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VHE γ-ray emitting pulsar wind nebulae discovered by H.E.S.S.

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Abstract. Recent advances in very-high-energy (VHE) gamma-ray astronomy have opened a new observational window on the physics of pulsars. The high sensitivity of current imaging atmospheric Cherenkov telescopes, and in particular of the H.E.S.S. array, has already led to the discovery of about a dozen VHE-emitting pulsar wind nebulae (PWNe) and PWN candidates. These include the plerions in the composite supernova remnants MSH 15–52, G 21.5–0.9, Kes 75, and Vela, two sources in the Kookaburra, and the nebula of PSR B1823–13. This VHE emission is generally interpreted as inverse Compton emission from the relativistic electrons and positrons accelerated by the pulsar and its wind; as such, it can yield a more direct spatial and spectral view of the accelerated particles than can be inferred from observations of their synchrotron emission. The VHE-emitting PWNe detected by the H.E.S.S. telescopes are reviewed and the implications for pulsar physics discussed.

Keywords: Gamma-ray observations; pulsars; nebulae
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INTRODUCTION

The High Energy Stereoscopic System (H.E.S.S.) is an array of four imaging Cherenkov telescopes designed to study astrophysical gamma-rays in the energy domain between about 100 GeV and several tens of TeV. Its wide field of view and unprecedented sensitivity have allowed the discovery of a large number of new very high energy (VHE) gamma-ray sources. Several of these are associated with pulsar wind nebulae (PWNe); they are individually reviewed in the following section. Their general properties and the criteria on which the associations rests are then discussed, and PWN candidates among the H.E.S.S. sources are presented.

The Crab Nebula

This "standard candle" of VHE gamma-ray astronomy can serve to recall the processes thought to be responsible for the observed emission. The non-thermal radiation seen across most of the electromagnetic spectrum, from the radio domain up to gamma-rays below 1 GeV, is generally interpreted as synchrotron radiation from relativistic electrons and positrons created and accelerated by the pulsar. The higher-energy emission component observed in VHE gamma-rays is usually interpreted as inverse Compton (IC) scattering by the same accelerated leptons, although hadronic emission models have also been proposed for VHE emission from plerions. Target photons for IC scattering include the cosmic microwave background (CMB), interstellar dust and stellar emission, and the synchrotron photons themselves.

Observations of the Crab Nebula with H.E.S.S. have revealed clear evidence for steepening at high energies of the VHE gamma-ray spectrum, which can be described by a power law of photon index $\Gamma = 2.39 \pm 0.03_{\mathrm{stat}}$ with an exponential cutoff energy $E_{\mathrm{c}} = 14.3 \pm 2.1_{\mathrm{stat}}$ TeV [1]. Such spectral curvature is consistent with expectations from model calculations of the IC emission spectrum.

VHE PULSAR WIND NEBULAE

The PSR B1509–58 nebula in MSH 15–52

The Crab Nebula is the prototype of a purely *plerionic* supernova remnant (SNR), but many of the PWNe

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detected in VHE gamma-rays are found in SNRs of the more general *composite* type. In such objects the PWN is located inside the shell of emission due to the supernova blast wave, which can a priori also emit VHE gamma-rays. The composite SNR MSH 15–52, also known as G 320.4–1.2, contains a bright, non-thermal X-ray nebula around the young pulsar B1509–58 (see e.g. [2]). The good angular resolution of H.E.S.S. allowed the discovery of an extended source of VHE gamma-rays in this SNR, with a morphology similar to that of the non-thermal X-ray nebula [3]. This correspondence, and the fact that the available spectral data can be described by a simple leptonic model with a plerion magnetic field value of $\sim 17\,\mu$G, motivate the identification of the PWN as the source of the VHE emission.

This H.E.S.S. discovery provided the first illustration of the potential for VHE gamma-ray morphological studies of PWNe. The synchrotron emission observed at lower frequencies reflects the spatial distribution of a combination of the accelerated electron density and the magnetic field strength, and the latter can in general be quite non-uniform in PWNe. By contrast, in a typical IC emission scenario the target photons are approximately uniformly distributed on the scale of the SNR, so that the VHE emission directly reflects the spatial distribution of the high-energy electrons. In the case of MSH 15–52, the observed VHE morphology confirms that these electrons are predominantly distributed along a NW-SE axis.

Two new sources: G 21.5–0.9 and Kes 75

Although the distribution of target photons for IC emission it not uniform in the Galaxy, it varies relatively smoothly in contrast to the distribution of target material for hadronic gamma-ray emission processes. Moreover, the CMB provides a minimum target photon density which is uniformly distributed. Sensitive VHE gamma-ray observations can thus reveal any sufficiently intense source of high-energy electrons in the Galaxy, again in contrast to sources of high-energy hadrons, for which the presence of dense target material is also a necessary condition for detectability. The survey of the Galactic plane undertaken with H.E.S.S. thus has a strong potential for detecting energetic PWNe.

Follow-up observations in the ongoing H.E.S.S. survey of the Galactic plane have most recently led to the discovery of VHE gamma-ray emission from two young PWNe [4]. G 21.5–0.9 was long thought to be a purely plerionic SNR like the Crab, but has been recently recognised as composite; it harbours the recently discovered PSR J1833–1034, which has the second highest spin-down luminosity in the Galaxy after the Crab. The composite SNR Kes 75, also known as G 29.7–0.3, contains the X-ray emitting PSR J1846–0258, with a large inferred surface magnetic field.

Both objects are relatively weak sources of VHE gamma-rays, with measured fluxes $\sim 2\%$ of the Crab Nebula's, and have hard spectral indices, $\Gamma \sim 2.2$ [4]. They are both unresolved in H.E.S.S. observations, and due to the small diameter of the remnants the possibility that VHE gamma-rays might originate in the shell cannot be excluded at present. Nonetheless, in both cases the position is fully compatible with that of the central pulsar, and the broad-band emission can be reproduced in a leptonic scenario with a nebular magnetic field of about $10 - 20\mu$G, much lower than the equipartition value.

The Vela X plerionic nebula

The Vela SNR is a large (diameter $\sim 8^\circ$), nearby (distance $D \approx 290$ pc) composite remnant. It contains a radio-emitting plerionic nebula, Vela X, powered by the young and energetic Vela pulsar, PSR B0833–45. Observations of this region with H.E.S.S. revealed an extended source of VHE gamma-rays centred to the south of the pulsar [5], overlapping a diffuse hard X-ray emission feature first detected with *ROSAT* [6] and aligned with a bright radio filament within the plerion.

The radio, X-ray and VHE gamma-ray emission regions in this PWN are all markedly offset from the pulsar position. This may be due to the supernova explosion occurring in an inhomogeneous medium, and the resulting asymmetric reverse shock displacing the PWN [7]. Such an offset may be typical of older PWNe; the Vela pulsar's spin-down age of 11 kyr is significantly larger than those of the pulsars considered above.

The VHE gamma-ray spectrum of this source can be described by a power law of photon index $\Gamma = 1.45 \pm 0.09_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}$ with an exponential cutoff energy of $13.8 \pm 2.3_{\mathrm{stat}} \pm 4.1_{\mathrm{sys}}$ TeV; this constitutes the first clear measurement of a peak in the spectral energy distribution at VHE energies [5]. Assuming the CMB is the main target photon component for IC scattering in outer regions of the Galaxy, a total energy of $\sim 2 \times 10^{45}$ erg in non-thermal electrons between 5 and 100 TeV could be deduced. These results demonstrate how VHE observations of IC emission allow direct inference of the *spatial* and *spectral* distribution of non-thermal electrons in a PWN.

Two VHE sources in the Kookaburra

The ongoing H.E.S.S. survey of the Galactic plane allowed the discovery of two VHE sources in the Kookaburra complex of radio and X-ray emission [8]. The stronger of the two VHE sources, HESS J1420–607, is most plausibly associated with the radio and X-ray nebula of the energetic pulsar PSR J1420–6048. The second source, HESS J1418–609, is similarly associated with radio and X-ray emission exhibiting the properties of a PWN, the so-called Rabbit [9].

In both sources, the VHE emission has a large physical extent and appears significantly offset from the pulsar position, which may be due to "crushing" of the PWN as hypothesised for Vela X, or perhaps to the effects of rapid motion of the pulsar through the medium [8]. Both PWNe have been proposed as possible counterparts of an unidentified *EGRET* source coincident with the Kookaburra. The clear separation by H.E.S.S. of two VHE sources, coincident with each of the two PWNe, illustrates the advantages of good angular resolution in identifying the counterparts of gamma-ray sources.

HESS J1825–137 and PSR B1823–13

HESS J1825–137 is a strong VHE source discovered in the first H.E.S.S. survey of the Galactic plane [10]. PSR B1823–13, a Vela-like pulsar, lies at its northern edge, and exhibits an asymmetric X-ray nebula extending towards the centre of the VHE source; the detected X-ray nebula only extends over $\sim 5'$, however, much less than the VHE size [11]. In contrast to the sources above, there is no good morphological match of HESS J1825–137 with emission detected at other wavelengths.

Morphological studies of HESS J1825–137 in the VHE gamma-ray domain have nonetheless yielded compelling evidence for its association with PSR B1823–13. In particular, the VHE emission has an asymmetric profile with a sharp peak immediately south of the pulsar position; the shape of this profile is similar to that of the X-ray nebula, but the VHE profile extends over a much larger scale [12]. More importantly, deeper H.E.S.S. observations have revealed the energy-dependent morphology of HESS J1825–137, marking the first time such an effect is detected in VHE gamma-rays. This manifests itself as a steepening of the power-law spectral index with increasing distance from PSR B1823–13, as would be expected from radiative losses of high-energy electrons injected by the pulsar [13]. These losses could also account for the fact that the PWN appears larger in VHE gamma-rays than in X-rays.

VHE PWN CANDIDATES

Association criteria

A total of eight fairly well-established associations of VHE gamma-ray sources with PWNe have been reviewed above. To these may be added the plerion in the composite SNR G 0.9+0.1, discussed below, as well as the VHE emission associated with PSR B1259–63 [14]. This latter object is in a different class from the other PWNe and candidate PWNe discussed here, however, in that it is dominated by the interaction with its binary companion, as evidenced by its orbital variability.

TABLE 1. Apparent efficiencies for VHE PWNe

VHE source	$F_{0.3-30}$ *	PSR name	ε
Crab nebula	1.7×10^{-10}	B0531+21	0.02%
MSH 15–52	3.3×10^{-11}	B1509–58	0.4%
G 21.5-0.9	3.1×10^{-12}	J1833–1034	0.02%
Kes 75	3.6×10^{-12}	J1846–0258	2%
Vela X	$9 \quad \times 10^{-11}$	B0833–45	0.01%
HESS J1420–607	2.2×10^{-11}	J1420–6048	0.8%
HESS J1825–137	1.1×10^{-10}	B1823–13	7%

* in units of erg $\mathrm{cm^{-2}\,s^{-1}}$

For most of these VHE sources, the association rests on a positional and morphological match to a PWN known at lower energies. When this is not the case, i.e. for HESS J1825–137, an alternative criterion is morphological and spectral evidence in the VHE domain for association with a known pulsar. This section examines other candidate associations, for which the above criteria are not currently fulfilled with the available data.

Pulsar energetics

An additional criterion when considering the association of a VHE source with the nebula of a known pulsar is the apparent efficiency for VHE gamma-ray emission, relative to the pulsar's spin-down luminosity $\dot{E}$. This assumes that the VHE source is at the pulsar distance D, generally determined from its radio dispersion measure. For definiteness, we use the VHE energy flux $F_{0.3-30}$ in the the energy range 0.3–30 TeV, roughly representative of the H.E.S.S. spectral analysis range. The apparent efficiency ε is then defined as $\varepsilon \equiv \left(4\pi D^2 F_{0.3-30}\right)/\dot{E}$.

Table 1 list the VHE energy fluxes and apparent efficiencies for the seven well-established VHE PWNe in which the pulsar has been detected and timed. The fluxes $F_{0.3-30}$ were obtained by integration of the best-fit spectral model given in the references above. The pulsar parameters $\dot{E}$ and D were obtained from the ATNF Pulsar Catalogue [15], version 1.25, using the NE2001 model of the Galactic free electron distribution for the distance [16]. For Kes 75, a distance of 19 kpc has been estimated based on HI absorption measurements.

The apparent efficiency reflects the true efficiency only to the extent that the emitting particles' lifetimes are short compared with the evolutionary time scale of the PWN. In general the VHE-emitting electrons may have been injected in the early phases of the PWN evolution, when the pulsar's $\dot{E}$ was larger, so that the apparent efficiency overestimates the true efficiency [13].

Possible associations with known pulsars

Besides HESS J1825–137, two other VHE sources discovered in the initial H.E.S.S. survey of the Galactic plane may be associated with energetic pulsars [10]. Near the edge of the bright source HESS J1616–508 is PSR J1617–5055, an X-ray emitting young pulsar with a period of 69 ms. One of the brightest and largest sources discovered in the Galactic plane survey, HESS J1804–216, contains the young and energetic pulsar B1800–21. Although HESS J1303–631, the first unidentified source discovered by H.E.S.S., has no established counterpart, it does coincide with the energetic pulsar J1301–6305 [18]. One additional possible association is with HESS J1702–420 discovered in the Galactic plane survey [17]. The nearby pulsar J1702–4128 would require a high but not impossible efficiency to power the entire H.E.S.S source.

Two additional VHE PWN candidates have recently been discovered in the H.E.S.S. survey data [19]. HESS J1718–385 extends south from the position of the Vela-like pulsar J1718–3825, and exhibits a spectrum peaked in the VHE gamma-ray domain like that of Vela X. Although there is no morphological correspondence to any PWN detected at other wavelengths, the spectrum and the lack of other plausible counterparts make HESS J1718–385 a good VHE PWN candidate. HESS J1809–193 similarly extends to the southwest of the energetic pulsar J1809–1917; the existence of a diffuse X-ray nebula south of this pulsar makes the identification of HESS J1809–193 as a VHE PWN plausible, but other associations are possible, in particular with two SNRs [20]. The most recently detected VHE PWN candidate is HESS J1912+101, which coincides with the energetic pulsar J1913+1011 [22]; there is no detected PWN around this pulsar at other wavelengths, however.

Table 2 summarises the VHE energy fluxes and required efficiencies for these candidate associations, in decreasing order of the pulsar's $\dot{E}/D^2$; the numbers were derived in the same manner as in Table 1. In almost every case the pulsar is significantly offset from the centre of the VHE source, but as was seen above, this seems to be typical of older VHE PWNe. Deeper VHE or longer wavelength observations would be needed in order to individually establish any of these candidate associations. Nonetheless, a statistical population study shows that the number of expected chance coincidences between high spin-down luminosity pulsars and detected VHE sources is small [21], suggesting that many of these candidates must be real associations.

TABLE 2. Required efficiencies for VHE PWN candidates

VHE source	$F_{0.3-30}$ *	PSR name	ε
HESS J1616–508	3.7×10^{-11}	J1617–5055	1%
HESS J1804–216	2.9×10^{-11}	B1800–21	2%
HESS J1809–193	2.8×10^{-11}	J1809–1917	2%
HESS J1912+101	1.8×10^{-11}	J1913+1011	2%
HESS J1718–385	4.3×10^{-12}	J1718–3825	0.5%
HESS J1303–631	2.3×10^{-11}	J1301–6305	7%
HESS J1702–420	1.4×10^{-11}	J1702–4128	11%

* in units of erg cm^{-2} s^{-1}

Possible VHE PWNe with undetected pulsars

The example of the composite SNR G 0.9+0.1 shows that H.E.S.S.-discovered sources can be associated with PWNe even if the corresponding pulsar has not been detected. VHE gamma-ray emission from G 0.9+0.1 was discovered in deep H.E.S.S. observations of the Galactic Centre region. The observed gamma-ray excess is well described as a point-like source at a position consistent with that of the plerion [23]. The upper limit derived on the intrinsic source extension, using the precise point spread function of H.E.S.S., argues for the plerion rather than the shell as the source of the VHE emission.

Another possible such association is with HESS J1813–178; this relatively compact VHE source was discovered in the Galactic plane survey [10], and subsequently found to be coincident with a shell-type radio SNR, G 12.82–0.02, and a bright, non-thermal, hard X-ray source [24]. The angular resolution of H.E.S.S. or of the available X-ray data could however not discriminate between the shell and a possible embedded PWN as the source of the respective emission. Recent X-ray observations show strong evidence for a PWN origin of the X-ray emission, establishing the composite nature of G 12.82–0.02 and suggesting the possibility of a PWN origin for the VHE emission [25, 26].

A similar case is that of HESS J1640–465, another source discovered in the Galactic plane survey, coincident with the previously known SNR G 338.3–0.0 [17]. Recent *XMM-Newton* observations also revealed a non-thermal nebula inside the SNR shell, indicating a composite nature for G 338.3–0.0, with the possibility that the VHE emission originates in the PWN [27]. As a final example, one of the potential counterparts suggested for the Galactic survey source HESS J1634–472 was the radio SNR candidate G 337.2+0.1, coincident with an X-ray source detected by *ASCA*. A recent hard X-ray observations of this region shows evidence for a PWN origin of the X-ray emission [28] and raises the possibility of a PWN association for the VHE emission.

SUMMARY AND PROSPECTS

Of the VHE gamma-ray sources detected by H.E.S.S., nine have fairly well-established PWN counterparts, not including the VHE emission associated with PSR B1259–63. These currently constitute the most numerous class of identified Galactic VHE gamma-ray sources. Several of these VHE-emitting PWNe exhibit a large physical extent and are significantly offset from the pulsar position; one possible explanation is that these are older PWNe strongly affected by the passage of an asymmetric reverse shock in the parent SNR.

In a leptonic interpretation of the VHE emission, the target photons for IC scattering have an approximately known and uniform density in individual PWNe, which allows direct inference of the *spectral* and *spatial* distribution of the energetic electrons, in contrast to observations of synchrotron emission at lower energies. VHE observations can thus be used to infer pulsar pair production multiplicities [29], although significant uncertainties remain in the extrapolation to lower energies. VHE gamma-ray astronomy thus provides a new, independent observational window into the physics of PWNe.

Given smoothly varying Galactic target photon densities and the uniform target density provided by the CMB, a survey in VHE gamma-rays should reveal all sufficiently intense Galactic sources of high-energy electrons. Seven more VHE sources discovered by H.E.S.S. may be associated with known energetic pulsars, and three additional sources are coincident with possible PWNe with undetected pulsars. More observations of these sources in VHE gamma-rays and at other wavelengths are necessary to study the possibility of these associations. PWNe may yet prove to constitute the fastest-growing class of identified Galactic gamma-ray sources.

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