Status of Very High Energy γ-ray Astronomy as of early 2008

Arache Djannati-Ataï

Astroparticule et Cosmologie (APC), CNRS, Universite Paris 7 Denis Diderot, Paris, France [1]

Abstract

Data obtained in the very high energy γ-ray band with the new generation of imaging telescopes, in particular through the galactic plane survey undertaken by H.E.S.S., low threshold observations with MAGIC and more recently by operation of VERITAS, have revealed few tens of galactic and extragalactic sources, providing a wealth of information on a variety of high energy acceleration sites in our universe. Also, the water Cherenkov instrument Milagro has provided few extended sources after seven years of data integration. An overview of these results with focus on some of the most recent highlights is given.

Key words: gamma rays: observations, intergalactic medium, supernovae: general, cosmic rays: general, X-rays: binaries, pulsars: general
PACS:

1. Introduction

Almost two decades after the establishment of the Crab nebula as the first TeV emitting source, thanks to the pioneering work at the Whipple Observatory in Arizona [1], the field of very high energy (VHE) γ-ray astronomy has entered the maturity age. Although limited in aperture (3-6$\times 10^{-3}$ sr, currently) and duty cycle ($\sim 10\%$), the imaging atmospheric Cherenkov telescopes (IACTs) have proved to be the most sensitive, thanks to precise angular reconstruction of the shower origin and to powerful background rejection capabilities. The new generation of these instruments has allowed the discovery of more than 70 galactic and extragalactic sources. The major contributions have come from H.E.S.S. in Namibia (system of four 13 m diameter telescopes, 2003), MAGIC in La Palma (single 17 m diameter dish, 2004), CANGAROO-III in Woomera (three 10 m diameter dishes, one more pending, 2004), and VERITAS (four 12 m diameter telescopes, 2006) in Arizona. Large aperture and duty cycle instruments, the water Cherenkov detector Milagro (1999-2007) and the particle counter array Tibet As-γ (1992), although disposing of a much lower sensitivity, have also interestingly contributed to the field through large exposures obtained after few-years scale integration times. A brief overview of the field, as of early 2008, is given below.

2. Galactic sources

By late 2002, the TeV sky consisted of only 6 confirmed sources, and was dominated by point-like extragalactic ones. Only one source, the Crab nebula, was firmly detected in the Galaxy. A major breakthrough was accomplished by the 2004-2007 HESS Galactic Plane Survey (GPS): covering the inner Galaxy ($l \in [-85°, 60°], b \in [-2.5°, 2.5°]$), this survey has, up to now, resulted in the discovery of 40 galactic sources and the diffuse emission in the central 100 pc of the Milky Way, while confirming 4

Email address: djannati@apc.univ-paris7.fr (Arache Djannati-Ataï).

[1] UMR 7164 (CNRS, Université Paris VII, CEA, Observatoire de Paris)

and invalidating 2 sources previously published by CANGAROO. The Milagro sky survey has resulted in less prolific but nonetheless interesting discoveries: 3 extended sources, 4 less significant hot-spots, and evidence for diffuse emission along the Galactic Plane [27,28]. When adding the Crab, 3 discoveries [2] and 2 confirmations made in the northern hemisphere by MAGIC and VERITAS, the total number of known galactic sources is well in excess of 50 (see Tables 1, 2 and 3). In the following, different galactic VHE source classes will be discussed with focus on recent results.

2.1. *Supernova Remnants*

Following the original proposition of W. Baade and F. Zwicky back in 1934 [2], but based on quantitative arguments (energetics, chemical composition) and diffusive shock acceleration models (e.g. [54], [55], [47]), shell-type SNRs are considered as prime acceleration sites for the galactic cosmic-rays, at most up to the *knee* ($\sim 10^{15}$ eV) ([48]). The first signature of acceleration of cosmic electrons within shell-type SNR shocks dates back to 1995 [56] when ASCA observations of SN 1006 rims established the non-thermal nature of their X-ray emission. γ-ray emission from SNRs, as a signature of interactions of accelerated ionic cosmic-rays with internal or nearby matter have long been sought after by space- and ground-based instruments. VHE γ-rays were first detected from RX J1713.7−3946 by the CANGAROO [6] collaboration. The confirmation of this signal by HESS was made through the realization of the first ever resolved image in the γ-ray band [7]. The latter image exhibited a clear shell morphology, strongly correlated with non-thermal X-rays. γ-ray emission processes at play in RX J1713.7−3946, whether leptonic or hadronic, have been and are still under debate. Some of the pros and cons in each case are discussed briefly hereafter. The γ- to X-ray correlation tends to favour leptonic models, but that is at the expense of a rather low magnetic field strength $B \sim 10\,\mu$G, lower than what is required by models of dynamical field amplification (see e.g. [50]) in non-linear shocks in order to explain the observed X-ray filamentary features, i.e. $B \sim 58 - 100\,\mu$G [52]. Hadronic scenarios face also difficulties –e.g. the required mean pre-shock hydrogen number density $n \sim 1\,\mathrm{cm}^{-3}$ violates the upper limit $n < 0.02\,\mathrm{cm}^{-3}$ implied by the absence of thermal X-rays [51]– and have to recourse to quite low e^-/p ratios [49], but they seem to better fit the shape of the VHE spectrum [8]. On the other hand a detailed modeling of the interstellar radiation field for the calculation of the inverse Compton (IC) spectrum [53] improves the fit to leptonic models, though not for the latest published spectrum [9]. The uncertainties on age (1-10 kyr) and distance (1-6 kpc) leave also some margin to different models; hence, for the time being, no clear-cut distinction between them can be made. The situation is analog for the two other spatially resolved γ-ray SNRs, RX J0852.0−4622 and RCW 86, recently reported by HESS [12,11]. The former shows also a strong correlation with non-thermal X-rays and an absence of thermal X-rays, but has a thiner VHE shell morphology (Fig. 1). RCW 86 is at variance with the two other TeV shell-type SNRs in that it exhibits both thermal and non-thermal X-rays.

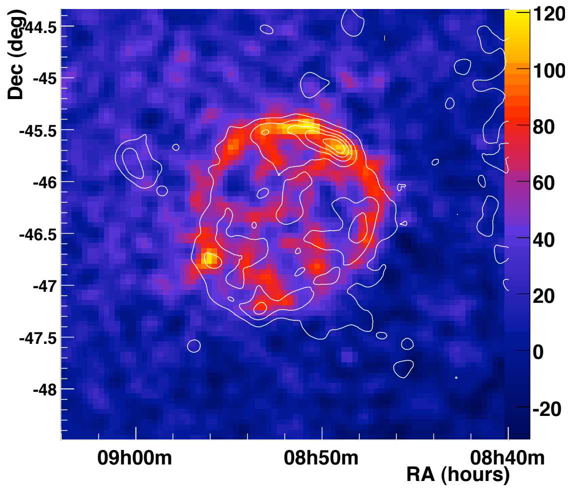

Fig. 1. . Smoothed VHE image of RX J0852.0−4622 obtained by HESS, shown together with X-ray contours from the ROSAT All Sky Survey > 1.3 keV [11].

In the case of the very young and radio-bright SNR, Cassiopeia A –point-like in γ-rays, detected initially by the HEGRA collaboration [13] and confirmed recently by MAGIC [15]– it seems again difficult to determine unambiguously the nature/loci of the emitting particles with the current γ-ray data. Neutrinos, expected as secondary products of cosmic-ray interactions with ambient matter, could be used to probe decisively the hadronic component of cosmic accelerators (see e.g. [58]). Estimation of event rates for the brightest γ-ray SNRs, based

[2] the detection of one source, Cyg−X1, needs still confirmation, see table 1.

on their VHE flux measurements, seem, however, to imply the necessity of very large volume detectors: indeed the potential signal to noise ratios for a 1 km^3 class neutrino detector seem to be low, e.g. the expected signal and background rates for RX J1713.7−3946, for an integration time of 5 years, are of order of 14 and 41, respectively [57].

VHE γ-ray observations of SNRs interacting with high density (i.e. $n > 10^3$ cm^{-3}) molecular clouds in their vicinity is an alternative probe of ionic acceleration by SNR shock waves. In this regard, older SNRs (i.e. with age > few 10^4 yr) are potentially attractive targets since accelerated electrons must have lost much of their energy through radiative cooling and should not reach multi-TeV energies [59]. The VHE loci of W41/HESS J1834-026 [37,16], IC 443/MAGIC J0616+225 [14], also reported by VERITAS [17], and W 28/{HESS J1800-240, HESS J1801-233} [18], are coincident with such molecular clouds and suggest that these objects are accelerating ionic cosmic-rays. The presence of OH masers (tracers of shocked molecular matter) in IC 443 and the northeastern region of W 28 supports this hypothesis. The VHE emission reported recently from another SNR/molecular cloud association with a much younger object, CTB37A/HESS J1714-385 [20] enhances further this class of possible hadronic accelerators, although, a PWN-type contribution is also possible due to the discovery of an extended non-thermal X-ray source near the VHE peak. Another new candidate for this class is the formerly 'dark' source (see below), HESS J1731−347, recently identified with a ∼ 30 kyr SNR, G353.6−0.7 [22].

2.2. *Pulsar Wind Nebulae (PWNe)*

Relativistic particles of the shocked winds of pulsars shine through synchrotron and IC radiation from radio to γ-rays and form Plerions (*Pleres Plera* or filled bags). The *Chandra* and *XMM-Newton* imaging and spatially resolved spectroscopy of X-ray synchrotron nebulae have provided a wealth of details on pulsar winds and their interactions with the medium (e.g., [23]). Two morphological types have emerged: those which show a toroidal structure around the pulsar, with one or two jets along the torus axis, and those dominated by a cometary structure, with the pulsar close to the comet apex. Also, the spectral softening of the extended emission as a function of distance to the pulsar, observed for many PWNe, has been successfully interpreted as the synchrotron cooling of the X-ray emitting electrons.

Table 1
Class A: Galactic sources with a firmly established counterpart and for which the VHE emission origin/morphology (not necessarily the emission process) is also fairly well identified; see text.

VHE Class	Object	discovery[a]
Shell	RX J0852.0−4622	CANGAROO [5,10,11]
Shell	RX J1713.7−3946	CANGAROO [6–8]
Shell	RCW 86	HESS [12]
SNR	Cassiopeia A	HEGRA [13]
PWN	Crab nebula	Whipple[1,3,4]
PWN	G 0.9+0.1	HESS [33]
PWN	MSH 15−52	HESS (J1514−591) [34]
PWN	Vela X	HESS (J0835−455) [35]
PWN	G 18.0−0.7	HESS (J1825−137) [36,37]
PWN	K3/Kookaburra	HESS (J1420−607) [38]
PWN	G 21.5-0.9	HESS [40]
PWN	PSR J1718−3825	HESS (J1718−385) [39]
PWN	PSR J1809−1917	HESS (J1809−193) [39]
PWN[†]	Kes 75	HESS [40]
Binary	PSR B1259−63	HESS [41]
Binary	LS 5039	HESS [42,43]
Binary	LSI +61 303	MAGIC [44,45]
Binary	Cyg−X1[‡]	MAGIC [46]

[a] For extended PWNe the best fitted position of the source is quoted as well. Additional references to the discovery paper are given when relevant, e.g., confirmation of the source or discovery of important features (morphology, spectrum).
[†] Contribution from the SNR shell is not excluded for Kes 75.
[‡] The firm detection of this source is not established yet.

The first source discovered in the VHE domain, the Crab nebula, is a plerion and still exhibits a point-like emission to the precision of the current instruments (few arc-minutes). As was remarkably soon predicted by [60], the study of its synchrotron and IC components opened the way to the measurement of the magnetic field strength within the nebula [61]. The HESS GPS has revealed a large number of PWNe, most of which are very extended and associated to energetic and middle-aged pulsars, with age $\sim 10^4 - 10^5$ yr. HESS J1825−137 can be considered as the prototype of such objects: its γ-ray emission is extended, with a characteristic size of 0.3°, and offset to the south of the pulsar B 1823−13; the latter has spin-down characteristic age and power of $\tau_C = 21000$ yr and $\dot{E} = 10^{35}$ erg s^{-1}, respectively. It is remarkable that the X-ray nebula exhibits exactly the same feature and is offset to the south of the pulsar, except that its extension is of order of a few arc-minutes rather than a fraction of a degree.

Table 2
Class B: Galactic sources with a either an identified or a plausible counterpart but for which further data is required to firmly establish the association or type of emission; see text. The VHE types in last column are tentative scenarios put forward by different authors and are not exclusive of other possibilities; MoC-SNR stands for molecular cloud-SNR associations; OpC: open cluster; Lept.: leptonic

Object[a]	Poss. counterpart(s)	Type
MAGIC J0616+225[§]	IC 443	MoC-SNR [14]
HESS J1023−575	Westerlund2	OpC wind
HESS J1303−631	PSR J1303−6315	PWN
HESS J1357−645	PSR J1357−6429	PWN
HESS J1418−609	G 313.3+0.1	PWN
HESS J1616−508[†]	PSR J1617−5055	PWN/SNR
HESS J1640−465 [§]	G 338.3−0.0	PWN/SNR
HESS J1702−420	PSR J1702−4128	PWN
HESS J1713−381[§]	CTB37 B	MoC-SNR
HESS J1714−385[§]	CTB37 A	PWN/MoC-SNR
HESS J1731−347[†§]	G 353.6−0.7	Shell
HESS J1745−290	SgrA*/G 359.95−0.04	BH/PWN
HESS J1804−216[§]	G 08.7-0.1	PWN/SNR
HESS J1813−178[†§]	G 12.8−0.0	PWN/SNR
HESS J1800−240[‡§]	W 28 south	MoC-SNR
HESS J1801−233[§]	W 28 north-east	MoC-SNR
HESS J1834−026[§]	W41	MoC-SNR
HESS J1837−069[†]	PSR J1838−0655	PWN
HESS J1857+026[†]	PSR J1856+0245	PWN
HESS J1912+101	PSR J1913+1011	PWN
TeV J2032+4130[†]	extended X-ray	Pevatron/Lept. [26]

[a]References for the HESS sources are available at http://www.mpi-hd.mpg.de/hfm/HESS/public/HESS_catalog.htm;
[†]These sources were initially classified as dark.
[§]These sources have a rather well identified counterpart, except that the emission origin is still ambiguous.
[‡]This source splits in three sub-sources, J1800−240 A, B and C.

This can be naturally explained in terms of the cooling time of particles in the estimated average nebular magnetic field B $\sim 10\,\mu$G: the X-ray generating electrons have higher energies than those responsible via IC for the VHE γ-rays, hence they cool faster and have a shorter range, whereas the latter include relic particles, i.e. those injected and accelerated at early epochs of the pulsar activity [62]. This interpretation has been further supported by the discovery of the spectral softening of the VHE nebula as a function of the distance to the pulsar, analog to that seen in X-rays [63]. The offset of the nebula with respect to the pulsar can be understood in terms of the displacement caused by an anisotropic reverse shock, itself due to the explosion of the progenitor in an inhomogeneous medium. This explanation was first proposed by [64] for Vela X, another asymmetrical PWN in radio and X-rays, which is, as has been demonstrated by HESS [35], also offset in VHE γ-rays. A number of other extended offset nebulae have been discovered by HESS and the systematic search of molecular clouds in their vicinity [65] has revealed in many cases clouds at compatible kinematic distances to their associated pulsar, as candidates to explain their peculiar morphology. Another key point in the study of these middle-aged nebulae is the possibility to access both to their 'current' state through X-rays (fresh short-lived particles), and to their past history and evolution, e.g. those of the pulsar and magnetic field, through the the VHE emission (relic electrons) [65,66].

In this context the young Crab nebula appeared as a rather particular VHE source [3]. Very recently, two other very young nebulae were discovered by HESS: G 21.5−0.9 which harbors the second most energetic pulsar known in the Galaxy (after the Crab) and Kes 75, associated to the 325 ms, X-ray only, pulsar, PSR J1846-258 [40]. Despite their similar young ages to the Crab nebula, G 21.5−0.9 and Kes 75 exhibit much smaller X-ray to γ-ray luminosity ratios and hence a much lower nebular field. Also both objects are classified as composite SNRs and, as such, the possibility of VHE radiation from particles accelerated at the forward shock of the freely expanding shells should be considered. While this possibility remains open for Kes 75, the low gas densities inferred through thermal X-ray measurements for G 21.5−0.9 make the contribution of the SNR shell to its γ-ray emission unlikely.

2.3. *γ-ray binaries*

Although a plethora of binary systems are X-ray emitters, only three objects have been firmly detected in the VHE band up to now: PSR B1259−63/SS 2883, LS 5039 both reported by HESS and LSI +61 303, discovered by MAGIC [44]. PSR B1259−63 is a 48 ms radio pulsar, but for LS 5039 and LSI +61 303 the precise nature of the compact object is not known: the 4 $M_\odot$ upper limit on their mass is consistent both with neutron stars and low mass black holes. These two systems are much closer binary systems with periods of 3.9 and 26.5 days, respectively, as compared to the 3.4 yr period of PSR B1259−63/SS 2883.

[3] this was already the case at other wavelengths

The VHE emission of LS 5039 is clearly periodic, with enhanced and harder emission at the inferior conjunction. The variability of LSI +61 303 has been recently confirmed by VERITAS [45], but it is not clear yet if its emission is strictly periodic. The main question regarding these sources is whether the relativistic particles come from accretion-powered jets or from a rotation-powered pulsar wind as for PSR B1259−63/SS 2883. Also, although the interaction of the relativistic wind of the latter should play a major role, the precise emission mechanism, whether leptonic or hadronic, is unknown (see e.g. [67]).

The marginal detection of Cyg−X1, a $>13M_\odot$ black hole binary system, recently reported by MAGIC [46], if confirmed, is interesting in this context, since it should require rather an accretion-powered jet model.

2.4. *Unidentified Sources*

It is remarkable that most of the galactic sources are extended and many of them show a featureless morphology ; this precisely renders their identification difficult, except when a clear correlation with an object at other wavelengths exists, and/or a coherent multi-wavelength model is found. Finding the counterpart of a point-like source is, in principle, straightforward (when it exits), but the identification of the VHE emission process requires again a coherent model. Given these boundary conditions, the following classes of can be defined:
A) Sources with a firmly established counterpart and for which the VHE emission origin/morphology (not necessarily the emission process) is also fairly well identified, e.g the Crab nebula, TeV shell-type SNRs and γ-ray binaries fall into this class.
B) Sources with either an identified or a plausible counterpart but for which further data is required to firmly establish the association or the type of emission, e.g., PWN- and/or SNR-type.
C) Sources with no plausible counterparts (or 'dark' sources).

Source	Comments
HESS J0632+057	point-like, near Monoceros Loop [31]
HESS J1427−608	ext., PWN compatible [32]
HESS J1614−518	ext., soft [32]
HESS J1626−490	ext. hard [37]
HESS J1632−478	ext., IGR srce, no MOR [37]
HESS J1634−472	ext., soft, SNR, no MOR [37]
HESS J1708−410	ext., PWN compatible [37]
HESS J1745−303	ext., MoC-SNR to the north [37,21]
HESS J1841−055	ext. [32]
HESS J1858+020	ext. [32]
MGRO J1908+06	HESS J1908+063/GRO srce [30,27]
MGRO J2019+37	ext. $>1^\circ$ [27]
MGRO J2031+41	ext. [27]

Table 3
Class C: Galactic sources for which no clear counterpart exists at other wavelengths: 'ext.' stands for extended, hard means a photon spectral index $\Gamma < 2.2$ and 'no MOR' is to indicate the morphological incompatibility of the source with lower-wavelength objects, if any in its line of site.

The majority of the galactic sources fall into the last two classes (Tables 2 and 3) and hence many are still considered as unidentified. TeV 2032+4130, the first unidentified source discovered by HEGRA [24] in 2002, has been confirmed by MAGIC [25]. Recently an extended X-ray source matching the position of TeV J2032+413 was detected through deep *XMM-Newton* observations [26] and consequently this source is no more considered as a dark one, but is classified as B. This is the case also for five HESS sources, which were previously classified as dark: HESS J1731−347 has now an old shell-type SNR counterpart whereas a young SNR has been discovered and associated to HESS J1813−178; in addition two young and energetic pulsars have been discovered in the vicinity (line of sight) of HESS J1837−069 and HESS J1857+026, and HESS J1616−508 has now a faint X-ray counterpart. Among the three unidentified sources reported by Milagro [27], MGRO J2019+37 and MGRO J1908+06 have been recently confirmed by Tibet As-γ [29] and HESS [30], respectively, but remain still unidentified.

The dark sources are prime hadronic accelerator candidates. However, as noted first by [65,66], due to the large lifetime of VHE emitting electrons (up to few $10 \times$ kyr depending on the nebular field) the ratio of the X-ray luminosity to the γ-ray luminosity is a decreasing function of the system age and hence one expects TeV PWNe with so faint X-ray counterparts that they could well be below the sensitivity threshold of current X-ray instruments. Hence it is likely that some of the dark sources are indeed "γ-ray PWNe" without multi-wavelength counterpart.

It is also noteworthy that the extended class B source HESS J1023−575 is in coincidence with the second most massive young cluster in the Milky Way, Westerlund 2. Strong shocks created through the colliding winds of massive stars are believed to be able to accelerate particles up to TeV energies and their collective effects can in principle provide sufficient energy for the observed emission. If so, a new class of cosmic ray accelerators should emerge through observations of other clusters if this type.

2.5. *Galactic Center and its neighbourhood*

The point-like emission from the direction of Sgr A complex was discovered already 4 years ago by CANGAROO [69], and subsequently detected by Whipple [68], and HESS [70] collaborations; the latter has produced the most consistent measurements of its signal and spectrum. Due to the variety of potential TeV emitting sources –including the massive black hole Sgr A*– the identification of the Galactic Center TeV emission origin is a difficult task. Two paths have been followed by HESS: simultaneous observations of X-ray flares of Sgr A* with *Chandra* and the improvement of the source (HESS J1745$-$290) localisation. The former approach has resulted in an upper-limit on the flaring TeV component with respect to the steady emission during the observed X-ray flare [71] , while the latter has allowed to constrain the source localisation with comparable and extremely low statistical and systematic errors –better than $6''$. This precision is enough to exclude the SNR Sgr A East as the dominant source of the TeV emission, leaving the PWN candidate G 359.95$-$0.04 and Sgr A* as the most likely candidates [72]. The dark matter interpretation is also clearly disfavoured: the measured power-law spectrum seems quite incompatible with typical (quark or gluon-fragmentation type) neutralino annihilation scenarios [74].

HESS J1745$-$290 lies above a diffuse emission along the Galactic ridge. HESS data have shown a clear correlation with the giant molecular clouds of the central $\sim$100 pc of the Galaxy [73], and a spectrum which is harder (index of 2.3) than that expected for γ-rays, if they were produced through interactions of cosmic rays with the same spectrum as the one local to the solar system. One elegant explanation for this is the reduced effects of diffusion and escape due to the proximity of accelerators and targets. Another feature of the γ-ray emission is its deficit as compared to the density of molecular clouds around $l \simeq 1.5°$. This has been interpreted in terms of a time limited diffusion range of the cosmic rays under the assumption that they were accelerated only 'recently' (some 10000 years ago) near the Galactic Center [73], but the question remains open to alternative explanations such as assuming that the γ-ray emission is a superposition of point-like sources distributed according to the distribution of the molecular gas.

Table 4
VHE γ-ray emitting AGN, as of early 2008, ordered by redshift. The last column gives the reference to the discovery publication and, when relevant, to the confirmation papers.

Object	z	Class	Discovery	Ref.
M 87	0.004	FRI	HEGRA 2003	[80,81]
Mrk 421	0.031	HBL	Whipple 1992	[82,83]
Mrk 501	0.034	HBL	Whipple 1996	[84,85]
1ES 2344+514	0.044	HBL	Whipple 1998	[86,87]
Mrk 180	0.046	HBL	MAGIC 2006	[88]
1ES 1959+650	0.047	HBL	TA 2002	[89–91]
BL Lac	0.069	LBL	MAGIC 2006	[92]
PKS 0548-322	0.069	HBL	HESS 2006	[93]
PKS 2005-489	0.071	HBL	HESS 2005	[94]
RGB 0152+017	0.080	HBL	HESS 2008	[95]
W Comae	0.102	IBL	Whipple 2008	[97]
PKS 2155-304	0.116	HBL	Durham 1999	[96,98]
H 1426+428	0.129	HBL	Whipple 2002	[99–101]
1ES 0806+524	0.138	HBL	Whipple 2008	[102]
1ES 0229+200	0.140	HBL	HESS 2007	[103]
H 2356-309	0.165	HBL	HESS 2005	[104]
1ES 1218+304	0.182	HBL	MAGIC 2005	[105]
1ES 1101-232	0.186	HBL	HESS 2005	[104]
1ES 0347-121	0.188	HBL	HESS 2007	[106]
1ES 1011+496	0.212	HBL	MAGIC 2007	[107]
PG 1553+113	> 0.25	HBL	HESS 2005	[108]
3C 279	0.536	FSRQ	MAGIC 2007	[109]
S5 0716+71	unknown	HBL	MAGIC 2008	[110]

3. Extragalactic Sources

The first VHE emitting extragalactic source, Mrk 421, was discovered back in 1992 [82]. There has been a tremendous progress in this area since 2003 and, as of early 2008, 23 extragalactic sources are known to be VHE γ-ray emitters. All of these sources but one are blazars, i.e. belong to the class of radio-loud Active Galactic Nuclei (AGN) with one of radio jets pointing towards the observer at small angles ($\sim$ few degrees). The broad band spectra of blazars is characterized by two broad peaks, in mm$-$soft Xrays and MeV$-$GeV bands, respectively. The lower energy peak is understood as synchrotron emission of energetic leptons within the relativistic jet, and the generally agreed upon origin for the second component is IC scattering of either synchrotron photons (SSC) [4] or ambient photons (EC) [5] by the same population of leptons. Alternatively, hadronic models are put forward for the higher energy component; however the observed strong correlations between the X-ray and the γ-ray emissions favour rather leptonic models [6].

As listed in Table 4, the High frequency peaked BL Lac objects, or HBLs, i.e. those for which the lower energy component peaks in X-rays, are the most prominent TeV emitting blazars. The three exceptions are: the BL Lac itself, classified as an LBL (Low freq. BL Lac), W Comae, an Intermediate BL Lac object, and 3C 279 a flat spectrum radio quasar, or FSRQ.

M 87, the well-known nearby FRI radio-galaxy, is the first non-blazar source and its detection is of particular interest. Its two-day time variability scale, first measured by HESS [81] and recently confirmed by VERITAS [76], constrains the size of the emission region $\sim 5\delta\,\mathrm{R_s}$, dramatically close to that of the black hole Schwarzschild radius $\mathrm{R_s}$, the expected Doppler factor δ being quite small given the large declination angle of M 87 jet to the line of sight ($\sim 30°$).

There have been two recent highlights in blazar observations: 1) the very fast variability of PKS 2155−304 observed by HESS during a dramatic flaring episode in July 2006; the best measured individual flare rise time is of 173±23 seconds [77] and implies, within one-zone SSC models when using causality, a huge Doppler factor of order 100 which is in conflict with those deduced from the unification models between blazars and radiogalaxies[79]; this requires the development of inhomogeneous models; 2) evidence reported by MAGIC for time lag between high- and low-energy band photons during 2 flares of Mrk 501, which may be an indication of progressive acceleration of leptons within the jet [78].

Beyond the understanding of blazars themselves, measurement of their VHE spectrum and its attenuation through pair creation due to Extragalactic Background Light (EBL) can be used to constrain the EBL density itself and, thereby, the star formation history of the universe. The most recent result is the discovery of VHE γ-rays from 3C 279 by Magic at z = 0.536. The HESS detections of hard spectra from 1ES 1101−232 (z = 0.186) and H 2356−309 (z = 0.165) implied already a low level of EBL in the optical/near-infrared wavelengths [104], very close to the lower limit given by the integrated light of resolved galaxies. The detection of 3C 279 represents a major step in redshift and should put severe limits in the sub-micron to 2μ band. It is remarkable that the possibility of constraining the EBL through γ-ray measurements was predicted more than 15 years ago following the detection by Egret of the same source, 3C 279 [111].

[4] for Self-Synchrotron Compton
[5] for External Compton
[6] There exists however a noteworthy exception in the history of the field: a TeV flare without any counterpart in X-rays was detected during observations of 1ES 1959+650 on June 4, 2002 [75].

4. Summary

The field of VHE γ-ray astrophysics has gone through a dramatic evolution since 2004, thanks to the high sensitivity of the new generation IACTs. The HESS GPS represents a major step in that it has revealed, beyond the large number of sources, diverse classes of γ-ray emitting galactic objects and acceleration sites: young shell-type SNRs, SNRs interacting with molecular clouds, middle-aged offset PWNe, very young composite PWNe and γ-ray binaries. Given the large number of still unidentified sources, other potential classes of sources could emerge, including the promising case of massive star clusters. The increasing number of blazar sources in the extragalactic domain allows now for population studies, and one non-blazar source, M 87 is under scrutiny, in particular by VERITAS. Also, while the early attempts to constrain the intergalactic radiation field suffered from the very limited number of sources and a reduced range in redshift, the growing number of objects, and especially the detection of 3C 279 obtained at a low energy threshold by MAGIC, have definitely opened the path towards the cosmological application of γ-ray astrophysics. There is no doubt that VHE γ-ray astronomy is now a genuine branch of astronomy with multiple connections to cosmology and fundamental physics.

References

[1] Weekes, T.C., et al. 1989, ApJ, 342, 379
[2] Baade, W. & Zwicky, F. ,1934, "Cosmic Rays from Super-novae", Proc. Nat. Acad. Sci. 20(5), 259
[3] Bailon, P. et al., 1993, Astrop. Phys. 1, 341
[4] Hillas, A. M., et al., 1998, ApJ503, 744
[5] Katagiri, H., et al., 2005, ApJL619, L163
[6] Muraishi, H. et al., 2000, A&A 354, L57.
[7] Aharonian, F.A., et al., 2004, Nature 432, 75.

[8] Aharonian, F.A., et al., 2005, A&A 449, 223.
[9] Aharonian, F.A., et al., 2007, A&A 464, 235.
[10] Aharonian, F. A., et al., 2005, A&A437, L7
[11] Aharonian, F.A., et al., 2007, ApJ 661, 236
[12] Hoppe, S., et al. for the HESS collab. Proc. 30th International Cosmic Ray Conference, Merida, 2007
[13] Aharonian, F. A., et al., 2001, A&A370, 112
[14] Albert, J., et al. 2007, ApJL 664, L87
[15] Albert, J., et al. 2007, ApJL 474, 937
[16] Albert, J., et al., 2006, ApJ, 643, L53
[17] Humensky, T. B., et al. 2007, 30th International Cosmic Ray Conference, Merida, Mexico
[18] Rowell, G., et al., 2007,, ArXiv e-prints 0710.2017
[19] Aharonian, F. A., et al., 2006, ApJ 636, 777 A&A accepted [arXiv:0803.06829]
[20] Aharonian, F. A., et al., 2008, arXiv:0803.0702
[21] Aharonian, F. A., et al., 2008, A&A 483, 509
[22] Tian, W. W., et al., 2007, ApJ 679, L85.
[23] Kargatslev, O., 2008, arXiv:0801.2602
[24] Aharonian, F., et al., 2002, A&A, 393, L37
[25] Oña-wilhelmi, E. et al., 30th ICRC, Merida, Mexico, 2007
[26] Horns, D., Hoffmann, A. I. D., Santangelo, A., Aharonian, F. A., Rowell, G. P., 2007, A&A, 469, L17
[27] Abdo, A. A., et al., 2007, ApJ, 664, L91
[28] Huentemeyer, P. et al., 30th ICRC, Merida, Mexico, 2007
[29] Wang, Y. et al., 30th ICRC, Merida, Mexico, 2007
[30] Djannati-ataï, A. et al., 30th ICRC, Merida, Mexico, 2007
[31] Fiasson, A. et al., 30th ICRC, Merida, Mexico, 2007
[32] Aharonian, F. A., et al., 2008, A&A477, 353
[33] Aharonian, F. A., et al., 2005, A&A432, L25
[34] Aharonian, F. A., et al., 2005, A&A435, L17
[35] Aharonian, F. A., et al., 2006, A&A448, L43
[36] Aharonian, F. A., et al., 2005, Science 307, 1938
[37] Aharonian, F. A., et al., 2006 ApJ636, 777
[38] Aharonian, F. A., et al., 2006, A&A456, 245
[39] Aharonian, F. A., et al., 2007, A&A472, 489
[40] Djannati-ataï, A. et al., 30th ICRC, Merida, Mexico, 2007
[41] Aharonian, F. A., et al., 2005, A&A442, 1
[42] Aharonian, F. A., et al., 2005, Science 309, 746
[43] Aharonian, F. A., et al., 2006, A&A460, 743
[44] Albert, J., et al., 2006, Science 312, 1771
[45] V. A. Acciari et al., 2008, ArXiv e-prints 0802.2363
[46] Albert, J., et al., 2007, ApJL665, L51
[47] Drury, L., 1983, Sp. Sci. Rev., 36, 57
[48] Lagage P.O. & Cesarsky, C., 1983, J. Astron. Astrophys., 125, 249
[49] Katz, B., Waxman, E., 2008, J. Cosm. Astrop. Phys. 1, 18
[50] Bell A.R. & Lucek, S.G., 2001, Mon. Not. R. Astron. Soc., 321, 433
[51] Cassam-Chenai, G., Decourchelle, A., Ballet, J., et al. 2004, A&A, 427, 199
[52] Voelk, H. J., Berezhko, E. G., & Ksenofontov, L. T. 2005, A&A, 433, 229
[53] Porter, T. A., Moskalenko, I. V., & Strong, A. W. 2006, ApJ, 648, L29
[54] Ginzburg V.L. & Syrovatskii, S.I. 1964, The Origin of Cosmic Rays (New York: Macmillan)
[55] Blandford R.D., Eichler D. 1987, Phys. Rep. 154, 1
[56] Koyama, K. et al., 1995, Nature 378, 255.
[57] Kappes, A. et al., 2007, ApJ 656, 870.
[58] Becker, J. K., 2008, Phys. Rep. 458, 173.
[59] Yamazaki, R. et al., 2006, MNRAS 371(4), 1975
[60] Gould, R.J. 1965, Phys. Rev. Lett., 15, 577.
[61] de Jager, O. C., & Harding, A. K., ApJ 396, 161
[62] F. Aharonian et al. 2005, A&A 442, L25
[63] Aharonian, F. A., et al. 2006, A&A 460, 365
[64] Chevalier, R. A., Mem. Soc. Astron. Ital. 69, 977
[65] Lemière, A. 2006, Ph.D. thesis, Univ. of Paris 7 and College de France, Paris
[66] de Jager, O. C. & Djannati-ataï, A., 2008, Springer Lecture Notes on Neutron Stars and Pulsars: 40 years after their discovery, eds. W. Becker
[67] Dubus, G., 2006, A&A, 456, 801
[68] Kosack, K. et al., 2004, ApJ 608, L97.
[69] Tsuchiya, K. et al., 2004, ApJ 606, L115.
[70] Aharonian, F.A. et al., 2004, A&A 425, L13.
[71] Hinton, J. et al., 30th ICRC, Merida, Mexico, 2007
[72] Van Eldik, C. et al., 30th ICRC, Merida, Mexico, 2007
[73] Aharonian, F. A., et al., 2007, Nature 439, 695
[74] Aharonian, F., et al., 2006, PhRvL, 97, 221102
[75] Gutierrez, K., et al., 2006, ApJ 644, 742
[76] Colin, P., et al. 2007, 30th International Cosmic Ray Conference, Merida, Mexico
[77] Aharonian, F. A., et al. 2007, ApJL 664, L71
[78] Albert, J., et al., 2007a, ApJ, 669, 862
[79] Sauge, L., Henri, G., 2006, ApJ 640, 185
[80] Aharonian, F. A., et al. 2003, A&A 403, L1
[81] Aharonian, F. A., et al. 2006, Science 314, 1424
[82] Punch, M., et al. 1992, Nature 358, 477
[83] Zweerink, J. A., et al. 1997, ApJL 490, L141
[84] Quinn, J., et al. 1996, ApJL 456, L83
[85] Aharonian, F. A., et al. 1997, A&A 327, L5
[86] Catanese, M., et al. 1998, ApJ 501, 616
[87] Schroedter, M., et al. 2005, ApJ 634, 947
[88] Albert, J., et al. 2006, ApJL 648, L105
[89] Nishiyama, T., et al. 1999, 26th International Cosmic Ray Conference, Salt Lake City, USA 3, 370
[90] Weekes, T., et al. 2002, IAUC 7903
[91] Aharonian, F. A., et al. 2003, A&A 406, L9
[92] Albert, J., et al 2007, ApJL 666, L17
[93] Superina,G., et al. 2007, 30th International Cosmic Ray Conference, Merida, Mexico
[94] Aharonian, F. A., et al. 2005, A&A 436, L17
[95] Aharonian, F. A., et al., 2008, A&A 481, L103
[96] Chadwick, P. M., et al. 1999, ApJ 513, 161
[97] Swordy, S. et al., 2008, ATEL #1422
[98] Aharonian, F. A., et al. 2005, A&A 430, 865
[99] Horan, D., et al. 2002, ApJ 571, 753
[100] Aharonian, F. A., et al. 2002, A&A 384, L23
[101] Djannati-ataï, A., et al., 2002, A&A 391, 25
[102] Swordy, S. et al., 2008, ATEL #1415
[103] Aharonian, F. A., et al. 2007, A&A 475, L9
[104] Aharonian, F. A., et al. 2006, Nature 440, 1018
[105] Albert, J., et al. 2006, ApJL 642, L119
[106] Aharonian, F. A., et al. 2007, A&A 473, L25
[107] Albert, J., et al. 2007, ApJL 667, L21
[108] Aharonian, F. A., et al. 2006, A&A 448, L19
[109] Teshima, M., et al. 2007, ArXiv e-prints 0709.1475,
[110] Teshima, M. et al., 2008, ATEL #1500
[111] Stecker, F. W., de Jager, O. C. & Salomon, M. H., 1992, ApJ 390, L49