

## TeV Gamma-Ray Astrophysics

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**Abstract** The window of TeV Gamma-Ray Astrophysics was opened less than two decades ago, when the Crab Nebula was detected for the first time. After several years of development, the technique used by imaging atmospheric Cherenkov telescopes like HESS, MAGIC or VERITAS, is now allowing to conduct sensitive observations in the TeV regime. Water Cherenkov instruments like Milagro are also providing the first results after years of integration time. Different types of extragalactic and galactic sources have been detected, showing a variety of interesting phenomena that are boosting theory in very high energy gamma-ray astrophysics. Here I review some of the most interesting results obtained up to now, making special emphasis in the field of X-ray/gamma-ray binaries.

**Key words:** BL Lacertae objects: general — Galaxy: center — gamma rays: observations — intergalactic medium — supernovae: general — X-rays: binaries

### 1 INTRODUCTION

There are different astrophysical scenarios in which particles are accelerated up to TeV energies. Interestingly, these particles can produce TeV gamma-ray photons that can travel in straight lines from the original sources to the observer. Therefore, observational TeV astronomy can provide very useful information to constrain astrophysical scenarios for particle accelerators.

Although the idea to detect gamma-rays of TeV energies using the Cherenkov light that they produce when entering the atmosphere was introduced about 50 years ago, it took a few decades of effort to clearly detect the first source, the Crab Nebula in 1989. After a few years of observations with the third generation of imaging atmospheric Cherenkov telescopes, about 75 TeV sources have been detected. Gamma-ray observations in the TeV regime can certainly be considered nowadays as a new branch of observational astronomy.

Here I review the beginning of TeV Gamma-Ray Astrophysics (Sect. 2), the current instrumentation (Sect. 3), the most interesting results obtained up to now (Sect. 4), and make special emphasis in the field of X-ray/gamma-ray binaries (Sect. 5). I finish with some comments on future instrumentation (Sect. 6) and with the conclusions (Sect. 7).

### 2 HISTORICAL BACKGROUND

A detailed description of the early history of the atmospheric Cherenkov technique can be found in Weekes (2005, 2006), while interested readers can find an extensive review on gamma-ray astronomy with imaging atmospheric Cherenkov telescopes in Aharonian & Akerlof (1997). Here I summarize the most significant facts to provide the reader an historical background.

The idea that perhaps about 0.01% of the night-sky photons were the result of Cherenkov light emitted by cosmic rays and secondary particles entering the atmosphere of the Earth was introduced by Blackett

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(1949). A few years later, Galbraith & Jelley (1953) built a rudimentary instrument with a 25 cm mirror inside a garbage can and a photomultiplier, and detected light-pulses of short duration correlated with cosmic radiation detected by an air shower array.

Cherenkov light from an air shower is emitted within a cone of  $\sim 120$  m radius at ground level. Therefore, a receiver of modest dimensions has a huge effective area. Moreover, the light pulses preserve the direction of the primary particle, and the amount of light is proportional to the energy of the primary particle. Therefore, this technique could be used to do gamma-ray astronomy at Very High Energies (VHE).

During the 60s two experiments using searchlight mirrors from the second world war were built in Crimea (1960–1965) and Ireland (1962–1966). The Whipple 10 m telescope, inaugurated in 1968 and still working, was the first large optical reflector built for gamma-ray astronomy. All these instruments were first generation Cherenkov telescopes in which no gamma-ray and hadronic primary differences were considered in the analysis. The background of air showers produced by cosmic rays is so high compared to TeV gamma rays (a factor between 1000–10000) that, even if cosmic rays are isotropic, no astrophysical sources of VHE gamma rays were detected. It was clear that the technique had to be improved to get rid of as much as cosmic ray showers as possible.

A possible solution to the gamma/hadron separation problem was first pointed out by Jelley & Porter (1963), who enumerated several advantages of using Cherenkov light images (including stereoscopy). The images could be produced if the single photomultiplier placed in the focus was replaced by an array of photomultipliers in the focal plane of the telescope (Weekes & Turver 1977). There are several factors that cause the observed shape and size of a Cherenkov image: not only the nature of the primary, its energy and trajectory, but also the physical process in the particle cascade, Coulomb scattering of shower electrons, geomagnetic deflections, the distance of the shower core from the optic axis, the Cherenkov angle of emission, and the effect of atmospheric absorption, together with the factors related to the focusing system and the detector itself. All of them have to be considered when trying to estimate the nature and original energy and trajectory of the particle.

After performing detailed Monte Carlo simulations of the air showers, Hillas (1985) found that the images produced by gamma rays (similar to ellipses) would be in most cases significantly different than those produced by cosmic rays. Moreover the fitted ellipses would point towards the center of the image and provide further information that could be used to characterize the showers. These developments finally allowed to detect the Crab Nebula at  $9.0\sigma$  with the Whipple 10 m telescope equipped with a 37-pixel camera on the focal plane (Weekes et al. 1989). This was the first unambiguous detection of a TeV gamma-ray source, provided by a second generation Cherenkov telescope.

The HEGRA experiment, with 5 telescopes of 3.4 m diameter each, demonstrated the advantages of stereoscopic observations using an array of telescopes (Pühlhofer et al. 2003). By observing Cherenkov images of gamma-ray showers simultaneously with more than one telescope, one can determine the direction of gamma-rays accurately as crossing points of image axes. Therefore, one can explore the spatial structure of the gamma-ray objects as well as discriminating background cosmic-ray showers more easily. Moreover, the energy resolution of gamma-rays is improved knowing the production height of Cherenkov light. All these facts improve the background rejection and the sensitivity of the Imaging Atmospheric Cherenkov Telescopes (IACTs). Indeed, HEGRA achieved an angular resolution of  $0.1^\circ$  for observations above 0.5 TeV, with an energy resolution of about 15% and a sensitivity of  $\sim 3\%$  of the Crab Nebula flux in 100 h of observations. The IACTs of third generation use (or will use) arrays of telescopes, of more than 10 m diameter each, working stereoscopically.

### 3 CURRENT INSTRUMENTATION

There are currently four IACTs of third generation:

- CANGAROO-III (Collaboration of Australia and Nippon for a GAMMA Ray Observatory in the Outback)<sup>1</sup>
- HESS (High Energy Stereoscopic System)<sup>2</sup>

<sup>1</sup> <http://icrhp9.icrr.u-tokyo.ac.jp/index.html>

<sup>2</sup> <http://www.mpi-hd.mpg.de/hfm/HESS/>

- MAGIC (Major Atmospheric Gamma Imaging Cherenkov)<sup>3</sup>
- VERITAS (Very Energetic Radiation Imaging Telescope Array System)<sup>4</sup>

Their main properties are listed in Table 1. As it can be seen, CANGAROO-III and HESS are located in the Southern Hemisphere, while MAGIC and VERITAS are placed in the Northern Hemisphere. This allows for a double check of some of the most southern or northern sources, always welcome in TeV astrophysics. CANGAROO-III, due to its low elevation, has a high threshold of about 500 GeV. The other instruments can reach the 100–200 GeV regime and even lower in the case of MAGIC, thanks to its huge dish and the high elevation of the site. All these IACTs have to be pointed to the specific regions of the sky to be studied.

**Table 1** Third Generation of Imaging Atmospheric Cherenkov Telescopes (IACTs)

IACT	Location	Elevation [km]	Telescopes	Aperture [m]	FOV [°]	Pixels/ camera	Energy [GeV]
CANGAROO-III	Woomera, Australia	0.2	4	10	4.0	427	>500
HESS	Gamsberg, Namibia	1.8	4 (+1)	12 (28)	5.0	960	>100
MAGIC	La Palma, Spain	2.2	1 (+1)	17 (17)	3.5	576	> 60
VERITAS	Arizona, USA	1.3	4	12	3.5	499	>100

HESS started stereoscopic observations in 2003, MAGIC normal operations in 2004 and CANGAROO-III in 2005, while VERITAS started stereoscopic observations at the end of 2006 and has just completed the array in 2007. The most interesting results published up to now have been provided by HESS and MAGIC, and I will concentrate on them. As a reference, the flux sensitivity at the  $5\sigma$  level in 50 h of observations is 2% of the Crab Nebula at 250 GeV with MAGIC and  $\simeq 1\%$  with HESS.

In parallel to IACTs, other TeV detectors using different techniques have been built during the last decade. Among them, the Milagro Gamma Ray Observatory<sup>5</sup>, a water Cherenkov extensive air shower array, started operations in 2000, and has provided its first impressive results during the last year. Milagro, located in New Mexico (USA), explores the 2–150 TeV energy range and has a FoV of 2 sr. It can thus provide an unbiased sky survey of the northern skies at multi-TeV energies.

## 4 GENERAL RESULTS

Note that reviews on some of the results obtained by HESS and MAGIC were also presented in this conference and can be found in Santangelo (2007) and Bartko (2008), respectively.

In the reviews on TeV astronomy written during the last years or decades it has been usual to provide a list of the known sources. Since this number is about 75 sources at the time of writing (and growing!), this is not practical any more. Instead, it is more instructive to show only the distribution of TeV sources in the sky, in galactic coordinates, and using different symbols for each type of object. A plot of this kind is shown in Fig. 1 (courtesy of Robert Wagners' <http://www.mppmu.mpg.de/~rwagner/sources/>). According to these data, there are 19 extragalactic sources and 56 galactic sources. Let us now review the main properties of these sources and some of the physics that can be learned from them.

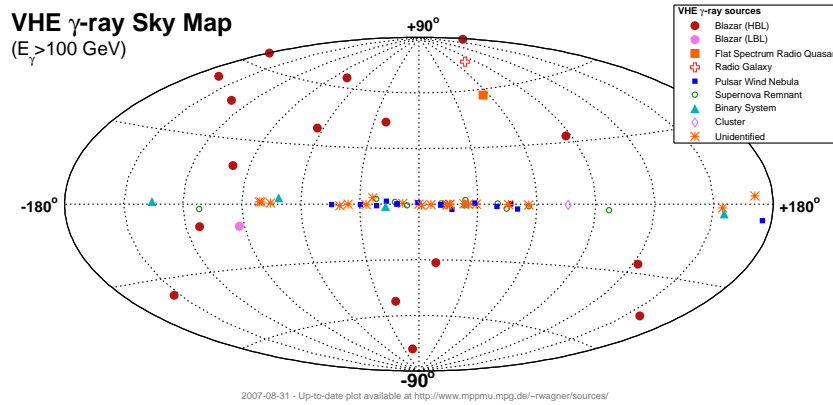
### 4.1 Extragalactic Sources

**High frequency peaked BL Lacertae objects (HBL).** BL Lacertae objects are Active Galactic Nuclei (AGN) with relativistic jets pointing close to the line of sight. The relativistic electrons in the jets produce synchrotron radiation from radio to X-rays thanks to the presence of magnetic fields. On the other hand, VHE gamma-ray emission can be produced if these electrons suffer inverse Compton (IC) scattering with ambient photons (although hadronic processes can also be at work). These photons can be those emitted by the synchrotron mechanism (Synchrotron Self Compton or SSC), or photons from external photon fields (External Compton or EC). The Spectral Energy Distributions (SEDs) of BL Lacertae objects show a

<sup>3</sup> <http://wwwmagic.mppmu.mpg.de/>

<sup>4</sup> <http://veritas.sao.arizona.edu/>

<sup>5</sup> <http://www.lanl.gov/milagro/>; <http://umdgrb.umd.edu/cosmic/milagro.html>



**Fig. 1** VHE gamma-ray sky map as of 2007 August 31 from Robert Wagners' <http://www.mppmu.mpg.de/~rwagner/sources/>. 19 extragalactic sources with redshifts between 0.0044 (M87) and 0.536 (3C 279) are plotted together with 56 Galactic sources including pulsar wind nebulae, supernova remnants, X-ray binaries and many unidentified sources. Look at <http://tevcat.uchicago.edu/> for an interactive web page on all TeV sources.

characteristic double bump formed by the synchrotron peak and the Compton peak. The objects where the synchrotron peak is placed at high frequencies (UV to X-rays) are more easily detectable at TeV energies, since the energy gain in the Compton process does not need to be so dramatic. These objects are called High frequency peaked BL Lacertae objects (or HBL). After the discovery of the first TeV source, the three following ones were the HBLs Markarian 421 ( $z = 0.031$ ; Punch et al. 1992), Markarian 501 ( $z = 0.034$ ; Quinn et al. 1996) and 1ES 2344+514 ( $z = 0.044$ ; Catanese et al. 1998). Since then, 13 HBL have been discovered at TeV energies with redshifts between 0.047 and 0.212.

**Extragalactic Background Light (EBL).** The newly discovered high redshift HBLs have allowed to study the attenuation of the TeV emission by photon-photon absorption and pair creation due to Extragalactic Background Light (EBL). In particular, the HESS detections of 1ES 1101–232 ( $z = 0.186$ ) and H 2356–309 ( $z = 0.165$ ) showing very hard spectra, imply a low level of EBL (Aharonian et al. 2006a). In other words, most of the light emitted at optical/near-infrared wavelengths appears to be very close to the lower limit given by the integrated light of resolved galaxies. This effectively excludes contribution from other sources like the first stars formed, and shows that the intergalactic medium is more transparent to gamma-rays than previously thought. It is interesting to note that, based on the current observational techniques, any possible TeV extragalactic background would not be detected (even if it is not very absorbed).

**Rapid flares in HBLs.** Rapid flares in Markarian 501 and PKS 2155–304 have recently been discovered by MAGIC and HESS, respectively. In the first case, the source showed flux-doubling times down to 2 minutes and an indication of a  $4 \pm 1$  min time delay between the peaks of  $F(<0.25$  TeV) and  $F(>1.2$  TeV), which may indicate a progressive acceleration of electrons in the emitting plasma blob (Albert et al. 2007a), but also be the result of a vacuum refractive index in the context of quantum gravity (Albert et al. 2007b). In the case of PKS 2155–304, flux-doubling times down to 3 minutes were measured, and assuming an emitting region with the size of the Schwarzschild radius of a  $10^9 M_{\odot}$  black hole, Doppler factors above 100 are required, challenging our current understanding of blazar jets (Aharonian et al. 2007a).

**Low frequency peaked BL Lacertae objects (LBL).** LBLs have their synchrotron peak in the sub-millimeter to optical bands. The first firm detection of an LBL has recently been reported by MAGIC for the prototype source BL Lacertae ( $z = 0.069$ , Albert et al. 2007c) ruling out, thanks to simultaneous optical data, previous claims of much higher detections by the Crimean group. The multi-wavelength data favors a leptonic scenario.

**The radio galaxy M87.** The Fanaroff-Riley type I radio galaxy M87 ( $z = 0.0043$ ) has been detected at VHE gamma-rays by HESS (Aharonian et al. 2006b), confirming a previous detection reported by HEGRA. The observed fast variations indicate that the emission comes from a region with a dimension similar to the Schwarzschild radius of the central black hole. These observations confirm that TeV gamma-rays are emitted by extragalactic sources other than blazars, where jets are not relativistically beamed towards the observer.

**The FSRQ 3C 279.** The Flat Spectrum Radio Quasar (FSRQ) 3C 279, with a redshift of  $z = 0.536$ , has recently been reported to be a TeV emitter by the MAGIC Collaboration (Teshima et al. 2007). If confirmed, this is the most distant AGN ever detected at TeV energies.

**No starburst galaxy detection.** It is interesting to note here that the two starburst galaxies NGC 253 and Arp 220 have been observed with HESS and MAGIC, respectively. In the case of NGC 253, the new observations rule out a previously claimed detection by CANGAROO-II (see Aharonian et al. 2005a). In the case of Arp 220, the nearest ultraluminous infrared galaxy, the obtained upper limits are consistent with theoretical expectations (Albert et al. 2007d). No starburst galaxy has ever been firmly detected at VHE gamma rays.

**Gamma-Ray Bursts (GRBs).** Observations of long duration GRBs have been conducted by the MAGIC telescope. In the case of GRB 050713a, since the redshift of the GRB was not measured directly, the flux upper limit estimated by MAGIC is still compatible with the assumption of an unbroken power-law spectrum extending from a few hundred keV to energies above 175 GeV (Albert et al. 2006a). From 2005 April to 2006 February MAGIC observed a total of 9 GRBs, obtaining upper limits in all cases. For the 4 bursts with measured redshift, the upper limits are compatible with a power law extrapolation from the fluxes obtained at tens-to-hundred of keV (Albert et al. 2007e). On the other hand, observations of short duration GRBs have been possible with Milagro. Indeed, 17 GRBs lasting less than 5 s have fallen in the field of view of Milagro between 2000 January and 2006 December, and upper limits have been obtained for all of them (Abdo et al. 2007a). Although the detection of long duration GRBs at high redshift can be difficult due to absorption by the EBL, this is not the case for the expected more nearby short duration GRBs. In any case, no detection has been found for a relatively close burst at  $z = 0.225$  (see Abdo et al. 2007a for details).

## 4.2 Galactic Sources

**Galactic Plane Surveys.** While serendipity in discovering extragalactic sources would be rare, this is not the case for galactic ones, where galactic plane surveys can play a major role in the discovery space. The most extreme examples come from the galactic plane surveys conducted by HESS (Aharonian et al. 2005b; 2006c) and Milagro (Abdo et al. 2007b).

The HESS survey of the inner Galaxy covers  $\pm 30^\circ$  in longitude and  $\pm 3^\circ$  in latitude, with an average flux sensitivity of 2% of the Crab Nebula at energies above 200 GeV. Up to 14 new sources were discovered, 12 being extended and 4 of them significantly elongated (Aharonian et al. 2006c). Most of them are suggested to be supernova remnants and/or pulsar wind nebulae, while two of them could be X-ray binaries and about 6 remain unidentified (of which 3 have no suggested counterpart).

The Milagro galactic plane survey for declinations above  $-7^\circ$  reveals three multi-TeV sources apart from the already known emission from the Crab Nebula. Their nature remains unknown. The most significant one, MGRO J2019+37 (see also Abdo et al. 2007c), is clearly extended with a diameter of the peak emission of  $\sim 1^\circ$  and contains several GeV sources.

**The Galactic Center.** Observations of the Galactic Center (GC) region with HESS have revealed a point-like source in a position within  $1'$  of Sgr A\* (Aharonian et al. 2004a). These observations are in strong disagreement with previous ones reported by CANGAROO-II and show fluxes somewhat below previous ones reported by Whipple. Although variability of the supermassive black hole could be invoked, the TeV source has never been seen to vary by any given instrument. MAGIC observations have confirmed the HESS results: the flux, the spectrum and the lack of variability (Albert et al. 2006b). It should be noted that the TeV source at the Galactic Center could also be the VHE counterpart of the SNR Sgr A East or of a recently discovered pulsar wind nebula, in which cases no variability would be expected. The possibility that the TeV emission has its origin in dark matter annihilation processes has been recently studied, although the

observed power-law spectrum appears to be incompatible with the most conventional scenarios (Aharonian et al. 2006d).

**The Galactic Center Ridge.** Deep HESS observations have revealed that after subtracting the TeV contribution from the Galactic Center source and from the SNR G 0.9+0.1 (see below), a distribution of diffuse emission along the plane is found (Fig. 2-left). This diffuse emission appears to be well correlated with CS emission that traces molecular gas (a good target for inelastic proton-proton interactions and neutral pion decay). Indeed, the observed TeV morphology can be reproduced using a cosmic ray density distribution and diffusion away from a central source of age  $\sim 10^4$  years (Aharonian et al. 2006e).

**SuperNova Remnants (SNR).** SNR are thought to be the sites of cosmic ray acceleration up to the knee, and TeV photons, which are not deflected by galactic magnetic fields, can provide valuable information in this respect. Two SNR displaying a shell at TeV energies have been found by HESS: RX J1713.7–3946 and RX J0852–4622 (Aharonian et al. 2004b and 2005c, respectively). Interestingly the TeV shells follow nicely the synchrotron keV emission seen by X-ray satellites. This suggests that a leptonic scenario could be at work, where relativistic electrons produce the synchrotron X-ray emission and IC up-scatter ambient photons to produce TeV emission. However, detailed TeV spectra appear to be more compatible with a hadronic origin, where VHE gamma-rays are produced by inelastic  $pp$  interactions and  $\pi^0$  decay (Aharonian et al. 2006f, 2007b, 2007c). Observations at lower energies with the *GLAST* satellite will allow to unveil the nature of these VHE sources.

Two composite supernova remnants, SNR G 0.9+0.1 and HESS J1813–1718, have also been found (Aharonian et al. 2005d, 2006c). In the first case the VHE emission appears to originate in the plerionic core and can be plausibly explained by IC scattering of relativistic electrons. On the other hand, TeV emission has also been found in two SNR near molecular clouds: HESS J1834–087/W41 (Aharonian et al. 2006c; Albert et al. 2006c) and MAGIC J0616+225/IC 443 (Albert et al. 2007f). More precisely the TeV emission appears to originate, specially in the second case, in the interaction between the SNR and the molecular cloud, clearly suggesting a hadronic scenario. Finally, it is worth to note here that a previously claimed detection of SN 1006 has been ruled out by the upper limits obtained by HESS (Aharonian et al. 2005e).

**Pulsar Wind Nebulae (PWN).** The majority of the newly identified TeV sources are PWN ( $\sim 18$  sources). In these objects a rapidly spinning neutron star produces a relativistic wind of electrons that produce X-ray synchrotron radiation. IC up-scattering of ambient photons, either CMB or from nearby stars, produces the observed TeV emission. A good example of an extended TeV PWN closely matching its X-ray emission is that of MSH 15–52 (Aharonian et al. 2005f). On the other hand, the PWN HESS J1825–137 has been the first TeV source to display an energy-dependent morphology, in the sense of a softening of the spectrum with increasing distance from the pulsar. This favors a leptonic scenario where there is cooling of the electrons in the nebula. Interestingly, the data is not compatible with a constant spin-down power, and a higher injection power in the past is required (Aharonian et al. 2006g).

**Pulsars.** Although extensive searches have been conducted, no pulsed emission from the Crab pulsar has been detected with MAGIC, constraining the exponential cutoff energy to be below 27 GeV, while for a super-exponential the cutoff energy is below 60 GeV (Albert et al. 2007g). A search for pulsed emission in 11 pulsars by HESS reveals that the VHE gamma-ray production efficiency in young pulsars is less than  $10^{-4}$  of the pulsar spin-down luminosity (Aharonian et al. 2007d).

**Galactic open clusters.** The extended source HESS J1023–575 has been found to be coincident with the young stellar cluster Westerlund 2, in the well-known HII complex RCW49 (Aharonian et al. 2007e). Considered emission scenarios include emission from the colliding wind zone of WR 20a, collective stellar winds, diffusive shock acceleration in the wind-blown bubble itself, and supersonic winds breaking out into the ISM.

**Unidentified sources.** Although some of the  $\sim 24$  still unidentified sources have signatures of a PWN, there are good examples of sources with no clear counterparts. The best example might be TeV J2032+413, a steady and extended (FWHM  $\simeq 14 \pm 3'$ ) source displaying a hard spectrum ( $\Gamma \simeq 1.9$ ) discovered by HEGRA (Aharonian et al. 2002, 2005g). Although the apparent absence of counterparts at lower energies suggested a dark accelerator, several radio emitting X-ray sources have been recently discovered in its center of gravity (see Paredes et al. 2007 and references therein). More recently, an extended (FWHM  $\simeq 12'$ ) X-ray

source matching the position of TeV J2032+413 has been revealed through deep *XMM-Newton* observations (Horns et al. 2007). In any case its nature, whether hadronic or leptonic, remains unknown.

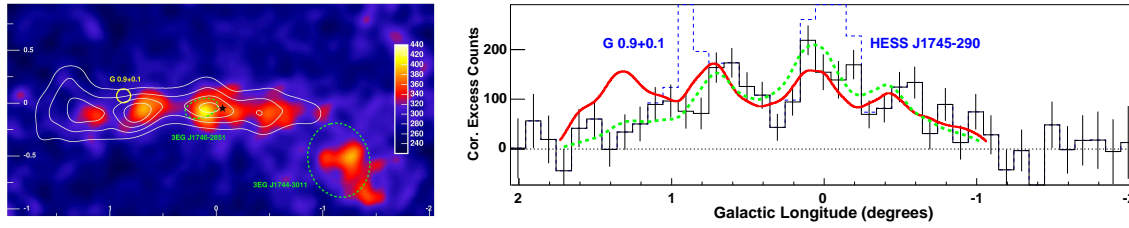
## 5 X-RAY/GAMMA-RAY BINARIES

Four X-ray binaries have been unambiguously detected up to now at TeV energies: PSR B1259–63 (Aharonian et al. 2005h), LS 5039 (Aharonian et al. 2005i), LS I +61 303 (Albert et al. 2006d) and recently Cygnus X-1 (Albert et al. 2007h).

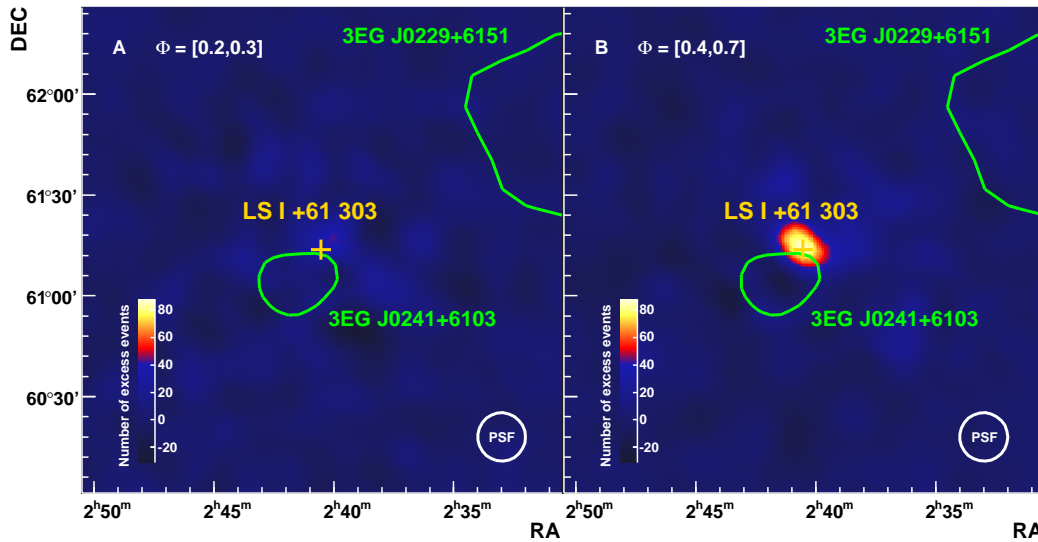
**PSR B1259–63** is composed of a 48 ms radio pulsar orbiting a B2 Ve star every 1237 d in a highly eccentric orbit with  $e = 0.87$ . The pulsed radio emission is not detected when the neutron star is behind the decretion disk of the companion. The observed TeV spectrum can be fit with a simple power law, but the lightcurve is puzzling when compared to previously available models. Although it is clear that the interaction between the relativistic wind of the young non-accreting pulsar and the polar wind and/or equatorial (but inclined) decretion disk of the donor star plays a major role, the exact mechanism producing the TeV emission is not known. Pure leptonic scenarios invoking IC scattering have been put forward (Khangulyan et al. 2007a), as well as hadronic scenarios where TeV emission is produced by  $\pi^0$  decay and radio/X-ray emission by  $\pi^\pm$  decay and IC scattering (Neronov & Chernyakova 2007). As it is the case for SNR, observations in the GeV range by *GLAST* will provide the answer.

**LS I +61 303** is composed of a rapidly rotating early type B0 Ve star with a stable equatorial decretion disk and mass loss, and a compact object with a mass between 1 and  $4 M_\odot$  orbiting it every  $\sim 26.5$  d (see Casares et al. 2005a and references therein). The TeV emission detected by MAGIC is highly variable: upper limits have been found during periastron passage and a peak occurs near apastron (Albert et al. 2006d; see Fig. 3). The spectrum can always be fitted with a simple power law. It is worth to note that the VERITAS Collaboration has recently confirmed the orbital TeV variability (Maier 2007). Massi et al. (2004) reported the discovery of an extended jet-like and apparently precessing radio emitting structure at angular extensions of 10–50 milliarcseconds. Due to the presence of (apparently relativistic) radio emitting jets, LS I +61 303 was proposed to be a microquasar. However, recent VLBA images obtained during a full orbital cycle show a rotating elongated morphology that Dhawan et al. (2006) interpreted in the context of the interaction between the wind of the companion and the relativistic wind of a young non-accreting ms pulsar, similarly as in PSR B1259–63 (see Dubus 2006 for details on the model). The pulsed radio emission would not be detected because of free-free absorption. However, recent detailed simulations of this pulsar-wind interaction reveal a problem in this scenario: to explain the observed GeV luminosity the spin-down power of the putative pulsar should be so high that the wind of the companion could not collimate the radio emitting particles (Romero et al. 2007). The nature of the source is thus still a matter of debate.

**LS 5039** contains a compact object of unknown nature, with mass between 1.4 and  $5 M_\odot$ , orbiting every 3.9 days an ON6.5 V((f)) donor in a slightly eccentric orbit (Casares et al. 2005b). The TeV flux of this binary system is clearly periodic, with enhanced emission at inferior conjunction of the compact object, suggesting that photon-photon absorption (which has an angle dependent cross-section) within the system plays a major role (Aharonian et al. 2006h). However, the non-zero flux observed at superior conjunction of the compact object and the lack of variability at  $\sim 200$  GeV argues against this simple interpretation, and suggests that there may be an orbital phase-dependent electron acceleration and/or that the TeV emission could be produced away from the compact object (Khangulyan et al. 2007b). The detection of elongated asymmetric emission in high-resolution radio images obtained with the VLBA and the EVN was interpreted as evidence of its microquasar nature, and suggested that the source was persistently producing mildly relativistic ejections with a velocity of  $\sim 0.15c$  (Paredes et al. 2000, 2002). Although the X-ray spectra are compatible with those of accreting black holes during the so-called low/hard state (Bosch-Ramon et al. 2005), the radio spectra are optically thin with a spectral index of  $-0.5$  (Martí et al. 1998; Ribó et al. 1999). Theoretical modelling in the microquasar scenario (Bosch-Ramon et al. 2006) has allowed to reproduce the observed SED from radio to VHE gamma-rays (Paredes et al. 2006). However, the lack of clear accretion signatures and the similarities with the SEDs of PSR 1259–63 and LS I +61 303 has led other authors to model its multi-wavelength emission using the scenario of wind interactions (Dubus 2006). One of the predictions of this kind of modelling is the periodic change in the direction and shape of the extended radio



**Fig. 2** Left: VHE gamma-ray count map of the GC region after subtracting the GC source and SNR  $G\ 0.9+0.1$ . A diffuse emission is clearly seen correlated with molecular gas traced by CS emission shown in white contours. Right: The red line shows the CS distribution, while the green dashed curve is the applied model to explain the data (see text). From Aharonian et al. (2006e).



**Fig. 3** Smoothed VHE sky maps of LS I +61 303 in the orbital phase range 0.2–0.3 close to periastron passage (left) and in phase range 0.4–0.7 near apastron (right). The variability is apparent. From Albert et al. (2006d).

morphology, as well as in the peak position of the radio core, depending on the orbital phase. Therefore, high resolution VLBI observations can help to unveil the real nature of the system.

**Cygnus X-1** is the most recent addition to the selected group of TeV emitting X-ray binaries (Albert et al. 2007h). This binary system contains an O9.7 Iab donor and an accreting black hole of at least  $10 M_{\odot}$  orbiting it every 5.6 days in a circular orbit. It shows nearly persistent radio emission, which sometimes has been resolved in jet-like features that reveal its microquasar nature (Stirling et al. 2001). A ring-like structure at arcminute scales has been detected, showing the strong influence of the jet into its surrounding ISM (Gallo et al. 2005). Cygnus X-1 was detected by MAGIC only in a short  $\sim 80$  minute time interval with a soft spectrum ( $\Gamma \simeq 3.2$ ) extending up to  $\sim 1$  TeV, while upper limits are obtained for the rest of the  $\sim 40$  h observations. The position of the TeV emission is compatible with that of Cygnus X-1, excluding the ring-like structure. The TeV excess was found at orbital phase 0.91, when the black hole is behind the star and photon-photon absorption should be huge. For instance, Bednarek & Giovanelli (2007) computed the

opacity to pair production for different injection distances from the center of the massive star and angles of propagation, finding that photons propagating through the intense stellar field towards the observer would find in their way opacities of about 10 at 1 TeV. An origin in the jet of this microquasar and away from the compact object would relax these values. The TeV detection took place during a particularly bright hard X-ray state of Cygnus X-1. Simultaneous hard X-ray observations by *Swift*/BAT in the 15–50 keV energy range reveal that the TeV excess was found right before the onset of a hard X-ray peak. Observations one day later reveal that no TeV excess was found during the maximum and decay phase of another hard X-ray peak. Although one could speculate with the limited available data, more simultaneous multi-wavelength observations are necessary to build reliable models. In any case, this is the first experimental evidence of VHE emission from a stellar-mass black hole, and therefore from a confirmed accreting X-ray binary.

Finally, two X-ray binaries have been proposed as counterparts of unidentified VHE sources: IGR J16320–4751 for HESS J1632–478 and IGR J16358–4726 for HESS J1634–472 (Aharonian et al. 2006c). However, their extended TeV emission appears to rule out these associations.

## 6 THE FUTURE

Regarding the near future, it is expected that online analyses will be able to send alerts from Cherenkov telescopes to other astrophysical facilities. On the other hand, given the success of instruments like HESS and MAGIC, in the longer term the community wants to improve the sensitivity by up to a factor of  $\sim 10$  and increase the energy range to cover from  $\sim 30$  GeV to  $\sim 100$  TeV. In this context, a new Cherenkov telescope is being designed: the CTA (Cherenkov Telescope Array)<sup>6</sup>. It is important to note here that a guest observer program is planned for CTA.

## 7 CONCLUSIONS

The third generation of IACTs has revealed several tens of sources in the TeV sky. The nature of some of these sources was already known, and TeV observations can help to unveil the leptonic or hadronic nature of the accelerated particles, the ISM particle density, the magnetic fields, etc. On the other hand, new types of sources have been discovered, boosting theory. However, a lot of theoretical work is still needed to properly model some of these sources. In addition, there are unidentified sources whose nature remains unknown. New instruments like *GLAST* and CTA will allow to conduct population studies and unveil the nature of some of the sources in the near (and mid-term) future. In conclusion, the TeV sky is starting to shine and is revealing new and very interesting laboratories for astrophysics.

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<sup>6</sup> <http://www.mpi-hd.mpg.de/hfm/CTA/>

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