Supernova remnants and pulsar wind nebulae with Imaging Atmospheric Cherenkov Telescopes (IACTs)

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Abstract. The observation of very-high-energy (VHE, E > 100 GeV) gamma rays is an excellent tool to study the most energetic and violent environments in the Galaxy. This energy range is only accessible with ground-based instruments such as Imaging Atmospheric Cherenkov Telescopes (IACTs) that reconstruct the energy and direction of the primary gamma ray by observing the Cherenkov light from the induced extended air showers in Earth’s atmosphere. The main goals of Galactic VHE gamma-ray science are the identification of individual sources of cosmic rays (CRs), such as supernova remnants (SNRs), and the study of other extreme astrophysical objects at the highest energies, such as gamma-ray binaries and pulsar wind nebulae (PWNe).

One of the main challenges is the discrimination between leptonic and hadronic gamma-ray production channels. To that end, the gamma-ray signal from each individual source needs to be brought into context with the multi-wavelength environment of the astrophysical object in question, particularly with observations tracing the density of the surrounding interstellar medium, or synchrotron radiation from relativistic electrons.

In this review presented at the European Cosmic Ray Symposium 2014 (ECRS2014), the most recent developments in the field of Galactic VHE gamma-ray science are highlighted, with particular emphasis on SNRs and PWNe.

1. Introduction
Galactic gamma-ray astronomy at very high energies (VHE, E > 100 GeV) has experienced a dramatic increase in activity over the past 10 years, thanks to the advent of the current generation of ground-based imaging atmospheric Cherenkov telescopes (IACTs), such as H.E.S.S. [1], MAGIC [2] and VERITAS [3]. This energy range is currently only accessible with ground-based instruments, featuring large effective areas, due to the comparatively low photon fluxes emitted from sources at these energies. Up to now, more than 70 individual Galactic sources in this energy regime have been detected, belonging to a large variety of source classes, ranging from young supernova remnants (SNRs) and pulsar wind nebulae (PWNe) to gamma-ray binaries and massive stellar clusters (see e.g. TeVCat [1]). For a comprehensive review on the subject, see [4].

The main quests of Galactic VHE gamma-ray science are 1) the study of the most extreme non-thermal astrophysical environments in the Milky Way at the highest energies, and 2) the search for the most powerful sources of Galactic cosmic rays that accelerate particles up to PeV energies (“PeVatrons”). VHE gamma rays are produced in the interaction of ultra relativistic
electrons or protons with the ambient interstellar matter or radiation fields via $\pi^0$ production and subsequent decay (protons) or inverse Compton scattering (electrons).

Ground-based gamma-ray astronomy with IACTs covers a very interesting energy range (100 GeV – 100 TeV) to study the origin of Galactic cosmic rays. One of the most popular explanations for the “knee” in the cosmic ray energy spectrum at a few PeV is a transition from Galactic to extra-galactic sources of cosmic rays [see, e.g., 5; 6], implying that the most powerful Galactic accelerators feature spectra with steep cut-offs at these energies. One way to prove this interpretation is the detection of individual Galactic sources of secondary gamma rays from the hadronic channel with spectra extending up to 100 TeV [see, 7, and references therein], an energy which lies at the extreme end of the capabilities of current IACTs, due to the very low fluxes at these energies.

The best candidates for accelerators of Galactic cosmic rays up to PeV energies are the expanding shocks of young ($\sim 1000$ yr) SNRs which are believed to accelerate particles through the Fermi-type process [8; 9]. Indeed, VHE gamma-ray emission has been detected from several Galactic SNRs, predominantly by H.E.S.S. in a systematic scan of the Galactic Plane as well as dedicated follow-up observations [10].

The most abundant Galactic VHE gamma-ray source class, however, are pulsar wind nebulae (PWNe) which are characterized by large-scale non-thermal emission throughout the electromagnetic spectrum surrounding young and powerful pulsars. PWNe are believed to be caused by highly relativistic electrons accelerated at the termination shock of a stream of energetic particles originating from the pulsars’ magnetosphere. These shock-accelerated electrons diffuse into the surrounding interstellar medium (ISM) and cool via synchrotron (SR) and inverse-Compton (IC) radiation through the interaction with ambient magnetic (SR) or photon (IC) fields [for a detailed review see, 11]. VHE gamma-ray observations offer a unique window into the acceleration processes and particle propagation present in PWNe through the observation of IC radiation, as opposed to SR which dominates at lower energies. The latter is influenced not only by the characteristics of the underlying population of relativistic electrons, but also by the magnetic field distribution which generally is an unknown quantity. In contrast, IC radiation in gamma-rays is only governed by the target photon field energy density (usually dominated by the well-known cosmic microwave background) which allows to directly measure the spectrum and spatial distribution of the relativistic electrons.

The discrimination between the two gamma-ray production channels, namely $\pi^0$ decay and IC scattering, is one of the main challenges of VHE gamma-ray astronomy. Here it is necessary to compare the VHE gamma-ray signal to emission seen in other wavelength regimes, such as radio continuum, X-rays and molecular line transitions. For instance, a correlation of the VHE gamma-ray signal with non-thermal X-ray and/or radio emission may point towards relativistic electrons which radiate through IC and SR emission in the respective energy bands. On the other hand, if the VHE gamma-ray emission corresponds well with the spatial distribution of dense molecular gas, measured through the observation of molecular line transitions, relativistic protons are the most likely explanation, due to production and subsequent decay of neutral pions in dense target environments.

2. Imaging Atmospheric Cherenkov Telescopes (IACTs)

IACTs detect gamma-rays through the observation of Cherenkov light emitted by secondary charged particles in the extensive air showers caused by the primary gamma ray (see Fig. 1). IACTs consist of large (12 - 28 m) optical reflecting mirrors coupled with very fast cameras and readout electronics to facilitate the imaging of the very short ($\sim 10$ ns) flashes of Cherenkov light. The cameras of the three major IACTs H.E.S.S., VERITAS, and MAGIC, consist of $\sim 1000$ - 2000 pixels of photomultiplier tubes (PMTs) and feature a field of view of up to 5 deg.

To improve the rejection of background caused by charged primaries (mainly protons) all
current IACTs work in an array configuration of up to five individual telescopes. Through this stereoscopic approach where the same shower is seen from several angles the Cherenkov images of the electromagnetic showers from gamma-ray primaries can be well discriminated from the predominantly hadronic showers caused by cosmic rays. Also, the reconstruction of the direction and energy of gamma rays is significantly improved in stereoscopic observations, yielding angular resolutions better than 0.1 deg and systematic uncertainties of energy reconstruction below 20\% for modern IACTs.

All three major IACTs currently in operation have recently undergone large hardware upgrades. MAGIC, situated on the Canary island of La Palma, was upgraded through the addition of a second telescope of the same size enabling stereoscopic observations increasing background rejection and overall sensitivity. The cameras of the VERITAS 4-telescope array, located in Arizona (USA), were upgraded with high quantum efficiency PMTs, significantly lowering the energy threshold and sensitivity of the system [12]. The H.E.S.S. array, located in the Khomas Highland of Namibia, received a major upgrade by the addition of a fifth, larger 28 m telescope (see Fig. 2) lowering the energy threshold from 100 to about 30 GeV, as well as improving the overall effective area by about a factor of two.

3. **Pulsar wind nebulae**

A detailed description of our current understanding of the structure and evolution of PWNe is beyond the scope of this paper, and the reader is referred to [11] for a detailed review of
the subject. However, I would like to highlight one very interesting aspect seen in the current sample of well observed PWNe that highlights the importance of VHE gamma-ray observations in particular. Figure 3 shows the ratio between the observed gamma-ray and X-ray luminosities of PWNe as a function of their age. Apparently, young PWNe are comparatively strong X-ray emitters whereas older systems predominantly radiate in gamma-rays. Efficient SR in X-rays requires very energetic electrons of up to 1 PeV (as present, e.g., in the Crab nebula, see [13]) coupled with strong magnetic field of several 10s to 100 µG; conditions that are only present in young and still compact PWNe.

![Figure 3. Ratio between the observed gamma-ray and X-ray luminosities of PWNe vs. their age [14].](image)

During their evolution, PWNe expand in size by more than an order of magnitude which is accompanied by a corresponding decrease in the average magnetic field strength owing to the conservation of magnetic flux. Therefore, SR becomes a less and less efficient cooling mechanism as the system evolves, and at some point the B-field-independent IC emission takes over as the dominant radiation process. For a more detailed discussion of this aspect, please see [14].

VHE gamma-ray observations hence provide a new and unique window to understand PWN evolution over much longer time periods than previously possible through observations of SR. In fact, several evolved PWNe, such as HESS J1825–137 [15] and HESS J1303–631 [16], were first discovered in VHE gamma rays, while their comparatively faint X-ray counterparts were only confirmed later through deep follow-up observations.

### 3.1. New VERITAS observations of MGRO 2019+37

The very bright VHE gamma-ray source MGRO 2019+37 was first detected by the Milagro water Cherenkov detector with a flux of 80% of the Crab nebula but could not be clearly identified with any known astrophysical object [17]. It is located in the direction of Cygnus X, one of the richest star forming regions in the Galaxy. Recently, VERITAS observed this region and was able to decompose MGRO 2019+37 into two separate VHE gamma-ray sources, namely the pointlike source VER J2016+371 coincident with the center-filled SNR CTB 87 and the extended (∼1°) source VER J2019+378 spatially consistent with the powerful pulsar PSR J2021+3651 as well as the star formation region Sh 2104.

These two sources are also very well separated through their energy spectra (see Fig. 4 and 5). The spectra of both sources are well represented by a power law, however, with largely different indices: 2.4±0.4 for VER J2019+378 and 1.75±0.3 for VER J2016+371, the latter being among the hardest spectra ever measured for Galactic VHE gamma-ray sources.
Figure 4. The region around MGRO 2019+37 as seen with VERITAS. The image shows two different energy bands: 600 GeV - 1 TeV (green) and >1 TeV (red). Image from [18].

Figure 5. Differential energy spectra of VER J2016+371/CTB 87 and VER J2019+368 as measured by VERITAS. Image from [18].

VER J2016+371 most likely can be identified as a PWN due to its spatial consistency with CTB 87, and the ratio between the gamma-ray and X-ray flux being consistent with expectations for a typical magnetic field strength of 5 µG. The offset between the X-ray nebula and the center of the SNR may point towards an age older than 5-10 kyr, indicating significant movement of the pulsar since its birth [18].

The case is more complicated for VER J2019+378, mainly due to its extended morphology that overlaps with several plausible counterparts. The most commonly discussed counterpart to this source is the powerful pulsar PSR J2021+3651. With a spin-down power of $3.4 \times 10^{36}$ erg/s$^1$, it may easily account for the whole flux observed from VER J2019+378. Also, the presence of a non-thermal X-ray counterpart further strengthens a PWN interpretation. However, the tail of the X-ray emission as well as part of the VHE gamma-ray source overlap with the starforming region Sh 2104. Such regions of active star formation were discussed as potential sites of particle acceleration (see, e.g. [19]) and the partial overlap of non-thermal emission may indicate that this may contribute to some degree to the overall flux seen from VER J2019+378.

3.2. VERITAS observations of the unidentified gamma-ray source TeV J2032+4130

The gamma-ray source TeV J2032+4130 was serendipitously discovered by the HEGRA IACT array [20] and was the first source in this energy regime that could not be identified with any know object at lower wavelengths. Despite extensive efforts to uncover the nature of this source through multi-wavelength follow-up observations, no clear emission scenario could be established in the following years.

Things changed when this region was recently observed by VERITAS which was able to more tightly constrain the morphology and spectral shape of the VHE gamma-ray emission [21]. Through detailed comparisons of the VHE gamma-ray source with the distribution of the ambient ISM, a PWN scenario could be established as the most likely explanation for the observed emission. Figure 6 shows the new VERITAS gamma-ray map along with images tracing the interstellar gas distribution in this region. It seems that the VHE gamma-ray source
Figure 6. The four panels show the same region in different wavelength regimes: a) VERITAS significance map, b) 1.4 GHz image from the Canadian Galactic Plane Survey, c) Spitzer MIPS 24\(\mu\)m image d) Spitzer GLIMPSE 8\(\mu\)m image. The contours (white) are from the VERITAS source. See [21], and references therein.

completely fills a void in the ISM which is surrounded by higher density gas. The void could have been created either by a supernova explosion or by the collective wind from massive stars located in its center. In case of an SNR origin, the remnant must be quite old (>30 kyr) because younger remnants would probably still be detectable through non-thermal radio emission. Here, the VHE gamma-ray source could be the relic of an ancient PWN, which would be very faint in X-rays and thus eluding detection. This scenario is supported by the presence of an old pulsar (PSR J2032+4127), surrounded by a faint X-ray nebula, inside the void but slightly offset from the VHE source centroid.

To conclude, the recent VERITAS observations shed new light on an old mystery by discovering potentially one of the oldest PWNe ever seen in VHE gamma rays.

4. Composite SNRs

So-called composite SNRs are a critical phase in the evolution of the remnants of core-collapse supernovae where the expanding shock front of the SNR as well as a PWN in its center are efficient emitters of non-thermal radiation. On the one hand, these systems must be young enough such that the SNR itself has not yet fully dissipated into the ambient ISM. On the other hand, they must be old enough such that a sufficient amount of relativistic electrons have been injected by the central pulsar and diffused to give rise to an extended nebula of non-thermal radiation in the center of the SNR. The study of the co-evolution of SNR and PWN is a very active topic in high-energy astrophysics, particularly the interaction of the expanding PWN with the reverse-shock which moves inwards towards the SNR center. This interaction may give rise to alternating expansion and compression phases of the PWN and is probably also tightly coupled with certain features in the spectra of non-thermal radiation. Please see [22] for a detailed model describing the interesting dynamics of such systems.
4.1. **HESS J1818−154, a new composite supernova remnant discovered in VHE gamma rays and X-rays**

Recently, the HESS collaboration reported the detection of a new VHE gamma-ray source located in the center of the shell-type radio SNR G15.4+0.1 [23]. Interestingly, the VHE gamma-ray source appears to be point-like and statistically incompatible with originating from the shell of the SNR itself (see Fig. 7). The most plausible explanation therefore was the presence of a yet undetected PWN in the center of SNR G15.4+0.1, originating from a powerful but unknown pulsar.

A high-sensitivity follow-up X-ray observation with the space telescope *XMM-Newton* indeed revealed an extended diffuse non-thermal X-ray nebula compatible with the position of HESS J1818−154 (see Fig 8). At low energies (<4 keV) the X-ray source nearly covers the whole inside of the SNR, indicating that the PWN may already be in direct interaction with the reverse shock. At higher energies (>4 keV) the X-ray nebula is much more compact and probably centered on the yet undetected pulsar [23]. The energy-dependent size of the X-ray nebula probably indicates the presence of strong synchrotron cooling close to the pulsar which allows only lower energy electrons to propagate as far out as the boundaries of the SNR. The X-ray and VHE gamma-ray spectra are compatible with a standard PWN model with a moderate magnetic field strength (1.5-4.8 µG) and a total energy in electrons <3×10^{49} erg.

A detection of a powerful pulsar coincident with the newly discovered PWN would be the last missing piece to fully characterize the evolutionary state, total energy budget and potentially the distance of HESS J1818−154.

4.2. **A complex gamma-ray source coincident with the SNR W41**

The VHE gamma-ray source HESS J1834−087, coincident with the SNR W41, was originally detected in the first H.E.S.S. Galactic Plane survey [24] and later confirmed by dedicated observations with the MAGIC telescopes [25]. At first, due to limited statistics and resolution, it was unclear whether the VHE gamma-ray emission originates from the SNR shell or from an
Recent dedicated deep follow-up observations with H.E.S.S., featuring an exposure of 61 h and an analysis with improved angular resolution, provide now a much more detailed view of the spectral and morphological characteristics. Fig. 9 shows the new H.E.S.S. skymap of the area with overlaid radio contours of SNR W41. From this image, and from the radial profile of excess counts (Fig. 10) it becomes clear that the morphology is quite complex. The shape of the VHE gamma-ray excess is best fit with a two-component model consisting of a point-like source in the center of the SNR and an extended Gaussian component covering the whole SNR.

Based on this new information there are now three scenarios for the origin of the gamma-ray emission: A) The whole flux is produced by a PWN. However, because the total flux from HESS J1834−087 is quite large, the pulsar would need to be very powerful with a spin-down luminosity of the order of $\dot{E} \approx 10^{37}$ erg s$^{-1}$. B) Alternatively, the whole source may arise from the interaction of hadronic cosmic rays with dense molecular clouds detected in that region. This scenario is strengthened by the fact that recent radio observations revealed the existence of OH masers evidencing a direct interaction of the SNR shock with the surrounding dense molecular gas. C) A third option would be that HESS J1834−087 is powered by scenarios A) and B) at the same time. Such an interpretation is strengthened by the favored two-component morphology of the VHE gamma-ray emission. Also, here the energy requirements for the pulsar powering the PWN would be lower, because only part of the total flux may be attributed to this object.

5. Supernova remnants

Currently, several tens of GeV and VHE gamma-ray sources are known that are most likely connected to Galactic SNRs. The sample of well-studied SNRs in this energy regime is quite heterogeneous concerning the close environments of the SNR shocks as well as the plausible radiation mechanism producing the observed gamma-ray flux. They can be roughly divided into two groups (see Fig. 11):

1) Young SNRs (<5-10 kyr) are efficient particle accelerators, often have a non-thermal X-ray/synchrotron counterpart, and mostly expand into a relatively low density medium. For these sources, both leptonic and hadronic emission scenarios are discussed in the literature.
2) Middle-aged (10 – 30 yr) interacting SNRs are characterized by dense interstellar medium in the form of molecular clouds in direct contact with the SNR shock. These SNRs are often one to two orders of magnitude brighter in gamma-rays than young non-interacting SNRs of similar size (see Fig. 11). This enhancement in flux can be likely explained by the presence of a much denser target environment for escaping relativistic protons to interact with. Therefore, the bulk of the gamma-ray emission from these SNRs is attributed to hadronic processes.

In the following subsections a few interesting and very recent examples of SNRs from both of these categories are highlighted.

5.1. VERITAS observations of Tycho’s SNR

Tycho’s SNR is the remnant of a Type 1a supernova observed by astronomers 1572 AD. It is an ideal laboratory to study SNR evolution coupled with cosmic-ray acceleration because its age is precisely known, and because it evolves into a very clean and low-density environment. It has been detected in gamma rays with the Fermi-LAT observatory [27] and, at higher energies by VERITAS [28], see Fig 12. The absence of an IC peak in the spectrum between the GeV and TeV energy bands, which would be typical for leptonic scenarios, argue in favor of hadronic processes (see Fig. 13). Furthermore, high-resolution X-ray observations with Chandra provided evidence that hadronic cosmic-ray acceleration is taking place at the forward shock of Tycho’s SNR, based on detailed analyses of the morphology and spectrum of the emission in the shock region [29].

The original VERITAS spectrum had a rather high energy threshold >1 TeV, leaving a large gap between the Fermi-LAT and VHE gamma-ray coverage. As can be seen from the various models shown in Fig. 13, additional coverage in the sub-TeV regime may greatly help to distinguish between the various emission scenarios. Recent deep (105 h) follow-up observations with VERITAS [30] lowered the energy threshold significantly, due to an upgrade of the telescope cameras as well as improvements in the analysis software. Preliminary results show a significantly decreased energy threshold of a few 100 GeV. A future publication with the final spectrum analysis will certainly shed light on the details of hadronic particle acceleration and interaction in this incredibly well-studied SNR.
5.2. **HESS J1640−465, the most luminous Galactic VHE gamma-ray source**

One of last years highlights in Galactic VHE gamma-ray astronomy were new observational results for the very bright and prominent source HESS J1640−465. Due to its comparatively large flux (∼10% of the Crab) emission from this object was discovered early during the H.E.S.S. Galactic plane scan [24]. Its location is consistent with the SNR G338.30.0, and follow-up observations with *XMM-Newton* revealed an extended, highly absorbed X-ray source in the center of this SNR [31]. Because of this detection, HESS J1640−465 originally was mainly discussed in the context of a PWN scenario [see e.g. 32].

A detailed study of the HI absorption features of SNR G338.30.0 revealed that this object is probably located at a distance between 8 and 13 kpc [36]. Such a large distance made HESS J1640−465 the most luminous known Galactic VHE gamma-ray emitter, and it became clear that this is potentially one of the most extreme objects of its kind, no matter what the emission scenario might be.

A recent detailed follow-up study of this source by H.E.S.S. based on a dataset more than four times larger, and featuring an analysis with improved angular resolution, shed new light on the potential origin of the gamma-ray emission [34]. According to the new data, the intrinsic size of the VHE gamma-ray source shows significant overlap with the northern part of the SNR shell (see Fig 14). This is challenging to explain in PWN scenarios where one would expect the VHE gamma-ray emission region to be contained within the SNR shell. In fact, the new H.E.S.S. study shows that the VHE gamma-ray morphology would be compatible with originating solely from the northern SNR shell. In an hadronic scenario, the fact that only the northern part of the SNR shell is visible in VHE gamma rays could be explained by the large difference in ISM density between the North and the South. The SNR is located at the southern edge of a dense HII region, and only those protons accelerated by the shock that enter this particular area may find sufficient target material to produce a detectable gamma-ray signal [34].

Recently, a new Fermi-LAT study of the counterpart of HESS J1640−465 in the 100 MeV - 100 GeV energy range presented an updated spectrum extending the gamma-ray coverage to lower energies ([35], see also Fig. 15). These authors also favor an hadronic interpretation of
Figure 14. New H.E.S.S. skymap of HESS J1640−465. Also shown are the 610 MHz radio contours (solid, black) of the SNR G338.30.0 [33] and the intrinsic size of the VHE gamma-ray source (dashed, blue). Image from [34].

Figure 15. Combined Fermi-LAT (circles, red) [35] and H.E.S.S. spectrum (stars, blue) [34] of HESS J1640−465. The dashed line shows a hadronic model. Image from [35].

the gamma-ray signal, but cannot fully rule out a contribution from the PWN. Interestingly, a new pulsar located in the X-ray PWN was recently detected by NuStar that may be powerful enough to give rise to a significant fraction of the observed gamma-ray flux [37]. However, the spatial overlap of the VHE gamma-ray source with the SNR shell still points towards radiation mechanisms connected to the SNR itself, independent of the PWN. Despite the recent progress and new results for this very luminous object, it remains unclear if the emission is caused only by one process, or if we are observing a superposition of several distinct particle acceleration and radiation mechanisms at the same time. Only future gamma-ray observations featuring even higher angular resolution, like the Cherenkov Telescope Array (CTA) [38], may be able to provide the final answer.

5.3. A new treasure in the same region: HESS J1641−463

The detailed study of HESS J1640−465 (see Sect. 5.2) did not only provide new insights into the physics of this very prominent source, but also led to a new discovery [39]. In the tail of the point-spread function of the signal from HESS J1640−465 lies a second source, HESS J1641−463, which is an order of magnitude fainter than its bright neighbor (see Fig. 16).

Interestingly, the separation between these two sources becomes stronger with increasing energy (see Fig. 17). This is partly due to an improvement of angular resolution with increasing energy, due to the more accurate reconstruction of air showers for more energetic primary gamma rays. The main reason, however, is the significantly harder spectrum of HESS J1641−463 compared to HESS J1640−465. While the second source is barely visible at lower energies, both objects feature a comparable brightness for energies >5 TeV. A spectral analysis yields a power law photon index of \( \Gamma = 2.07 \pm 0.11_{\text{stat}} \pm 0.20_{\text{sys}} \), which ranks among the hardest spectra ever measured from Galactic VHE gamma-ray sources. Also, the data show that the spectrum extends to an energy of at least 20 TeV without any sign of a cut-off.

Various gamma-ray production scenarios are discussed for this object, including hadronic processes within the dense target environment surrounding this source [39]. In such a case,
owing to the hard spectrum showing no clear cut-off, the energies of the underlying relativistic protons could even extend to several hundreds of TeV to 1 PeV. Hence, HESS J1641−463 may be one of the first known representatives of a population of cosmic-ray accelerators that provide energies up to the knee in the local cosmic-ray spectrum. In one scenario, the protons originate from SNR G338.30.0, which is associated with HESS J1640−465. The reason why the latter does not look like a PeVatron today might be that the most energetic protons already escaped the source and have propagated into the dense molecular environment towards the North-East. There, they give rise to the very hard gamma-ray emission, seen from HESS J1641−463, through production and subsequent decay of neutron pions.

Alternative gamma-ray production scenarios, such as IC emission from relativistic electrons, are disfavored due to the non-detection of a spectral brake in the multi-TeV regime. However, given the statistical quality of the current dataset, such scenarios cannot be fully ruled out yet.

6. Summary
Over the last decade, the field of ground-based VHE gamma-ray astronomy with IACTs evolved into a rich and diverse new research discipline, bridging the gap between modern astronomy and astroparticle physics. The field now entered a phase of precision measurements to investigate details of the particle acceleration and subsequent radiation processes. Specifically in Galactic VHE gamma-ray science the focus lies on the discrimination between leptonic and hadronic gamma-ray production channels in the emission observed from SNRs, and the study of the evolution of PWNe generated by strong rotation-powered pulsars. Such studies do not only require a detailed analysis of the gamma-ray signal, but also the development of plausible
radiation scenarios involving the whole multi-wavelength environment of the sources. Ground-based VHE gamma-ray astronomy is also an important field to explore the origin of Galactic cosmic rays. This is achieved by identifying potential acceleration sites through secondary gamma-ray production from the decay of neutral pions produced in the interaction of hadronic cosmic rays with the interstellar medium.

CTA, a next generation IACT, is currently in development and will consist of 100 individual telescopes of different sizes [38]. This new observatory will feature an increase in sensitivity by up to a factor of 10 compared to current IACTs and will provide the community with a wealth of new high-precision data to tackle the remaining open questions in an inter-disciplinary context.

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