of primary particles in the collision shock. Two objects of this kind, WR 147 and WR 146, were observed by MAGIC (Aliu et al. 2008a) for 30.3 and 44.5 effective hours, respectively. No evidence for VHE γ-ray emission was detected in either case, and upper limits to the emission of 1.5%, 1.4%, and 1.7% (WR 147) and 5.0%, 3.5%, and 1.2% (WR 146) of Crab units were derived for lower energy cuts of 80, 200, and 600 GeV, respectively.

3.4. Compact binaries: Cygnus X-1 and LS I +61 303

In both SNRs and PWNe particle acceleration proceeds on the parsec distance scales in the shocks formed in interactions of either SN ejecta or pulsar winds with the ISM. A different population of much more compact particle accelerators, which has been revealed by current IACTs, is formed by the TeV binaries (TVBs). These systems contain a compact object –either a neutron star (NS) or a black hole (BH)– that accretes, or interacts with, matter outflowing from a companion star: hence they are VHE-loud X-ray binaries (XRBs). Four TVBs have been detected so far: PSR B1259−63 (Aharonian et al. 2005a), LS 5039 (Aharonian et al. 2005b, 2006e), LS I +61 303 (Albert et al. 2006b), and Cyg X-1 (Albert et al. 2007d).

Cygnus X-1 is the best established candidate for a stellar mass BH and one of the brightest X-ray sources in the sky. MAGIC observed it for 40 hours along 26 different nights between June and November 2006. These observations imposed the first limits to the steady γ-ray emission from this object, $\lesssim 1\%$ of the Crab nebula flux above ~500 GeV, and obtained a very strong evidence (4.1 σ post-trial significance) of a short-lived, intense flaring episode during 24 September 2006, in coincidence with a historically high flux observed in X-rays (Malzac et al. 2008) and during the maximum of the ~326 d super-orbital modulation (Rico 2008). The detected signal is point-like, consistent with the position of Cygnus X-1, and excludes the nearby radio nebula powered by the relativistic jet.

LS I +61 303 is a peculiar binary system composed of a compact object (NS or BH) and a Be star in a highly eccentric orbit, which displays periodic emission throughout the spectrum from radio to X-ray frequencies. MAGIC observations have determined that this object produces γ-rays up to at least ~4 TeV (Albert et al. 2006b), and that the emission is periodically modulated by the orbital motion ($P_{\rm TeV} = (26.8 \pm 0.2)\,$d) (Albert et al. 2009). The peak of the emission is found always at orbital phases $\phi \simeq 0.6 - 0.7$. During December 2006 a secondary peak was detected at $\phi \simeq 0.8 - 0.9$. In October-November 2006, a multi-ν campaign was carried out that involved radio (VLBA, e-EVN, MERLIN), X-ray (*Chandra*) and VHE γ-ray (MAGIC) instruments (Albert et al. 2008c), which excluded the existence of large scale (~$0.1''$) persistent radio-jets and found a possible hint of a temporal X-ray/TeV correlation.

3.5. Crab nebula and pulsar

The Crab nebula, a steady emitter that is used as a calibration candle, has been observed extensively from the radio up to ~70 TeV. A large fraction of MAGIC observation time is devoted to this object. Out of it, 16 hours of optimal data were used to measure the 0.06–8 TeV energy spectrum (Albert et al. 2008a). The peak of the spectral energy distribution (SED) has been measured at an energy $E = (77 \pm 35)$ GeV. The VHE source is point-like and the position coincides with that of the pulsar.

Discrimination between different processes of pulsar magnetospheric emission (e.g., polar-cap vs outer-gap scenario) is one clear goal of VHE astrophysics. Polar-cap (e.g., Daugherty & Harding 1982, 1996) and outer-gap (e.g., Cheng et al. 1986; Romani 1996) models essentially differ by the location of the gap in the pulsar magnetosphere. In the former case this is close to the NS surface, whereas in the latter it is further away from it. Thus, the influence of the magnetic field ($B \sim 10^{11-13}$ G) is crucially different in these models. In polar-cap models, it produces absorption (due to $\gamma + B \rightarrow e^{\pm}$) leading to a super-exponential cutoff of the emission (mostly curvature radiation). In outer-gap models, only a (milder) exponential cutoff is present, and the highest photon energies depend on the electron energy.

Quite recently, thanks to a special trigger setup, MAGIC detected statistically significant (6.4 σ) <25 GeV pulsed emission from the Crab pulsar (Aliu et al. 2008b). That result revealed a relatively high energy cutoff, indicating that the Crab pulsar's γ-ray emission occurs far out in the magnetosphere, hence excluding the polar-cap scenario for the VHE emission of the Crab pulsar. This is the first time that a pulsed γ-ray emission is detected from a ground-based telescope, and opens up the possibility of a systematic study of pulsar emission cutoffs, knowledge of which will help clarify the mechanism and region of production of VHE radiation in pulsars.

3.6. Galactic center

The possibility of indirect dark matter detection through its annihilation into VHE γ-rays has aroused interest to observe the Galactic Center (GC). H.E.S.S. and MAGIC observed the GC, measuring a steady flux consistent with a differential power-law slope of ~2.2, up to energies of ~20 TeV with no cutoff (Aharonian et al. 2004; Albert et al. 2006c). Within the error circle of the measurement of the central source HESS J1745-290 are three compelling candidates for the origin of the VHE emission: the shell-type SNR Sgr A East, the newly discovered PWN G 359.95–0.04, and the putative massive BH Sgr A* itself.

Plausible radiation mechanisms include IC scattering of energetic electrons, the decay of pions produced in the interactions of energetic hadrons with the ISM or dense radiation fields, and curvature radiation of UHE protons close to Sgr A*. These considerations disfavor DM annihilation as the main origin of the detected flux, whereas a more conventional astrophysical mechanism is likely to be at work (e.g., Aharonian et al. 2006f). Furthermore, the lack of flux variability on hour/day/year timescales suggests that particle acceleration occurs in a steady object, such as a SNR or a PWN, and not in the central BH.

The GC diffuse emission correlates with molecular clouds and suggests an enhanced CR spectrum in the Galactic center (Aharonian et al. 2006g). Its morphology and spectrum suggest recent in situ CR acceleration: because the photon indexes of the diffuse emission and of the central source HESS J1745-290 are similar, the latter source could be the accelerator in question.

4. Active galactic nuclei (AGN)

Supermassive black holes (SMBHs) are believed to reside in the cores of most galaxies. The fueling of SMBHs by infalling matter produces the spectacular activity observed in active galactic nuclei (AGNs).

The current AGN paradigm includes a central engine, most likely a SMBH, surrounded by an accretion disk and by fast-moving clouds, which emit Doppler-broadened lines (Urry & Padovani 1995). In ~10% of all AGNs, the infalling matter turns on powerful collimated jets that shoot out from the SMBH in opposite directions, likely perpendicular to the disk, at relativistic speeds.

If a relativistic jet is viewed at small angle to its axis the observed jet emission is amplified by relativistic beaming and dominates the observed emission. Such sources are called blazars. Given the blazars' compactness (as suggested by their short variability timescales), all GeV/TeV photons would be absorbed through pair-producing $\gamma\gamma$ collisions with target X-ray/IR photons. Beaming ensures the intrinsic radiation density to be much smaller than the observed one, so that γ-ray photons encounter a much lower $\gamma\gamma$ opacity and hence manage to leave the source: reversing the argument, γ-ray detection is a proof of strongly anisotropic (e.g., beamed) emission.

The SEDs of blazars are generally characterized by two broad humps, peaking at, respectively, IR/X-ray and GeV-TeV frequencies (Ulrich et al. 1997). The mainstream interpretation of the blazars SEDs is synchrotron-Compton emission, i.e. synchrotron emission (peaked in the IR/X-ray range) from a time-varying population of ultra-relativistic electrons moving in a strong magnetic field, and IC emission (peaked in the ~100 MeV–100 GeV range) from soft photons scattering off energetic electrons. Depending on the relative efficiency of the relativistic particles' cooling through scattering with photon fields that are internal to jet or external to it, the synchrotron and Compton components peak at, respectively, UV/X-ray and GeV–TeV energies (synchrotron-self-Compton [SSC] scheme: e.g., Maraschi et al. 1992) or at

IR/optical and MeV–GeV energies (external-IC [EIC] scheme, see Dermer & Schlickeiser 1993). Hybrid SSC/EIC models have also been proposed (Ghisellini 1999). Alternative models of VHE emission involve, e.g., two electron populations, one –primary– accelerated within the jet and the other –secondary– generated by electromagnetic cascades initiated by primary protons/nuclei that had been accelerated in the jet (Mannheim 1993); or a population of extremely energetic protons emitting by synchrotron radiation (Aharonian 2000).

The emitting particles are accelerated within the relativistic jets which transport energy from the central SMBH outwards (Rees 1967). The X-ray and γ-ray emission, with its extremely fast and correlated multi-frequency variability, indicates that often a single region dominates the emission.

Blazar observations have been a top priority for VHE astrophysics ever since the discovery of TeV emission from Mkn 421 (Punch et al. 1992). In fact, VHE data are of crucial importance to constrain, and perhaps to close, the SSC model. Even in the simplest one-zone SSC model of blazar emission, knowledge of the whole SED up to the VHE regime is required for a complete description of the emitting electrons' distribution and environment (e.g., Tavecchio et al. 1998). However, accurate knowledge of blazar emission mechanism(s) requires *simultaneous* broadband γ-ray and X-ray (i.e., IC and synchrotron) data. In fact, a simultaneous SED can act as a snapshot of the emitting population of particles at a given time.

In the following we describe a few selected items from MAGIC's recent activity in AGN physics.

4.1. The July 2005 flares of Mkn 501

MAGIC observed the bright and variable VHE γ-ray emitter Mkn 501 during six weeks in summer 2005 (Albert et al. 2007c). In two of the observation nights, the recorded flux ($> 4\times$ that of the Crab nebula) revealed rapid changes with doubling times $\lesssim 3$ min. For the first time, short (~20 min) VHE γ-ray flares with a resolved time structure could be used for detailed studies of particle acceleration and cooling timescales.

Interestingly the flares in the two nights behave differently: while the 2005 June 30 flare is only visible at energies 0.25–1.2 TeV, the 2005 July 9 flare is conspicuous in all energy bands (120 GeV to >1.2 TeV). A photon-by-photon analysis of the July 9 flare (Albert et al. 2008d) revealed a time delay between the flare peak at different energies: at a zero-delay probability of $p = 0.026$, a marginal time delay of $\tau_l = (0.030 \pm 0.012)\,\mathrm{s\,GeV^{-1}}$ towards higher energies was found using two independent analyses, both exploiting the full statistical power of the dataset. Several explanations for this delay may be considered. We mention here an energy-dependent speed of photons in vacuum, as predicted in some models of quantum gravity where Lorentz invariance violation (LIV) is a manifestation of the foamy structure of space-time at short distances. Such LIV could manifest themselves in modifications of the propagation of energetic particles, i.e. a non-trivial dispersion relation (Amelino-Camelia et al. 1998).

The dependence of the speed of light on the photon energy E can be parameterized as $c' = c\,[1 \pm (E/E_{\rm S1}) \pm (E/E_{\rm S2})^2 \pm ...]$. The energy scales $E_{\rm S1}$, $E_{\rm S2}$ are usually expressed in units of the Planck mass, $M_{\rm P} \equiv 1.22 \times 10^{19}$ GeV/c^2. If the linear term dominates, then $c' = c\,[1 \pm (E/E_{\rm S1})]$. A favored way to search for such a dispersion relation is to compare the arrival times of photons of different energies arriving to Earth from pulses of distant astrophysical sources. Assuming a simultaneous emission of the γ-rays (of different energies) at the Mkn 501 site, a formal value of E_{S1} can be inferred. However, since it is not possible to exclude that the observed delay is due to some conventional astrophysical effect at the source, only a lower limit of $E_{S1} > 0.21 \times 10^{18}$ GeV (95% c.l.) can be established (Albert et al. 2008d).

4.2. Multi-frequency campaigns

Coordinated simultaneous multi-ν observations, yielding SEDs spanning ~17 decades in energy, are essential for a deeper understanding of blazar emission. A number of multi-ν campaigns have been carried out on known northern-hemisphere blazars, that involved space-borne telescopes (*Suzaku*, *Swift*, *Chandra*, *XMM-Newton*, *INTEGRAL*) and ground-based IACTs (Whipple, H.E.S.S., MAGIC, and VERITAS) and optical and radio telescopes.

The observations of Mkn 501 in July 2006 revealed the lowest X-ray (with *Suzaku*) and VHE state ever observed: no variability in VHE γ-rays was found, while an overall increase of about 50% during one day was seen in X-rays; a one-zone SSC mode describes this quiescent state of Mkn 501 well (Anderhub et al. 2009a).

Coordinated observations of OJ 287 carried out in April and November 2007 by the Nobeyama millimiter array, the KANATA optical telescope, the X-ray telescope *Suzaku*, and MAGIC captured the source in quiescent and flaring state respectively. According to a simple SSC model, the spectral variations observed between the quiescent and the active phase are due to an increase in the energy density of the emitting electrons with small changes of both the magnetic field and the electrons' maximum Lorentz factor (Seta et al. 2009).

Mkn 421 was observed together with *XMM-Newton*, VERITAS, and Whipple in April 2006 and May 2008 to probe multiband variability (Acciari et al. 2009a). A more recent observation of a flare of Mkn 421 in summer 2008 could be followed accurately from optical to VHE γ rays, with the participation of *AGILE*, GASP-WEBT, VERITAS and MAGIC (Donnarumma et al. 2009).

A coordinated observation of 1ES 1959+650 was carried out in May 2006 when the source was simultaneously in a historical minimum in VHE γ-rays and relatively high in the optical and X-ray bands (Tagliaferri et al. 2008).

4.3. Blazars detected during optical outbursts

MAGIC has been performing target of opportunity observations upon high optical states of known or potential VHE blazars. Up to now, this strategy has proven very successful with the discovery of Mkn 180 (Albert et al. 2006e), 1ES 1011+496 (Albert et al. 2007e), and S5 0716+71 (Anderhub et al. 2009b).

The 18.7-hr observation of 1ES 1011+496, triggered by an optical outburst in March 2007, resulted in a $6.2\,\sigma$ detection at $F_{>200\,\mathrm{GeV}} \simeq 1.6 \times 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. An indication of an optical–VHE correlation is given, in that in spring 2007 the VHE γ-ray flux is >40% higher than in spring 2006, where MAGIC observed the blazar as part of a systematic search for VHE emission from a sample of X-ray bright ($F_{1\,\mathrm{keV}} > 2\,\mu$Jy) HBLs (Albert et al. 2008e).

In April 2008, triggered by an optical flare, MAGIC observed S5 0716+71. The 6.8σ detection (in 2.6 hr) measured a flux of $F_{>400\,\mathrm{GeV}} \approx 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

4.4. The region of 3C 66A/B

MAGIC observed the region around the distant blazar 3C 66A for 54.2 hr in August–December 2007 (Aliu et al. 2009b). The observations resulted in the discovery of a γ-ray source centered at celestial coordinates RA = $2^{\mathrm{h}}23^{\mathrm{m}}12^{\mathrm{s}}$ and DEC= $43°0.'7$ (MAGIC J0223+430), coinciding in sky coordinates with the nearby radio galaxy 3C 66B. The energy spectrum of MAGIC J0223+430 follows a power law with a normalization of $(1.7 \pm 0.3_{\mathrm{stat}} \pm 0.6_{\mathrm{syst}}) \times 10^{-11}$ TeV^{-1}cm^{-2}s^{-1} at 300 GeV and a photon index $\Gamma = -3.10 \pm 0.31_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}}$. The possible association of the excess with the distant blazar 3C 66A and the nearby radiogalaxy 3C 66B is discussed in Aliu et al. (2009b).

4.5. Detection of the flat-spectrum radio quasar 3C 279

Observations of 3C 279, the brightest EGRET AGN, during the WEBT multi-ν campaign revealed a post-trial $5.77\,\sigma$ detection on 2006 Feb. 23, supported by a marginal signal on the previous night (Albert et al. 2008f). The overall probability for a zero-flux lightcurve can be rejected on the $5.04\,\sigma$ level. Simultaneous optical R-band observations by the Tuorla Observatory Blazar Monitoring Program revealed that during the MAGIC observations the optical flux of the source was about twice the long-term baseline flux – but with with no indication of short time-scale variability at optical frequencies. The observed VHE spectrum can be described by a power law with a differential photon spectral index of $\Gamma = 4.1 \pm 0.7_{\rm stat} \pm 0.2_{\rm syst}$ between 75 and 500 GeV. The measured flux is $F_{100\,\rm GeV} = (5.15 \pm 0.82_{\rm stat} \pm 1.5_{\rm syst}) \times 10^{-10}$ $\rm cm^{-2} s^{-1}$.

The detection of 3C 279 has extended the test on the transparency of the universe to VHE γ-rays out to $z = 0.536$ (see section 4.7).

4.6. The Feb. 2008 flare of M 87

The giant radio galaxy M 87, one of the best-studied SMBH systems, has long been known as a VHE γ-ray emitter (Aharonian et al. 2006h). To assess variability timescales and the location of the VHE engine in M 87, the H.E.S.S., VERITAS, and MAGIC collaborations carried out a shared monitoring of M 87, resulting in ~120 hr of observations in 2008 (Acciari et al. 2009b). On 2008 Feb. 1, MAGIC observed an $8\,\sigma$ signal (Albert et al. 2008g) and triggered observations from the other IACTs as well as from *Swift*. MAGIC measured, for the first time, the energy spectrum below 250 GeV, which can be described by a power law with a spectral index $\Gamma = 2.30 \pm 0.11_{\rm stat} \pm 0.20_{\rm syst}$.

Our analysis revealed a variable ($5.6\,\sigma$) night-to-night γ-ray flux above 350 GeV, while no variability was found for 150–350 GeV. This fastest variability Δt observed so far in TeV γ-rays in M 87, while confirms the $E > 730$ GeV short-time variability reported earlier (Aharonian et al. 2006h), is of the order of one day or less. This restricts the emission region to a size of $R \leq \Delta t\, c\, \delta = 2.6 \times 10^{15}$ cm $= 2.6\,\delta$ Schwarzschild radii (Doppler factor δ), and suggests the core of M 87 rather than the brightest known knot in the M 87 jet, HST-1, as the origin of the TeV γ-rays. During the MAGIC observations, HST-1 was at a historically low X-ray flux level, whereas at the same time the core luminosity reached a historical maximum.

This strongly supports the core of M 87 as the VHE γ-ray emission region. The simultaneous strong increase of the radio flux from the nucleus of M 87 provides further support to the concept that the charged particles are accelerated to VHEs in the immediate vicinity of the BH (Acciari et al. 2009b).

4.7. Intergalactic background light

One further aspect of TeV spectra of blazars is that they can be used as probes of the Intergalactic Background Light (IBL), i.e. the integrated light arising from the evolving stellar populations of galaxies (see Hauser & Dwek 2001). The TeV photons emitted by a blazar interact with the IR/optical photons of the IBL field and are likely absorbed via pair production. Whatever its intrinsic shape at emission, after travelling through the IBL-filled space, a blazar spectrum will reach the observer distorted by absorption. This effect, which is stronger for more distant objects (e.g., Stecker et al. 1992), is the most likely origin of the avoidance zone (i.e., no flat spectra at high redshift) in the observed spectral slope vs redshift plot.

Usually, either *(i)* the shape and intensity of IBL(z) is assumed, and the VHE spectrum is corrected before the SSC modeling is performed (e.g., de Jager & Stecker 2002; Kneiske et al. 2004); or *(ii)* based on assumptions on the intrinsic VHE spectrum, EBL(z) is solved for: e.g., based on analysis of the observed hard VHE spectra of the distant blazars 1ES 1101-232 and H 2359-309, a low EBL energy density at $z \lesssim 0.2$ has been derived (Aharonian et al. 2006i). The two approaches can be used in combination to estimate the distance to the VHE source (Mazin & Goebel 2007).

The detection in VHE γ-rays of 3C 279 at $z = 0.536$ provided us with a new opportunity to check the transparency of the Universe out to a relatively large redshift. Assuming for 3C 279 a maximally flat intrinsic spectrum, corresponding to $\Gamma^* = 1.5$, a quite low upper limit to the IBL is inferred, consistent with the light arising from pure galaxy counts. The results support, at higher redshift, the conclusion drawn from earlier measurements (Aharonian et al. 2006i) that the observations of the *Hubble Space Telescope* and *Spitzer* correctly estimate most of the light sources in the Universe.

5. Gamma-ray bursts

There is a prevailing consensus that the basic mechanism of GRB emission is an expanding relativistic fireball (Rees & Meszaros 1992, Meszaros & Rees 1993, Sari et al. 1998), with the beamed radiation ($\delta \sim O(10^2)$ due to internal/external shocks (prompt/afterglow phase, respectively). If so, the emitting particles (electrons and/or protons) are accelerated to very high energies. In the fireball shock framework, several models have predicted VHE emission during both the prompt and afterglow phases of the GRB (e.g., Meszaros 2006).

MAGIC observed part of the prompt-emission phase of GRB 050713a as a response to an alert by the *Swift* satellite (Albert et al. 2006d). However, no excess at >175 GeV was detected, neither during the prompt emission phase nor later – but the upper limits to the MAGIC flux are compatible with simple extrapolations of the Swift $\Gamma \simeq 1.6$ power-law spectrum to hundreds of GeV. In general, however, the cosmological distances of these sources prevent VHE detection because of IBL absorption: the average redshift of the GRBs for which MAGIC was alerted (and whose z are known) is $\bar{z}$=3.22, whereas at 70 GeV the cosmological γ-ray horizon is $z \sim 1$.

One exceptional, but unfortunately missed, opportunity was GRB 080319B, nicknamed "naked-eye GRB" on account of its exceptionally high peak optical flux ($m_{\rm v}$ = 5.3; Racusin et al. 2008): according to (post factum) theoretical predictions of its intrinsic emission and owing to its relatively low redshft (z = 0.937) its VHE flux would have been detectable by current IACTs (Kumar & Panaitescu 2008; Zou et al. 2009). However, by the time of its occurrence dawn was approaching the MAGIC site so the telescope was closing down lest the photomultipliers could be severely damaged by excessive sunlight. So this unique event was missed.

6. Dark matter

Evidence for departure of cosmological motions from the predictions of Newtonian dynamics based on visible matter, interpreted as due to the the presence of DM, are well established – from galaxy scales (e.g., van Albada et al. 1985) to galaxy-cluster scales (e.g., Sarazin 1986) to cosmological scales (e.g., Spergel et al. 2003).

DM particle candidates should be weakly interacting with ordinary matter (and hence neutral). The theoretically favored ones, which are heavier than the proton, are dubbed weakly interacting massive particles (WIMPs). WIMPs should be long-lived enough to have survived from their decoupling from radiation in the early universe into the present epoch.

WIMPs could be detected indirectly, by their self-annihilation products in high-density DM environments. DM annihilation can generate γ-rays through several processes. Most relevant in the present context, a continuum γ-ray spectrum can be produced through the fragmentation and cascades of most other annihilation products. The best observational targets for DM detection are nearby high-M/L objects with little or no ongoing star formation, which are also expected to have the highest central densities known in galactic halos. Objects meeting these requirements are the Milky Way dwarf spheroidal satellite galaxies (e.g., Draco, Sculptor, Fornax, Carina, Sextans, Ursa Minor). A further issue concerns the shape of the inner halo profile, i.e. whether the latter is cuspy or cored.

These considerations (and uncertainties) have been incorporated in detailed predictions of the γ-ray flux expected from the annihilation of the neutralino pairs in Galactic dwarf spheroidal galaxies: the outlooks however suggest that detection by current IACTs is unlikely unless an implausibly halo clumpiness boosts the annihilation signal by several orders of magnitude (e.g., Bringmann et al. 2009).

No evidence of DM annihilation γ-rays has been unambiguously claimed so far. An apparently extended signal from the direction of NGC 253 (based on CANGAROO-III data) has been definitely interpreted as due to hardware malfunction (Itoh et al. 2007). MAGIC observations of the Draco and Willman-I satellite galaxies (7.8 hr and 15.5 hr respectively), returned 2σ upper limits of, respectively, $F_{>140\,\mathrm{GeV}} \lesssim 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $F_{>100\,\mathrm{GeV}} \lesssim 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Albert et al. 2008h; Aliu et al. 2009c).

Acknowledgements. We acknowledge the MAGIC collaboration for providing a stimulating, friendly, and effective working environment. We thank the Instituto de Astrofisica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma.

References

Acciari V.A., et al., 2009a, ApJ, in press
Acciari V.A., et al., 2009b, Science, 325, 444
Aharonian F. 2000, New Astron., 5 , 377
Aharonian F., et al. 2007, A&A, 464, 235
Aharonian F., et al. 2006a, ApJ, 636, 777
Aharonian F., et al. 2006b, A&A, 449, 223
Aharonian F., et al. 2006e, A&A, 460, 743
Aharonian F., et al. 2006f,,Phys. Rev. Lett., 9, 221102
Aharonian F., et al. 2006g, Nature, 439, 695
Aharonian F., et al. 2006h, Science, 314, 1424
Aharonian F., et al. 2006i, Nature, 440, 1018
Aharonian F., et al. 2005a, A&A, 442, 1
Aharonian F., et al. 2005b, Science, 309, 746
Aharonian F., et al. 2004, A&A, 425, L13
Aharonian F., et al. 2002a, A&A, 393, L37
Aharonian F., et al. 2001, A&A, 112, 307
Albert J., et al. 2009, ApJ, 693, 303
Albert J., et al. 2008a, ApJ, 674, 1037
Albert J., et al. 2008b, ApJ, 675, L25
Albert J., et al. 2008c, ApJ, 684, 1351
Albert J., et al. 2008d, Phys. Lett. B, 668, 253
Albert J., et al. 2008e, ApJ, 681, 944
Albert J., et al. 2008f, Science, 320, 1752
Albert J., et al. 2008g, ApJ, 685, L23
Albert J., et al. 2008h, ApJ, 679, 428
Albert J., et al. 2007a, A&A, 474, 937
Albert J., et al. 2007b, ApJ, 664, L87
Albert J., et al. 2007c, ApJ, 669, 862
Albert J., et al. 2007d, ApJ, 665, L51
Albert J., et al. 2007e, ApJ, 667, L21
Albert J., et al. 2006a, ApJ, 643, L53
Albert J., et al. 2006b, Science, 312, 1771
Albert J., et al. 2006c, ApJ, 638, L101
Albert J., et al. 2006d, ApJ, 641, L9
Albert J., et al. 2006e, ApJ, 648, L105
Aliu E., et al. 2009a, Ap. Phys., 30, 293
Aliu E., et al. 2009b, ApJ, 692, L29
Aliu E., et al. 2009c, ApJ, 697, 1299
Aliu E., et al. 2008a, ApJ, 685, L71
Aliu E., et al. 2008b, Science, 322, 1221
Amelino-Camelia G., et al. 1998, Nature, 393, 763
Anderhub H., et al. 2009a, ApJ, submitted
Anderhub H., et al. 2009b, ApJ, submitted
Berezhko E.G., & Völk H.J. 2006, A&A, 451, 981
Berezhko E.G., et al. 2003, A&A, 400, 971
Blasi P. 2005, Mod. Phys. Lett. A20, 3055
Bringmann T., et al. 2009, JCAP, 01, 016
Cheng K.S., et al. 1986, ApJ, 300, 500
Daugherty J.K., & Harding A. 1982, ApJ, 252, 337
Daugherty J.K., & Harding A. 1996, ApJ, 458, 278
De Angelis A., et al. 2008, Riv. Nuovo Cim., 31, 187
de Bloek W.J.G., et al. 2001, ApJ, 552, L23
de Jager O.C., & Stecker F.W. 2002, ApJ, 566, 738
Dermer C., & Schlickeiser R. 1993, ApJ, 416, 458
Donnarumma I., et al. 2009, ApJ, 691, L13
Ghisellini G. 1999, Nu.Phys. B, 69, 397
Hauser M.G., & Dwek E. 2001, ARA&A, 39, 249
Itoh C., et al. 2007, A&A, 462, 67
Kneiske T.M., et al. 2004, A&A, 413, 807
Kumar P., & Panaitescu A. 2008, MNRAS, 391, L19
Malzac J., et al. 2008, A&A, 492, 527
Mannheim, K. 1993, A&A, 269, 76
Maraschi L., et al. 1992, ApJ, 397, L5
Mazin D., & Goebel F. 2007, ApJ, 655, L13
Meszaros P. 2006, Rep. Prog. Phys., 69, 2259
Meszaros P., & Rees M.J. 1993, ApJ, 405, 278
Punch M., et al. 1992, Nature, 358, 477
Racusin J.L., et al. 2008, Nature, 455, 138
Rees M.J. 1967, MNRAS, 137, 429
Rees M.J., & Meszaros, P. 1992, MNRAS, 258, 41p
Rico J. 2008, ApJ, 683, L55
Romani R.W. 1996, ApJ, 470, 469
Sarazin C. 1986, Rev. Mod. Phys., 58, 1

Sari R., et al. 1998, ApJ, 497, L17
Seta et al. 2009, PASJ, in press
Spergel D.N., et al. 2003, ApJS, 148, 175
Stecker F.W., et al. 1992, ApJ, 390, L49
Tagliaferri G., et al. 2008, ApJ, 679, 1029
Tavecchio F., et al. 1998, ApJ, 509, 608
Torres D.F., et al. 2003, Phys. Rep., 382, 303
Ulrich M.-H., et al. 1997, ARA&A, 35, 445
Urry C.M., & Padovani, P. 1995, PASP, 107, 803
van Albada T.S., et al. 1985, ApJ, 295, 305
Weekes T.C., et al. 1989, ApJ, 342, 379
Zou Y.-C. et al. 2009, MNRAS, 396, 1163