High-energy gamma ray astronomy

Werner Hofmann
Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany
E-mail: Werner.Hofmann@mpi-hd.mpg.de

Abstract. High-energy gamma-ray astronomy is a field under very rapid development, addressing issues of astrophysics, of astroparticle physics and of fundamental physics. This contribution summarizes recent results, concentrating mainly on data from ground-based instruments both on Galactic and extragalactic sources.

I will first briefly address the instruments of gamma-ray astronomy, then present the newly emerging VHE gamma-ray sky, followed by a discussion of galactic and extragalactic gamma-ray sources.

1. Instruments
Gamma rays up to some 10 GeV are best observed from space, whereas at very high energies (VHE, > 100 GeV) only ground-based instruments with their larger detection areas provide sufficient detection rates. For space-based gamma-ray detection, 271 sources are known from the 3rd EGRET catalog [1], about 2/3 of which are unidentified. Recent revisions of background models tend to reduce the number of EGRET sources somewhat [2]. New results will soon be provided by the recently launched AGILE instrument, and in 2008 by GLAST, which is expected to detect around 10000 gamma-ray sources. At the time of this meeting, AGILE is still in the commissioning phase, but has already detected first sources, such as the blazar 3C 454.3 [3]. The bulk of the new results in recent years comes from the H.E.S.S. and MAGIC Cherenkov telescopes, which detect the Cherenkov light emitted by particles in gamma-ray induced air-showers. These instruments provide detection areas of about $10^5 \text{m}^2$, angular resolution for single gamma-rays of $0.1^\circ$ and better, and flux sensitivities of 1% of the Crab flux and below. Recently, the VERITAS system of four telescopes went into full operation at the Whipple base camp, also reaching a sensitivity of 1% of the Crab nebula in 50 h of observations [4]. Also, the Japanese/Australian CANGAROO III telescope system started to report results [5], clearing up discrepancies between H.E.S.S. and earlier CANGAROO I/II results and essentially in all cases confirming H.E.S.S. data. There is also significant progress in the direct detection of shower particles on the ground: using an improved analysis technique, the MILAGRO collaboration published sky maps (Fig. 1) which show a number of significant detections at gamma-ray energies in the 10 TeV range [6]: in 6 years of data, the Crab Nebula is seen with 15 σ significance. The ARGO-YBJ experiment, a resistive plate chamber carpet of 6000 m$^2$, started first data taking and reports detection of the Crab Nebula at the 5 σ level in 290 h, and of Mrk 421 during a flare [7]. Operating since a couple of years, the Tibet AS-γ instrument also detects the Crab Nebula, Mrk 421 and Mrk 501; a planned upgrade using 10000 m$^2$ of water-Cherenkov muon detectors is expected to boost sensitivity by a factor 10 above 10 TeV [8].
2. The emerging VHE gamma-ray sky
Over the last years, the number of known VHE gamma-ray sources increased rapidly; the last count gives more than 70 sources (Fig. 2) [9], among them 6 or more supernova remnants, about 20 pulsar wind nebulae and 20 unidentified sources, four binary systems, diffuse emission from clouds and 19 extragalactic sources. The H.E.S.S. Galactic Plane Survey (Fig. 3) shows the Galaxy lined with gamma ray sources, most of them representing extended objects with sizes of some 10 pc.

Figure 1. Gamma-ray significance map obtained with MILAGRO, for part of the Galactic plane, showing the three sources MGRO J2031+41, MGRO J2019+37 and MGRO J1908+06 [6].

Figure 2. Location and types of VHE gamma-ray sources known by mid-2007, from [9].

The performance of current instruments is illustrated by images like Fig. 4(a), showing resolved emission from a supernova shock wave [10], by the fact that gamma-ray energy spectra
Figure 3. The H.E.S.S. Galactic Plane Survey, imaging the central region of the Milky Way at TeV energies in the region between 60° and −80° Galactic longitude. Color scale indicates the significance of a gamma-ray excess at a certain location, integrated over a region of radius 0.22°.

from this source are measured over more than 2 orders of magnitude in energy and about 6 orders of magnitude in flux [10], or by the observation of periodic emission from the binary system LS 5039 (Fig. 4(b))[11], allowing the determination of the gamma ray period with 3-digit precision to 3.908 ± 0.002 days, well compatible with the orbital period measured in the optical of 3.90603 ± 0.00017 days. Another striking achievement relates to the precision with which source positions can be determined. Using improved techniques to calibrate telescope pointing, H.E.S.S. located the Galactic Center gamma-ray source with a precision of 12”, consistent with the black hole Sgr A* but excluding the nearby remnant Sgr A East (Fig 4(c)) [12].

3. Supernova remnants
At least six supernova remnants (SNR) are seen in TeV gamma rays: IC 443 [13, 14], RX J0852-4622 [15, 16], RCW 86 [17], RX J1713.7-3946 [10, 18], W28 [19] and Cas A [20, 24], three of those with resolved shell morphology (RX J0852-4622, RCW 86, RX J1713.7-3946). Striking in RX J1713.7-3946 (Fig. 4(a)) but also in RX J0852-4622 [15] is a very close correlation between gamma-ray emission and X-ray emission. This correlation emerges naturally in models where both types of radiation are produced by a single population of electrons, via synchrotron radiation and Inverse Compton scattering. In case of RX J1713.7-3946, a field of about 10 µG is required to match the relative flux levels [10]. The filaments seen in X-ray images of SNR are often interpreted as evidence for rapid cooling of electrons as they move away from the shock.
fronts, which requires much higher fields in the $100 \mu G$ range (e.g. [21]). With such fields, the number of electrons required to sustain the X-ray flux is reduced by a factor $O(100)$, and correspondingly is the Inverse Compton rate. Gamma-ray production by collisions of accelerated protons with gas is then invoked to explain the observed gamma-ray flux, providing a good fit of the energy spectrum [22]. In this model, the correlation between X-ray emission and gamma rays is not quite as straightforward to explain. It has been suggested [23] that turbulent B-fields are dynamically amplified by streaming cosmic rays, resulting in $B^2 \sim \rho v^3 s$, linking magnetic fields (responsible for X-ray production) and gas density (responsible for gamma rays via $\pi^0$ production). Two newly discovered supernova remnants may help to resolve the question if nucleons are accelerated in significant numbers: both in W28 and in IC 443 (Fig. 5) the gamma-ray emission seems to be concentrated in a region where the supernova shock interacts with dense molecular clouds. Since the latter serve as a target material for protons, this observation is a strong argument for the presence of protons accelerated by the remnant.

4. Pulsar wind nebulae
The first VHE gamma-ray source, the Crab Nebula discovered in 1989, is a pulsar wind nebula (PWN), where a relativistic flow of electrons and positrons is launched near the pulsar and feeds a wind termination shock, from which a power-law distribution of particles convects outward. Recent data from Magic [31] show for the first time the turnover towards low energy of the Crab gamma-ray spectrum, as expected for Inverse Compton radiation. A large number of PWN have recently been discovered; they differ from the Crab Nebula in that they are typically extended sources with a scale of some 10 pc, and surprisingly the gamma-ray PWN is often significantly displaced from its pulsar, with the Vela X PWN [25] or the PWN around PSR J1826+1334 [26] as prominent examples (Fig. 7(a)-(d)). For the latter PWN the morphology depends on gamma-ray energy, with the source shrinking towards the pulsar with increasing energy (Fig. 7(e)) as expected for electrons flowing away from the pulsar and suffering radiative energy losses. This is a clear indication that the gamma-ray source is indeed correlated with the pulsar and not a chance coincidence. A search for gamma-ray emission among 435 pulsars in the range of the H.E.S.S. Galactic Plane Survey shows that pulsars have a high probability to have detectable gamma-ray PWN provided that their spin-down energy flux is high enough,
Figure 5. VHE gamma-ray emission associated with the remnants IC 443 [13] and W28 [19]. In both cases, emission is concentrated in regions where the supernova shock wave is believed to interact with dense gas clouds. The gamma-ray sources south of the W28 shell also coincide with gas clouds, possibly illuminated by high-energy nuclei accelerated in the W28 remnant.

\[ \dot{E}/d^2 > 10^{35} \text{ergs s}^{-1}\text{ kpc}^{-2} \] [29]. This implies that typically about 1% of the spin-down energy loss is converted into gamma rays in the VHE energy range. X-ray observations of some of the previously unidentified gamma-ray sources, such as HESS J1640-465, have revealed PWN at their centers (Fig. 8); in these cases, the pulsar itself obviously escaped detection in pulsed radio emission.

Figure 6. Spectral energy distribution \( E^2dN/dE \) measured for the Crab nebula, showing the top end of the synchrotron spectrum and the new measurement of the Inverse Compton gamma-ray emission by MAGIC [31].
Figure 7. Example of pulsar wind nebulae: (a) the PWN MSH 15-52 associated with the pulsar PSR B1509-58, (b) PWN in the Koobaburra associated with PSR J1420-6047, (c) the PWN HESS J1825-137 associated with the pulsar PSR J1826+1334, (d) the Vela-X PWN emerging from the Vela pulsar [27]. Triangles denote pulsar locations. (e) Distance from the pulsar PSR J1826+1334 at which the surface brightness of the PWN drops to 50% of the flux at the pulsar position, as a function of gamma-ray energy [28].

5. Unidentified sources
A number of TeV gamma-ray sources remain unidentified, not because - like in case of many of the EGRET unidentified sources - there are too many counterpart candidates in the error circle, but rather because there are no plausible counterparts known in radio or X-rays; examples are shown in Fig. 9. Lack of radio and X-ray emission could be caused by absence of high-energy electrons, which would lead one to identify these objects with pure proton accelerators, possibly old supernova remnants, where electrons are suppressed since radiative losses exceed acceleration gains [33]. For at least some of the sources, a consistent multiwavelength description can also be obtained with an electron population with a cutoff in the TeV range, in which case in the KN regime high-energy gamma-rays can still be produced, but the synchrotron radiation peaks below the X-ray range and escapes detection. Also, the recently reported extended MILAGRO sources [6] are unidentified; two of them, MGRO J2031+41 and MGRO J2019+37 (Fig. 10) are in the Cygnus region and could either be associated with enhanced emission from clouds, or represent a superposition of unresolved sources in the Cygnus arm. The latter scenario is supported by the positional coincidence between the source MGRO J2031+41, extended on the 3′ scale, and the first unidentified TeV source, TeV J2032+4130, discovered by HEGRA [34] and confirmed by Whipple [35] and MAGIC [36], also extended but only on the 6′ scale. Extrapolated to the 20 TeV MILAGRO energy range, TeV J2032+4130 would contribute about 1/3 of the flux measured for MGRO J2031+41. The Tibet AS-γ experiment also reports hotspots in the Cygnus region [37], which are not highly significant after accounting for trials, but two of the
hotspots line up with the MILAGRO sources, the third with a less significant MILAGRO source candidate (Fig. 10).

Figure 8. XMM-Newton observations of the VHE gamma-ray source HESS J1640-465 for events above 2 keV (color scale) [30]. The white contours denote the 843 MHz MOST radio data showing the inner edge of the radio shell of G338.3-0.0. The yellow circle indicates the rms extension of HESS J1640-465.

Figure 9. Four examples of VHE gamma-ray sources without known counterparts [32].

6. Binary systems
Four binary systems were so far identified as TeV gamma-ray sources: PSR B1259-63 [38], LS 5039 [11], LS I +61 303 [39, 40] and, most recently, Cygnus X-1 [41]. In LS 5039 and LS I +61 303, the nature of the compact object is still open, it could either be a pulsar, with the pulsar wind driving the gamma-ray emission, or a black hole, in which case the emission would be accretion-powered. PSR B1259-63 is a pulsar in a highly elliptical 3.5 y orbit around a Be-type star, Cygnus X-1 a black hole in a nearly circular 5.6 d orbit. Periodic modulation of gamma-rays from LS 5039 has been established by H.E.S.S., as discussed earlier. New results on LS I +61 303 show periodicity with the orbital period, but with indications of variability from orbit to orbit [39] (Fig. 11). Emission is peaked at phase 0.6-0.7. MAGIC recently reported the detection of a flare from Cygnus X-1 [41] in one half night of 26 nights of observations, at 4σ significance after trials, coincident with an X-ray flare. The importance of binary systems is that along elliptical
Figure 10. MILAGRO measurements of VHE gamma-ray emission from the Cygnus region, showing significance contours. The two sources MGRO J2031+41 and MGRO J2019+37 represent significant detections even after accounting for number of trials in the search for sources [6]. Black dots: “hotspots” in the Tibet AS-γ array data, with corresponding significance [37].

Figure 11. Orbital variation of VHE gamma-ray emission from LS I +61 303, as measured by MAGIC [39] and, over different orbits, by VERITAS [40]. Right: orbit geometry, indicating in blue the region of strong gamma-ray emission.
7. Extragalactic sources of VHE gamma rays

Results discussed in the following concern (i) observations of new sources and new source types, and of very rapid variability of some sources and (ii) results related to the propagation of gamma rays in extragalactic space, where they are subject to absorption by extragalactic background light (EBL) and possibly to a time dispersion due to effects of quantum gravity. A more detailed discussion of acceleration and radiation processes in the sources is left to the review by Dermer [42].

Table 1 lists known extragalactic VHE emitters; the number has grown to 19. Most of them are of the BL Lac type, with a jet pointing at the observer and dominating the emission. Remarkable exceptions are M87, a FR I radio galaxy which surprisingly shows day-scale variability [43], and the recently discovered, by far most distant source, 3C 279, a FSRQ at redshift z=0.536 [44]. In one of 10 nights of observations MAGIC detected a signal from 3C 279, both in the low-energy band from 80-220 GeV and above 220 GeV. The high-energy signal is surprising, since – as discussed later – EBL absorption should dramatically steepen the energy spectrum for such distant objects. Another recent observation which challenges interpretation are the minute-scale variations observed for PKS 2155-304 during a giant outburst in July 2006 [46], with flux levels up to 15 times the Crab flux, and for Mrk 501 in 2005 [47] (Fig. 12). For PKS 2155-305, doubling times around 100 s need to be compared to the size of the supermassive black hole powering the AGN, with r/c of 1...2 \cdot 10^4 s, calling for very large Lorentz factors around 100 for the jet motion. It should be pointed out that two of the recent discoveries of sources, Mrk 180 [48] and 1ES 1101-496 [49], were triggered by variation in the optical emission of the objects.

Table 1. Extragalactic VHE gamma-ray sources, with their type, redshift, significance of detection and discovery experiment.

| Name   | Type   | Redshift | Signif. | Discovered |
|--------|--------|----------|---------|------------|
| M 87   | FR I   | 0.004    | ***     | HEGRA      |
| Mrk 421| BL Lac | 0.031    | ***     | Whipple    |
| Mrk 501| BL Lac | 0.034    | ***     | Whipple    |
| 1ES 2344+514 | BL Lac | 0.044 | *** | Whipple |
| Mrk 180| BL Lac | 0.046    | 5.5     | MAGIC      |
| 1ES 1059+560 | BL Lac | 0.047 | *** | TA         |
| BL Lac | BL Lac | 0.069    | 5.1     | MAGIC      |
| PKS 0548-322 | BL Lac | 0.069 | 5.8 | HESS       |
| PKS 2005-489 | BL Lac | 0.071 | *** | HESS       |
| PKS 2155-304 | BL Lac | 0.116 | *** | Durham     |
| H 1426+428 | BL Lac | 0.129 | 7.5 / 5 | Whipple    |
| 1ES 0229+200 | BL Lac | 0.14  | 6.6    | HESS       |
| H 2356-309 | BL Lac | 0.165 | *** | HESS       |
| 1ES 1218+304 | BL Lac | 0.182 | 9 / 6.4 | MAGIC      |
| 1ES 1101-232 | BL Lac | 0.186 | *** | HESS       |
| 1ES 0347-121 | BL Lac | 0.188 | *** | HESS       |
| 1ES 1011+496 | BL Lac | 0.212 | *** | MAGIC      |
| PG 1553+113 | BL Lac | 0.21   | *** | HESS/MAGIC |
| 3C 279 | FSRQ   | 0.536    | ~8 (trial?) | MAGIC |

The fast rise times of the bursts of PKS 2155-304 and Mrk 501 allow use for studies of quantum gravity, which predicts energy-dependent propagation speeds, with corrections of order \((E/M_QG)^q\) where \(M_QG\) is a characteristic scale of quantum gravity, usually assumed to be related to the Planck scale \(M_P\). Some models allow a linear dependence on energy, \(q = 1\), whereas in others the linear term is forbidden by symmetries and only higher orders contribute. In the Mrk 501 flare of July 9, 2005, the MAGIC collaboration reports an energy dependent shift of the peaking time (Fig. 13), with a 4 min lag in arrival times between the lowest and the highest photon energies [47]. If interpreted as an effect of quantum gravity, the shift would correspond...
to $M_{QG} = 0.03M_P$ for $q = 1$ [50]. Of course, acceleration and radiation processes in the source could cause energy dependent peaking times, and the only way to demonstrate that effects are due to quantum gravity is to observe a variation of the lag with distance of the source. Assuming that shifts intrinsic to the source and the QG effect do not conspire and cancel, the result can more conservatively be phrased as a lower limit of $M_{QG} > 0.02M_P$. Indeed, the analysis of HESS data from the outburst of PKS 2155-304 does not show any energy-dependent peaking, resulting in a lower limit of $M_{QG} = 0.04M_P$. It should be noted that significantly more stringent limits are obtained from other observations, such as the absence of birefringence in optical AGN spectra as predicted in certain classes of QG models, or on the basis of photon interactions or decays which are influenced by a modified dispersion [51, 52].

![Figure 12](image1.png)

**Figure 12.** Two AGN flares with minute-scale variability: Gamma-ray flux measured from PKS 2155-305 during the flare on July 28, 2006 [46], and for Mrk 501 on June 30, 2005 [47], shown on approximately the same flux scale (from [9]).

![Figure 13](image2.png)

**Figure 13.** Flare of Mrk 501 on July 9, 2005, as seen in two gamma-ray energy bands [47].

Interactions with EBL quanta cause a modification and in general a steepening of gamma-ray spectra. Such features - or the lack thereof - can be used to measure or put limits on the EBL density, which is of significant cosmological interest and which is - in particular in the infrared range - difficult to measure directly due to overwhelming foreground light. Since
the pair production cross section peaks near the threshold $2E_\gamma E_{EBL} = m_e c^2$, there is an approximate relation between the gamma-ray energy and the wavelength of the EBL photons probed. Particularly constraining are distant gamma-ray sources with hard observed spectra, such as 1ES 0229+200 [53]. Assuming that intrinsic blazar photon indices are not smaller than 1.5 - corresponding to inverse Compton scattering off an $E^{-2}$ electron population - the EBL density must be relatively low in order not to steepen spectra beyond the observed index. Several new analyses and results emerged recently. Raue and Mazin give an analysis which does not assume a specific spectral shape of the EBL [54], resulting in the limits shown in Fig. 14 for the IR EBL, which fall between previous upper limits and lower limits based on galaxy counts. Slightly more stringent limits can be obtained with loose assumptions concerning the shape (e.g. [53]). It has been pointed out that in certain models intrinsic gamma ray spectra with photon indices in the range below 1.5 are possible [55], which would result in less stringent limits; however, it would then be surprising that such hard spectra are not observed for any of the nearby AGN.

**Figure 14.** Limits on extragalactic background light (EBL) density in the infrared, derived from gamma-ray observations of AGN, with realistic and extreme assumptions concerning intrinsic AGN spectra (thick full and thick dotted line, resp.). Thin lines show different model predictions for EBL density [54]. Points show direct measurements and upper and lower limits, see [54] for details.

### 8. Conclusion and outlook

Very high energy gamma-ray astronomy has taken big steps forward in recent years, now providing sky maps, resolved sources, detailed light curves and spectra. Space does not allow to cover limits on gamma-ray emission from other object classes such as GRBs, starburst galaxies, galaxy clusters, or dark matter annihilation in dwarf galaxies. For some of these classes, emission is predicted at levels not too far from current sensitivity. Correspondingly, both HESS and MAGIC are upgrading their instruments, HESS by adding a large 600 m$^2$ dish, MAGIC by adding a second dish of identical size as the first. The upgrades increase sensitivity by factors 2-3 and help to lower energy thresholds. In the more distant future, arrays of Cherenkov telescopes such as the proposed CTA and AGIS could boost sensitivity at TeV energies by a factor of 10, reaching mCrab sensitivity, and HAWC, based on MILAGRO technology, could provide full-sky coverage at sensitivity better than 0.1 Crab.
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