Latest results on Galactic sources as seen in VHE gamma-rays

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As of early 2009, latest results on Galactic sources (mainly shell-type and plerionic supernova remnants), as observed in the very-high-energy \( \gamma \)-ray domain, are reviewed. A particular attention is given to those obtained with the H.E.S.S. experiment during its Galactic Plane Survey which now covers the inner part of the Milky Way. From the well identified \( \gamma \)-ray sources to those without any obvious counterpart and the putative Galactic diffuse emission, this observational window fully deserves to be celebrated during this International Year of Astronomy, as a new mean to image the Galaxy and reveal sites of particle acceleration, potentially at the origin of Galactic cosmic rays.

1 Introduction

Current generation of Imaging Atmospheric Cherenkov Telescopes (hereafter, IACTs) have recently revealed a new population of Galactic sources emitting in the very-high energy (VHE; \( E > 100 \text{ GeV} \)) gamma-ray domain.\(^{20}\) In particular, the H.E.S.S. experiment, through a Galactic Plane Survey performed over the last five years and covering the inner Galaxy (\( \ell \in [-90^\circ,60^\circ] \), \(|b| < 3^\circ\), see Figure 1), has accomplished a major breakthrough by revealing most of these new VHE \( \gamma \)-ray sources, as shown in Figure 2. A variety of source classes, identified (i.e. coincident) with sources known at traditional wavelengths, was found, among them several shell-type supernova remnants (hereafter, SNRs), isolated or interacting with the surrounding medium, many young and middle-aged offset pulsar wind nebulae (hereafter, PWNe), some young massive star clusters, and a bunch of \( \gamma \)-ray binaries. In regards with SNRs and PWNe, one of the main pending question concerns the nature of the observed VHE \( \gamma \)-ray emission, which relates to the parent population of accelerated particles, or, in other words, the difficulty in disentangling the hadronic and leptonic contributions to the observed emission. This is in turn intimately linked to the more general question of the origin of Galactic cosmic rays (hereafter, CRs). As we shall see in the following, these questions can be efficiently addressed through a detailed investigation of the broadband spectrum of these sources, from radio to VHE \( \gamma \)-ray domains, coupled with the recent theoretical developments of acceleration mechanisms.

Figure 1: H.E.S.S. significance image of the inner part of the Galaxy (\( \ell \in [-60^\circ,40^\circ] \), \(|b| < 3^\circ\)), as of 2008 (from Chaves et al., H.E.S.S. collaboration, 2008). The color transition from blue to red is set to 5 \( \sigma \).
Besides these sources whose nature is firmly established thanks to the existing multi-wavelength observations, many others fall into the category of the so-called dark sources (i.e. with no clear counterpart at other wavelengths). This can be first explained by the fact that the majority of the VHE γ-ray sources are extended, on scales of the order of tens of arcminutes, with no clear sub-structure. Although current IACTs have reached unprecedented sensitivities and angular resolutions, the morphology of most of the faint sources can not be characterised precisely. Moreover, instruments in other domains (radio, infrared, X-rays) usually feature angular resolutions at the arcsecond / subarcminute scales, often coupled with relatively small field of views, which (1) does not permit one to perform deep surveys of the whole Galactic Plane, and (2) makes it difficult to reveal large-scale structures coincident with these newly discovered sources.

![Figure 2: A history of VHE Galactic astronomy.](image)

In this contribution, latest results on VHE Galactic sources are reviewed, with a particular attention to those obtained with H.E.S.S.. The well-identified cases, such as shell-type SNRs and PWNe, are discussed in sections 2 and 3 respectively, together with the implications and new questions related to the acceleration mechanisms and the nature of the VHE γ-ray emission. Some interesting cases of dark sources are exposed in section 4 and the origin of the putative VHE Galactic diffuse emission is discussed in section 5. The conclusion focuses on the interest of population studies, through the log N – log S distribution of all the VHE Galactic sources known so far, and the perspectives with the next generation of IACTs (CTA, AGIS).

## 2 Shell-type supernova remnants

Since the first speculation of Baade & Zwicky in 1934, the question of SNRs as the main sources of Galactic CRs up to the knee (∼ 3 PeV) and beyond is not yet settled, in spite of several decades
of important observational and theoretical investigations. The broadband spectrum of these sources, from radio to VHE $\gamma$-ray domains, is the signature of particles accelerated at the shock fronts and radiating photons through several channels (synchrotron SC, non-thermal bremsstrahlung, inverse-Compton IC and $\pi^0$-decay). Therefore, it represents by far our best access to the acceleration processes in SNRs. Up to now, five previously known shell-type SNRs, namely Cas A, RX J1713.7-3946, RX J0852-4622, SN 1006, and more recently SN 1006, have been discovered in VHE $\gamma$-rays, the last four exhibiting a shell-type morphology matching that observed in X-rays. As discussed before, the main question concerns the nature of the VHE $\gamma$-ray emission from these shell-type SNRs (leptonic through IC emission or hadronic through $\pi^0$-decay decay from p-p interactions) and gives rise to an intense debate. On one hand, the correlation between X-ray and VHE $\gamma$-ray emission would support the leptonic scenario but implies, in a simple one-zone model, a spatially-averaged magnetic field of the order of a few tens of $\mu$G (except Cas A). This value seems uncomfortably low in comparison with the theoretical prediction of magnetic field amplification associated with the efficient production of CRs at forward shocks, by the (non-linear) diffusive shock acceleration (DSA) mechanism. Magnetic fields of $\gtrsim 100 \mu$G have been derived from the measured thickness of the X-ray filaments in several young SNRs, and, more recently, from the fast variability of small-scale X-ray dots and clumps, in case these localized structures effectively reflect the SC losses of high-energy electrons in strong (amplified) magnetic fields. On the other hand, for the four resolved shell-type SNRs, the lack of clear correlation between the tracers of the ISM and the VHE $\gamma$-ray emission, together with the tight constraints on the local density derived from the absence (or the faint level) of thermal X-ray emission, does not permit one to draw firm conclusions in favor of an hadronic origin in these shell-type SNRs.

Table 1: Observational constraints on VHE shell-type SNRs. Distances $d_{SNR}$ assumed here are 1, 1, 1, 2.2, 3.4, 4.8 and 2.3 kpc, for RX J1713, Vela Jr, RCW 86, SN 1006, Cas A, Kepler and Tycho, respectively. The first column gives the magnetic field values assuming a one-zone leptonic model, with standard seed radiation fields (CMB and Galactic infra-red and star-light emissions). The second column shows the magnetic field values derived from the thickness of the X-ray filaments. Third and fourth columns give the widths of VHE shells and of X-ray filaments, respectively. $\eta_{CR}$ in the sixth column represents the fraction of the energy of the explosion, $E_{51}$ (in units of $10^{51}$ erg), injected into CR protons, at the distance $d_{SNR}$ and for a gas density $n_0 = n_0/\mathrm{cm^{-3}}$. Such density can then be compared to those given in the last column, mainly derived from the level of thermal X-ray emission.

| SNR   | $B_{VHE}$ (\mu G) | $B_{filaments} [x d_{SNR}^{-2/3}]$ (\mu G) | Width_{VHE} [x d_{SNR}^{2/3}] (pc) | Width_{filaments} [x d_{SNR}^{2/3}] (pc) | $\eta_{CR}$ [x $E_{51}$ d_{SNR}^{-2}] | $n_{obs}$ (cm$^{-3}$) |
|-------|-------------------|------------------------------------------|----------------------------------|------------------------------------------|-------------------------------------|------------------------|
| RX J1713 | ~ 10               | 58–271                                     | ~ 4.5                            | 0.1–0.2                                   | 0.8–2.6/n_0.1                        | < 0.02 d_{SNR}^{-2/3} |
| Vela Jr  | ~ 6                | 200–240                                    | 2.2–3.9                          | 0.18–0.44                                 | ~ 2.5/n_0.1                          | < 0.03 d_{SNR}^{-2/3} |
| RCW 86  | ~ 30               | 50–115                                     | 2.2–4.7                          | 0.29–0.5                                  | 0.05–0.3/n_0.5                       | (0.3–0.7)$_{N_{7}} \sim 10S$ |
| SN 1006 | ~ 30               | 57–143                                     | 2.4–3.5                          | 0.13–0.2                                  | ~ 0.2/n_0.05                         | 0.05$_{SE} \sim 0.2_{NW}$ |
| Cas A   | ~ 100              | 485–550                                    | unresolved                      | 0.03–0.05                                 | ~ 0.01/n_11                          | ~ 11_shocked shell     |
| Kepler  | > 70               | 172–258                                    | –                                | 0.07–0.11                                 | < 0.05/n_0.7                         | < 0.15$_{SE}$           |
| Tycho   | > 70               | 240–360                                    | –                                | 0.04–0.05                                 | < 0.02/n_0.4                         | < 0.3$_{SC \, rim}$     |

Table 1 summarizes the relevant parameters of the five shell-type SNRs detected in VHE. However, it was proposed that the thickness of the X-ray filaments would trace the magnetic field damping downstream of the forward shock and, therefore, would not be a measure of the magnetic field strength. As for dots and clumps, which would reflect the inherent turbulence of the magnetic field, even in the case of a steady particle distribution.

Note that, in the framework of the non-linear DSA, the post-shock gas temperature, which is expected to lie in the X-ray domain for young SNRs, and consequently the thermal X-ray emission, can be reduced (shifted towards lower temperatures) due to strong particle acceleration. However, there are still discrepancies on the level at which the thermal X-ray emission could be suppressed.
\(\gamma\)-rays and of the two historical SNRs, Kepler and Tycho, for which upper limits have been obtained so far\(^5\). It appears clearly that the magnetic field values estimated from a one-zone leptonic model \((f_X/f_{\text{VHE}} \propto B^2)\), are significantly below those derived from the thickness of the X-ray filaments. The situation looks even worse in the case of Kepler and Tycho SNRs, for which only rather strongly amplified magnetic fields seem to be compatible with the non-detection of VHE \(\gamma\)-rays, within these simple assumptions\(^5\). On the other hand, the typical width of the X-ray filaments, over which amplified magnetic fields of about hundreds of \(\mu\)G may exist, are an order of magnitude below the widths of the resolved VHE \(\gamma\)-ray shells. Hence, in case the magnetic field has been damped quickly behind the forward shock, the observed emission could still be explained by IC emission, with a fairly weak spatially-averaged value. Moreover, a detailed modeling of the interstellar radiation field for the calculation of the IC spectrum may help to improve the fit to the VHE \(\gamma\)-ray spectra\(^5\). In regards with the hadronic scenario, the energy injected into CR protons, required to explain the VHE \(\gamma\)-ray flux, is quite demanding, especially if the constraints on the gas density from the level of thermal X-ray emission are taken at face value. Apart from these energetical considerations, \(\pi^0\)-decay from p-p interactions seems to better explain the highest energy (> 10 TeV) data points measured in RX J1713.7-3946, where the Klein-Nishina limit of IC scattering takes place\(^7\). Therefore, both scenarios, in their simplest form, suffer from severe limitations. The question of these shell-type SNRs as efficient Galactic CR accelerators can only be efficiently addressed through spectro-imaging analysis in X-rays and VHE \(\gamma\)-rays, two domains whose current instrumental characteristics are quite different\(^1\) together with theoretical developments of the DSA mechanism.

### 3 Plerionic supernova remnants

Besides shell-type SNRs, a significant fraction of VHE \(\gamma\)-ray sources is (or at least seems to be) associated with energetic pulsars\(^1\). These sources can generate bubbles of relativistic particles and magnetic field when their ultra-relativistic wind interacts with the surrounding medium (SNR or interstellar medium)\(^2\). Their confinement leads to the formation of strong shocks, which can accelerate particles up to hundreds of TeV and beyond, thus generating luminous nebulae seen across the entire electromagnetic spectrum in the SC emission from radio to hard X-rays, and through IC process and potentially \(\pi^0\)-decay from p-p interactions\(^21\), in the VHE \(\gamma\)-ray domain. On one hand, recent advances in the study of PWNe have been made from mainly radio and X-ray observations of the complex morphology of the inner PWNe structure at the arcsecond scales\(^20\). On the other hand, in the VHE domain, H.E.S.S. has proven to be capable to measure, in at least one case\(^31\), spatially resolved spectra at the tens of degree scales. These complementary VHE observations then permit one to probe the electron spectra in these sources and to investigate the associated magnetic field distribution\(^72\).

Two classes of VHE \(\gamma\)-ray PWNe have recently emerged, based on observational grounds: young systems such as the Crab nebula\(^30\), G0.9+0.1\(^15\), MSH 15-52\(^17\) and the newly discovered VHE \(\gamma\)-ray sources associated with the Crab-like pulsars of G21.5-0.9\(^64\) and Kes 75\(^69\) and evolved (extended and resolved) systems (i.e. with characteristic ages \(\tau_c \gtrsim 10^4\) yr), as exemplified by Vela X\(^28\), HESS J1825-137\(^31\), HESS J1718-385 and HESS J1809-193\(^38\). In the former case, the VHE \(\gamma\)-ray emission, when resolved, matches quite well the morphology seen in X-rays, while in the latter case, these VHE \(\gamma\)-ray PWNe were found to be significantly offset from the pulsar position, with large size ratios between the X-ray and VHE \(\gamma\)-ray emission regions. The evolution of the SNR blastwave into an inhomogeneous ISM\(^2\) and/or the high velocity of the pulsar\(^8\), together with a low magnetic field value (~ 5 \(\mu\)G\(^72\)), may explain these large offset

\(^{\text{a}}\)While soft X-ray (< 10 keV) telescopes feature angular resolutions at the arcsecond scales, both the imaging instruments above 10 keV and current IACTs reach angular resolutions of the order 5-10′ at best.
filled-center VHE γ-ray sources as being the relic nebulae from the past history of the pulsar wind inside its host SNR. Since VHE-emitting electrons are usually less energetic than X-ray-emitting ones, they do not suffer from severe radiative losses and the majority of them may survive from (and hence probe) early epochs of the PWN evolution. This interpretation has been further supported by the discovery of the spectral softening of the VHE nebula HESS J1825-137 as a function of the distance from the pulsar. Given the discovery of this large population of middle-aged PWNe, many new sources regularly revealed by the on-going H.E.S.S. Galactic Plane Survey could fall into this category, some of them being classified as PWN candidates. For instance, HESS J1356-645 lies close to the young (τc = 7.3 kyr) and energetic (E = 3.1 \times 10^{36} \text{ erg s}^{-1}) 166 ms pulsar PSR J1357-6429, for which only a marginal evidence of a 3'' diffuse X-ray emission (i.e. of a putative PWN) was found. Interestingly, the extended VHE γ-ray source coincides with a diffuse radio emission, originally catalogued as a SNR candidate. The on-going analysis of archival radio and X-ray data should thus help to constraint the nature of HESS J1356-645 (Aharonian et al., in prep.). Therefore, these sources can be confirmed as VHE γ-ray PWNe thanks to a detailed investigation of all the available multi-wavelength data, together with follow-up observations in radio, e.g. HESS J1857+026 - PSR J1856+0245, and with now Fermi/LAT (e.g. MGRO J1908+06 - HESS J1908+063 - 0FGL J1907.5+0617) in order to reveal the associated (presumably energetic) pulsars.

4 VHE γ-ray “nebulae”

From the well-identified cases such as shell-type SNRs and PWNe, to the PWN candidates for which further data are required to firmly establish the putative association, it is presented here some cases of VHE γ-ray nebulae, also called dark sources. HESS J1731-347 represents the best example in this regard. Originally classified as a dark source, a faint and extended (R ∼ 0.25°) non-thermal radio and X-ray shell-type SNR, named G353.6-0.7, coincident with the extended VHE γ-ray emission, was discovered in the archival data. At a distance of ∼ 3.2 kpc, estimated from HI absorption measurements toward an adjacent HII region, this SNR would have a physical diameter of ∼ 28 pc, significantly larger than the known VHE shell-type SNRs described in section 2. This would then suggest that G353.6-0.7 is an old (∼ 2.7 \times 10^4 \text{ yrs}) and intrinsically very bright SNR. However, its distance and the nature of the X-ray emission are poorly constrained. Even though some theoretical studies have proposed that old SNRs (∼ 10^{4-5} \text{ yrs}) could still emit in the VHE γ-ray domain, it is commonly thought that multi-TeV particles usually leave the acceleration site on timescales of a few thousands of years. Therefore, follow-up radio and X-ray observations are needed in order to shed further light on the nature of this newly discovered shell-type SNR.

This example serves as a discussion about the VHE γ-ray emission from SNRs. During the Sedov phase of the SNR evolution, accelerated particles are gradually injected in the ISM, the most energetic ones being released first. In case the SNR lies close to a molecular cloud (MC, at \lesssim 100 pc), delayed VHE γ-ray (and neutrino) emission of the latter, through p-p interactions, may arise at detectable levels with the current IACTs. The duration of VHE γ-ray emission from the cloud (∼ 10^4 \text{ yrs}) would then last much longer than that of the SNR itself, since it is determined by the time of propagation of CRs from the accelerator to the target. On a theoretical side, the detection of such emission would then indicate that the nearby SNR was acting in the past as an effective Galactic CR accelerator or PeVatron. On an observational side, in this recently revisited scenario (some of) the unidentified VHE γ-ray sources could be...
indirectly associated with old SNRs, the γ-ray emission being produced during the interaction of escaping CRs with nearby MCs. One would then expect a correlation between the VHE γ-ray emission and the tracers of molecular material ($^{12}$CO, $^{13}$CO and masers in case the SNR shock encounters the MC), as it might be the case for the VHE γ-ray emission detected by H.E.S.S. toward the old SNRs W41 (HESS J1834-087) and W28 (HESS J1800-240/J1801-233), the CTB 37 complex and HESS J1745-303. However, it is worth noting that some of these nebulae could be instead VHE γ-ray PWNe, as discussed in section 3: the large lifetime of VHE γ-ray emitting electrons in low magnetic field environments ($\sim 20 B^{-2}_{\mu G} E^{-1/2}_{\gamma, \text{TeV}} \text{kyr}$) makes the ratio of the VHE γ-ray luminosity to the X-ray luminosity an increasing function of the source age and size. Therefore, one would expect VHE γ-ray PWNe to be hardly detectable with current X-ray instruments, and more generally at any other wavelength (leading to a VHE-only, dark, source). Moreover, for most of these nebulae, the morphology is poorly characterized, where only the source barycenter and gaussian extension are usually provided. Many of them may well be multiple sources of different kinds, as for HESS J1800-240 (A, B, & C) and HESS J1745-303. Observations with the next generation of IACTs such as CTA and AGIS, with better sensitivities and angular resolutions, will undoubtedly help to search for counterparts with small field-of-view instruments and, thus, constrain the nature of the VHE γ-ray emission(s).

5 VHE Galactic diffuse emission... or unresolved sources?

This section is devoted to the recent detection by Milagro of a large-scale VHE γ-ray diffuse emission ($30^\circ < \ell < 110^\circ$ and $136^\circ < \ell < 216^\circ$, $|b| < 10^\circ$), after removing the contribution of the sources detected by this experiment. In the inner part of the Galaxy (between 30 and $65^\circ$ in longitude, i.e. excluding the peculiar Cygnus region), the traditional GALPROP model fails to fit the measured flux at $\sim 15 \text{ TeV}$. An optimized version of GALPROP has been designed to reproduce the EGRET data by relaxing the restriction of the local CR measurements. In this model, the electron spectrum is constrained by the EGRET data themselves, such that any hard and faint (relatively to the standard $\pi^0$-decay spectrum from CR protons) IC spectrum, as proposed by the authors, would not violate the GeV measurements, while explaining the measured flux at $15 \text{ TeV}$. Diffuse emission would thus be almost entirely explained by $\sim 100 \text{ TeV}$ electrons scattering off the CMB, with a flux, after propagation, of four times the one measured locally. Interestingly, this region has also been surveyed by H.E.S.S., featuring much better sensitivity and angular resolution than Milagro at the expense of a much smaller field of view (see Figure 3), though with a non-uniform coverage. So far, five VHE γ-ray sources have been detected by H.E.S.S. (and unresolved by Milagro) in this region, and the resulting summed spectrum is shown in Figure 3 together with the Milagro measurement. Roughly 20 % of the diffuse emission is already explained by these H.E.S.S. sources, and a larger fraction should be reached in a next future once the existing H.E.S.S. data will be carefully analyzed and the survey will become uniform. First studies of the VHE γ-ray source population, based on the second H.E.S.S. survey catalogue, had already suggested that at least 10 % of the VHE Galactic diffuse emission should be attributed to unresolved sources.

6 Conclusion

To conclude this review, the $\log N(>S) - \log S$ distribution of all the VHE Galactic sources known so far is shown in Figure 4. A slope of -1 corresponds to a uniform infinite plane distribution while a slope of $\sim -0.6$ indicates that the population follows the spiral arm distribution on Galactic scales (i.e. at distances of $\gtrsim 8 \text{ kpc}$), as expected from young stellar population generating SNRs...
Figure 3: Flux – Size plot of the VHE Galactic sources detected so far. The integrated flux is given between 1 and 10 TeV, in units of the Crab nebula in the same energy band. The size corresponds to either the intrinsic mean source width or, in the case of shell-type SNRs, the outer radius, in units of degrees. The red points represent the sources detected by Milagro during its Galactic Plane survey \((\ell \in [30,65]^{\circ}, |b| < 2^{\circ})\), while the blue points correspond to those revealed by H.E.S.S. in the same region of the sky. The solid lines show the sensitivities of the two instruments, according to their respective characteristics given in brackets, which degrades with the source extent as: \(S = S_0 \times (R_s^2 + \sigma_{psf}^2)^{1/2}/\sigma_{psf}\), where \(S_0\) is the nominal sensitivity and \(R_s\) is the effective source size. Note that this law does not hold anymore when the source size becomes comparable to the instrument field of view, which explains why the H.E.S.S. sensitivity curve is valid only for \(R_s \lesssim 1^{\circ}\). The inset plot shows the Milagro diffuse emission measured at 15 TeV, the expected diffuse flux from the optimized GALPROP model and the summed spectrum of all the H.E.S.S. sources falling into the region probed by Milagro.

...and PWNe. Even though there are inherent complications in the interpretation of such plot, the transition between the two regimes (at \(\sim 0.15\) Crab) seems to take place above the completeness limit of the H.E.S.S. survey. Extrapolating the curve down to 1 mCrab in sensitivity then implies that the next generation of IACTs like CTA \(^{84}\) and AGIS \(^{53}\) should detect at least 500 sources. As discussed in section \(^{4}\), many faint sources could actually be several sources, not clearly resolved yet, leading the log \(N(S)\) – log \(S\) to soften toward low fluxes. The paper focused mainly on the latest results and open questions related to shell-type SNRs and PWNe. Besides them, new classes of VHE \(\gamma\)-ray emitters in the Milky-Way are expected to emerge, either from multi-wavelength follow-up observations of the so-called dark sources, as it might be the case of HESS J1503-582 \(^{68}\), or through dedicated observations of sky regions of interest, as exemplified by the recent detection of VHE \(\gamma\)-rays towards the young stellar cluster Westerlund 2 \(^{37}\). Such detection has triggered many exciting questions on the nature of the VHE \(\gamma\)-ray emission and more generally on the contribution of such wind-blown bubbles to the Galactic CR flux. HESS J1848-018 could be the second case of this kind, where the VHE \(\gamma\)-ray emission is found to be slightly offset from the massive star-forming (Galactic “mini-starburst”) region W 43 \(^{65}\). Moreover, \(\gamma\)-ray binaries have now joined the club of VHE \(\gamma\)-ray emitters and many pending issues still need to be investigated. Next generation of VHE observatories, in tight link with incoming multi-wavelength instruments, will undoubtedly play a crucial role in the understanding of all these acceleration sites in the Galaxy and, very likely, in the discovery of an even larger diversity of VHE \(\gamma\)-ray sources than expected.
Figure 4: Log N(>S) – log S diagram of the VHE Galactic sources. The dashed lines represent the dispersion of the distribution after taking into account the statistical and systematical errors on the source spectra through a Monte-Carlo simulation. The red and orange solid lines correspond to the expectations from a uniform distribution in a thin disk (slope of -1) and a source population distributed along the spiral arms (slope of -0.6), respectively. The transition between these two regimes was set arbitrarily. The dot-dashed line shows the completeness limit of the H.E.S.S. survey (for a source extent of 0.2° in radius, and five hours of observations everywhere in the inner part of the Galaxy). The extrapolation down to 1 mCrab, a sensitivity that should be reached by the next generation of IACTs like CTA and AGIS, would then lead to the detection of about 500 VHE Galactic sources.

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