Highlights of Gamma-ray astronomy with imaging air Cherenkov telescopes

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Abstract. The observation of gamma-ray sources at energies between tens of GeV and tens of TeV has been driven by ground-based Cherenkov telescopes. The observational techniques and methods employed have been continuously refined in the past years and have lead to the discovery of a steadily growing number of sources and source types. Similar to other branches of observational Astrophysics in the past, the field undergoes currently a transition from a discovery-driven to an exploration-driven stage. In this context, recent developments are summarized and highlights are presented.

1. Introduction
The pioneering work of Jelley and Chudakov leading to the experimental detection of Cherenkov-light from extended air-showers (for a review of the history see e.g. [1]) paved the way for the break-through discovery of gamma-ray emission from the Crab nebula roughly four decades later [2] (for a historical perspective see [3]). The necessary improvement in sensitivity was achieved through the use of the air shower imaging technique [4]. The introduction of stereoscopic observations (HEGRA, GRANITE) and fast read-out electronics (CAT, HEGRA) combined with fine pixels (CAT) have marked the next important steps towards the current generation of imaging Cherenkov telescope arrays like the H.E.S.S., MAGIC, and VERITAS arrays (see Fig. 1 for pictures of the telescopes). Along with the dramatic improvement in sensitivity, the number of sources has increased well beyond one hundred\(^1\). Most notably is the broad range of source types which have been established. For a recent review of the field see, e.g., [5].

In the following, I will highlight the results which are of immediate relevance to the origin of Galactic and ultra-high energy cosmic rays. This includes the identification of shell-type supernova remnants as cosmic-ray sources as well as the release and propagation of energetic particles in the environment of the accelerators. Finally, the link of gamma-ray observations with the origin of ultra-high energy cosmic-rays is discussed and recent observations presented.

2. Gamma-rays and the origin of Galactic cosmic-rays
The currently favored paradigm of particle acceleration in astrophysical shocks favors super-nova blast waves as the origin of cosmic-rays. The general argument relies on the one hand on the power-law shape of the particle distribution resulting generically in diffusive shock acceleration

\(^1\) The current list of objects is available conveniently through the TeVCAT site at http://tevcat.uchicago.edu
Figure 1. Top left: H.E.S.S. telescopes in Namibia after the installation of the fifth large (600 m$^2$ mirror area) telescope (as of July 2012, picture by C. Medina, H.E.S.S. coll.), top right: the two MAGIC telescopes on the Canary island of La Palma (as of March 2009, picture MAGIC coll.), bottom: the four VERITAS telescopes in Arizona (picture VERITAS coll.).

and on the other hand on the available injection power which is sufficient to replenish the escape losses of the Galactic cosmic-rays which are close to $10^{41}$ erg/s. A modest efficiency of $\theta = E_{\text{acc}}/E_{\text{kin}} \simeq 0.1$ combined with a rate of SN explosion of roughly three per century is sufficient to replenish the estimated losses.

This basic argument in turn provides the underpinning for the predicted gamma-ray visibility of SNRs [6]. The initial difficulties in detecting gamma-ray emission from SNRs with the previous generation of instruments (e.g. HEGRA, CAT, Whipple) have lead to some concern and even belief that gamma-ray astronomy is a failure [8].

The paradigm of cosmic-ray acceleration in SNR has been strengthened by the discovery of gamma-ray emission from a number of shell-type SNR. Moreover, the large collection area $\mathcal{O}(10^3$ m$^2$), relative energy resolution of $\Delta E/E \approx 0.1$, and angular resolution for individual photons of $\sigma_{68 \%} \approx 0.1^\circ$ has demonstrated that these instruments are not only useful for discovery but also for detailed spectro-imaging of extended sources. The detected supernova remnants fall roughly in two categories: young shell-type supernova remnants where the bulk of gamma-ray emission is seen to originate from the rim of the SNR, mostly coinciding with non-thermal X-ray emission and evolved/mixed morphology supernova remnants which often emit gamma-rays in regions of large gas density (e.g. molecular clouds) in the vicinity of these objects (see Table 1 for a list of relevant objects including informations on the distance, gamma-ray luminosity, age, photon index from gamma-ray spectroscopy as well as references/comments.)

$^2$ The only shell-type supernova remnant detected at that time was Cassiopeia-A [7]
2.1. Gamma-ray observations of shell-type supernova remnants

A total of seven shell-type supernova remnants (ST-SNR) have been detected to be gamma-ray emitters. These objects are listed in the first part of Table 1. Two of the objects (Cassiopeia A and Tycho’s SNR) have not been spatially resolved, while for all other objects, the shell-like emission has been resolved both radially as well as azimuthally. A particular striking morphology is resolved in the case of SN 1006 where the emission is bi-polar, exactly matching the observed bi-polar morphology observed in non-thermal X-ray emission. This is obviously different from the azimuthal modulation observed in the cases of RX J0852.0-4622 and RX J1713.7-3946. Even though these two objects are at first glance similar, the radial dependence of the intensity is quite different: While for RXJ 0852.0-4622, the relative width of the emitting shell is 20 %, for RX J1713-3946, the relative width is significantly broader (close to 50 %). The morphological differences of the VHE emission are very likely related to the evolutionary state of the remnant as well as to its progenitor (supernova) and to the environment into which the blast wave expands.

A crucial result of the observed VHE emission is an estimate of the total cosmic-ray energy stored in the remnant:

\[ w_{\text{cr}} \approx L_{\text{VHE}} \cdot \tau \gamma \]

with \( \tau \gamma = 4.4 \times 10^{15} / n \) the energy-loss time for p-gas collisions and subsequent gamma-ray production in the gas with number density of \( n \) in units of cm\(^{-3}\). Taking a typical value of \( n \approx 1 \), the energy stored in cosmic-rays is below the canonical \( 10^{50} \) ergs which would demonstrate that the efficiency of the conversion of kinetic energy of the ejecta into cosmic-rays is close to 10 %. However, the ambient medium density has to be well below unity in order to explain the absence of shock-heated thermal cosmic-rays which could in principle recover the required efficiency. The non-detection of VHE gamma-rays from SN 1987A [9, 10] has started to constrain state-of-the-art modelling of shock acceleration [11] (see also Fig. 2). The still small number of shell-type SNRs which have been discovered to emit VHE gamma-rays limits us from drawing general conclusion and, to some extent paradoxically, demonstrates at the same time the considerable diversity in the phenomenology of particle acceleration in these objects.

A search for gamma-ray emission from a larger population of known SNR which have been observed during the extended Galactic plane survey [12] has demonstrated that the current generation of telescopes is sufficiently sensitive to provide meaningful upper limits which in some cases indicate that SNR are sometimes too dark (see Fig. 2).

2.2. Gamma-ray emission from evolved SNR

Besides young shell-type SNR, evolved as well as mixed-morphology SNR systems are strong sources of VHE gamma-rays. For most of these objects, the VHE emission coincides with regions of enhanced density of gas. This opens the interesting possibility to investigate the propagation of cosmic-rays in the neighboring environment (see, e.g. [37]). A particular interesting object is the mixed-morphology object W28 where more detailed modelling of the transport of cosmic-rays towards molecular clouds at distances between 12 and 20 pc from the shock indicate that the diffusion coefficient is at the level of a few p.c. of the Galactic value [38]. Within this context, G106.3+2.7 is an extreme case. In this evolved system, shock acceleration is not taking place anymore indicating that cosmic-rays are confined efficiently in the environment of this system.

2.3. Starburst galaxies

Starburst galaxies are particular interesting to explore the connection of supernova-driven shocks and the acceleration of cosmic-rays. Within a starburst galaxy a compact region undergoes an enhanced star-formation which was very likely triggered by an external event in the recent past (e.g. a merging event, tidal disruption, or instabilities). The star formation rate in this volume of enhanced gas density (and very likely turbulent motion) is of similar strength as in the remaining galaxy. The two closest starburst galaxies are NGC 253 at a distance of 2.6–3.9 Mpc and M82 at a distance of 3.9 Mpc (see [39, 40] for a discussion on the distance estimates).
Figure 2. The spectral energy density as expected for SN 1987A in 2010 and 2030 [11] in comparison with a recently published upper limit derived from observations with the H.E.S.S. system of air Cherenkov telescopes [9, 10] (left panel). On the right is the result of searching for VHE gamma-ray emission from Galactic SNRs. For each non-observed SNR, the corresponding constraint on the conversion of kinetic bulk energy into cosmic-rays is accumulated into a histogram. This histogram demonstrates that with the available sensitivity efficiencies below unity can be probed and in some cases, the resulting efficiency is even below 0.1 [12]

Table 1. Summary of observations and results of SNR observations (in order of discovery, CCO: compact central object, PWN: pulsar-wind nebula).

| Name             | distance | $L_{\gamma}$ (1-10 TeV) | age  | $\Gamma$ | matching X-ray VHE morph. | Comments/Ref. |
|------------------|----------|-------------------------|------|---------|---------------------------|---------------|
| Cas A            | 3.4      | 3.5                     | 0.33 | 2.6(4)  | unres.                    |               |
| RX J1713.7-3946  | 1        | 5.7                     | 1.6  | 2.04(4) | y                         | [15, 16, 17], CCO |
| RX J0852.0-4622  | 0.33     | 0.6                     | 0.66 | 2.24(4) | y                         | [18, 19], CCO |
| RCW 86           | 2.8      | 5.5                     | 1.8  | 2.5(1)  | n                         |               |
| SN 1006          | 2.2      | 0.8                     | 1    | 2.3(1)  | y                         |               |
| HESS J1731-347   | 3.2      | 16.7                    | 27   | 2.3(1)  | n                         | [22], [23] CCO |
| Tycho’s SNR      | 3.8      | 1.2                     | 0.4  | 1.9(5)  | unres.                    |               |
| Kepler’s SNR     | 4.8      | < 2.4                   | 0.4  |         | -                         | [25]          |
| SN 1987A         | 48       | < 110                   | 0.03 |         | -                         | [9, 10]       |
| G1.9+0.3         | 8.5      | < 3                     | 0.1  |         | -                         | [26]          |
| G330.2+1.0       | 5.0      | < 6                     | 1.0  |         | -                         | [26] CCO      |
| SNR with cloud interactions |
| IC443            | 1.5      | 0.3                     | 3-30 | 3.0(3)  | n                         | [27], [28]    |
| W28              | 1.9      | 0.5                     | 33   | 2.7(3)  | n                         | [29]          |
| G359.1-0.5       | 7.6      | 36                      | >10  | 2.7(2)  | n                         | [30], PWN?    |
| CTB37A           | 7.9      | 17                      | 17   | 2.3(1)  | n                         | [31], PWN?    |
| G106.3+2.7       | 12       | 158                     | 3000 | 2.3(3)  | n                         | [32]          |
| G318.2+0.1       | 3.5      | 1                       | 8    |         | -                         | [33]          |
| W49B             | 8        | 24                      | 1-4  | 3.1(4)  | n                         | [34]          |
| G22.7-0.2        | 4.2      | 1                       | -    | -       | n                         | [35]          |
| W51              | 5.5      | 7.2                     | 30   | 2.6(2)  | n                         | [36], PWN?    |
The large star formation rate density in the starburst region leads to a similarly enhanced rate of supernova explosions which in turn would increase the cosmic-ray energy density in this region as well as in the host galaxy. The details of cosmic-ray escape from the starburst region is not very well known such that the resulting gamma-ray emissivity depends on how calorimetric the entire system behaves. In the extreme case of a fully calorimetric system, the cooling time $t_{pp}$ due to inelastic scattering of energetic cosmic-rays with the gas of the starburst region/host galaxy is shorter than the escape time $t_{esc}$, which depends on the dominant form of cosmic-ray transport in the medium.

Starburst galaxies have been predicted already a few decades ago as potential gamma-ray sources and the diagnostics of parameters including the cosmic-ray energy density have been studied (see e.g. [41]). Despite early searches for gamma-ray emission from starburst galaxies, no conclusive signal has been found until the recent generation of telescopes have spent tens of hours of observation time on the most promising starburst galaxies (M82 in the northern hemisphere with VERITAS; NGC 253 in the southern hemisphere with HESS and CANGAROO).

The unambiguous discoveries of gamma-ray emission from both objects were reported by the HESS and VERITAS collaborations [39, 42] in the same year$^3$. A larger data-set on NGC 253 in combination with the Fermi-LAT discovery of lower-energy gamma-ray emission [44] allowed for more detailed interpretation [40]. In both cases, the observations confirm the original expectation that an increased star-formation rate leads to an increased cosmic-ray energy density. In the starburst region, the density is estimated to be a few hundred times larger than the Galactic value.

Finally, the unbroken power-law spectral shape observed with Fermi-LAT and ground-based instruments rules out that within the energy range a transition between advection and diffusion takes place. This in turn, can be used to provide an upper limit on the diffusion coefficient which again is roughly a factor of hundred smaller than the average value in the Galaxy for energies of approx 100 TeV.

### 3. Gamma-rays from extra-galactic sources

Besides starburst galaxies, AGN-type objects are the only extra-galactic VHE-emitters. Searches for VHE Gamma-ray emission from GRBs (e.g. [45]) and galaxy clusters have not been successful so far (e.g. Perseus cluster [46]).

The most abundant type of object are BL Lac type objects (total of 42), followed by flat-spectrum radio quasars (FSRQ: 3), and FR I radio galaxies (3). The BL Lac type objects are believed to be FR-I type radio galaxies with the jet angle aligned to the line of sight. Conversely, FSRQs are considered to be the beamed counter-part of FR-II radio galaxies. The BL Lac type objects are subdivided into three different categories depending upon the position of the synchrotron peak: LBL (low energy peaked BL Lacs), IBL (intermediate), and HBL (high frequency peaked BL Lacs). The latter is again the most abundant type of object with a total of 34 known sources.

The BL Lac type objects have been observed at red shifts up to $z = 0.61$ (KUV 00311-1938 [47]) which may start to be in tension with the expected absorption due to pair-production with the extragalactic background light [48]. Besides the existence of an axion-like pseudoscalar field [49, 50], cascading of ultra-high energy cosmic-rays (UHECRS) have been suggested to reduce the effect of absorption [51]. For the latter model, BL Lac type objects would be sources of UHECRS, most likely nuclei [52].

An interesting aspect of VHE-emission from FSRQs is the expected optical depth for VHE-photons emitted close to the bright nucleus. The recent detection of short-timescale (10 min) variability from the FSRQ PKS 1222+216 with MAGIC [53] is particular interesting as it would imply that a very compact emission region either exists far away from the base of the jet in

$^3$ An earlier claim by the CANGAROO collaboration was later withdrawn [43]
order not to be absorbed or that the optical depth is somehow reduced [54].

4. Summary and outlook
The VHE-observations reported here are meant to give an overview of recent results which are of direct relevance to cosmic-ray acceleration and propagation in the Galaxy. The VHE-emitting extra-galactic sources include various types of objects: Blazars (BL Lac type and Flat-spectrum radio quasars), starburst galaxies, and radio galaxies. Ground based observations have been extremely useful to measure and characterize variability on short time-scales (the large cadence of ground-based observations makes it challenging to understand long-term variability patterns).

Future observations with the new HESS Phase II telescope will provide new insights into high-z objects (probably FSRQs) and the location of the VHE emitting zone in the jet. Both, the spectroscopy as well as measurement of variability in the energy range below 100 GeV will be crucial to understand the origin of gamma-rays for these objects.

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