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Frank Mittelbach
November 10, 2008

Contents
**Pulsar Wind Nebula candidates recently discovered by H.E.S.S.**

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Abstract.

H.E.S.S. is currently the most sensitive instrument in the very-high-energy (VHE; \( E > 100 \text{ GeV} \)) gamma-ray domain and has revealed many new sources along the Galactic Plane, a significant fraction of which seems to be associated with energetic pulsars. HESS J1825-137 and Vela X are considered to be the prototypes of such sources in which the large VHE nebula results from the whole history of the pulsar wind and the supernova remnant host, both evolving in a complex interstellar medium. These nebulae are seen to be offset from the pulsar position and, for HESS J1825-137, a spectral steepening at increasing distance from the pulsar has been measured. In this context, updated H.E.S.S. results on two previously published sources, namely HESS J1809-193 and HESS J1912+101, and preliminary results on the newly discovered HESS J1356-645, are presented. These extended VHE sources are thought to be associated with the energetic pulsars PSR J1809-1917, PSR J1913+1011 and PSR J1357-6429, respectively. Properties of each source in the VHE regime, together with those measured in the radio and X-ray domains, are discussed.

Keywords: Astronomical Observations: \( \gamma \)-ray – Late stages of stellar evolution: Pulsars
PACS: 95.85.Pw, 97.60.Gb

**INTRODUCTION**

The recently opened astronomical window at VHE energies, with the help of the latest generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) such as H.E.S.S. (High Energy Stereoscopic System), has led to the discovery of more than 70 sources [1]. Among the about 50 Galactic objects [2] and besides the well-known shell-type supernova remnants (SNRs) RX J1713.7-3946, RX J0852-4622 and RCW 86, a significant fraction seems to be associated with energetic pulsars. These objects can generate bubbles of relativistic particles and magnetic field when their ultra-relativistic wind interacts with the surrounding medium (SNR or interstellar medium, hereafter ISM) (see [3, 4] for recent reviews). 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 synchrotron emission from radio to hard X-rays, and through the inverse Compton process and potentially \( \pi^0 \) decay from p-p interactions [5], in the VHE domain.

On one hand, recent advances in the study of pulsar wind nebulae (PWNe) have been made with the wealth of radio and X-ray observations, revealing the complex morphology of these sources at the arcsecond scale [3]. On the other hand, complementary VHE observations of these PWNe allow the spectrum of accelerated particles to be probed and to investigate the associated magnetic field distribution (see [6] for a recent discussion in this regard). 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. The discovery of VHE gamma-rays from HESS J1825-137 [7] and Vela X [8], both offset from their respective pulsars, confirm predictions [9, 10, 11] that anisotropic reverse shocks and/or high pulsar velocity can lead to the formation of a relic PWN, presumably emitting in the VHE domain.

In this contribution, updated H.E.S.S. results on two published sources, namely HESS J1809-193 and HESS J1912+101, are presented. Preliminary results on the newly discovered HESS J1356-645 are also shown. Standard quality selection criteria (see e.g. [12]) were applied for each data set, background modelling was performed according to the methods discussed in [13], and imaging and spectral results on each source were cross-checked through two independent data analyses, namely the Hillas [14] and Model 2D [15] methods. These three sources are thought to be associated with pulsars PSR J1809-1917, PSR J1913+1011 and PSR J1357-6429, respectively, and their properties as offset VHE PWN candidates are then discussed.
HESS J1809-193

HESS J1809-193 was initially discovered during the systematic search for VHE emission from pulsars in the Galactic Plane Survey performed with H.E.S.S. [16]. PSR J1809-1917, with a characteristic age $\tau_c$ of 51 kyr and a spin-down power $\dot{E}$ of $1.8 \times 10^{36}$ erg s$^{-1}$, was considered as the most likely counterpart. Since the original discovery, new data were taken and the total livetime now amounts to 41 hours (versus 25 hours before). Figures 1 and 2 show the updated H.E.S.S. image of the smoothed excess counts centered on HESS J1809-193 and its spectrum measured between 300 GeV and 30 TeV, respectively. General information on the source, in relation to PSR J1809-1917, is summarized in Table 1.

As discussed in [16], the region around HESS J1809-193 contains several candidates for TeV emission. Besides PSR J1809-1917, SNR candidates recently revealed in radio [17, 18] lie within the VHE source extent. These SNRs may contribute to the VHE emission observed by H.E.S.S. However, the discovery of large-scale ($\sim 6'$) X-ray emission, surrounding the compact PWN associated with PSR J1809-1917, and extending toward the VHE centroid [19, 20], strengthens the scenario of a relic PWN crushed due to an inhomogeneous SNR interior [9]. Then, HESS J1809-193 seems to share several similarities with firmly established VHE PWNe such as HESS J1825-137 [7]. Deeper radio observations could detect the synchrotron emission from this potential relic nebula.

HESS J1912+101

HESS J1912+101 was discovered during the continuation of the H.E.S.S. Galactic Plane Survey [21]. The VHE source, with a post-trials significance of 5.5 $\sigma$ for a livetime of 21 hours, is fairly extended (intrinsic Gaussian width of $0.26 \pm 0.03^\circ$), as shown in Figure 3. Its spectrum (Figure 4) is well fitted with a power law with spectral index of $2.7 \pm 0.2$.

As discussed in [21], the region around HESS J1912+101 contains several candidates for TeV emission. Besides PSR J1912+1017, SNR candidates recently revealed in radio [17, 18] lie within the VHE source extent. These SNRs may contribute to the VHE emission observed by H.E.S.S. However, the discovery of large-scale ($\sim 6'$) X-ray emission, surrounding the compact PWN associated with PSR J1809-1917, and extending toward the VHE centroid [19, 20], strengthens the scenario of a relic PWN crushed due to an inhomogeneous SNR interior [9]. Then, HESS J1809-193 seems to share several similarities with firmly established VHE PWNe such as HESS J1825-137 [7]. Deeper radio observations could detect the synchrotron emission from this potential relic nebula.
HESS J1356-645

Preliminary results on the newly discovered source HESS J1356-645 are here presented. The livetime of the observations amounts to 10 hours, which leads to the detection of a $\sim 8.5 \sigma$ (post-trials, see [12]) extended source, as shown in Figure 5. A power law fit of its spectrum (see Figure 6) gives a spectral index of $2.2 \pm 0.2$ and an integral flux between 1 and 10 TeV of about 11% of that of the Crab Nebula in the same energy band.

Since HESS J1356-645 is located at $\sim 2.5^\circ$ below the Galactic Plane, the identification of counterparts is easier than for the two previous sources. The only potential counterpart known is the recently discovered young ($\tau_c = 7.3$ kyr) and energetic ($\dot{E} = 3.1 \times 10^{36}$ erg s$^{-1}$) 166 ms pulsar PSR J1357-6429 [22], lying only $\sim 0.11^\circ$ from the VHE centroid. General results from Chandra and XMM-Newton observations were reported in [23, 24]. Marginal evidence of diffuse X-ray emission around the pulsar was found [24]. HESS J1356-645 is coincident with extended radio emission at 2.4 GHz, originally catalogued as an SNR candidate (G309.8-2.6, [25]). The inspection of archival public radio images from the Molonglo Galactic Plane Survey at 843 MHz (MGPS-2 [26]) and from the Parkes-MIT-NRAO (PMN) survey at 4.85 GHz [27] has revealed an extended structure which, although faint, appears coincident with the observed VHE emission as well. A study of the radio spectral index from these three images is on-going and could help to constraint the nature of HESS J1356-645.
TABLE 1. Characteristics of the three H.E.S.S. sources discussed here. Positions (with statistical errors of $\sim 2\arcmin$ for each axis) and intrinsic source rms were obtained after fitting with a 2D symmetric Gaussian. The offset is between the centroid of the VHE emission and the associated pulsar. $L_{1-10\text{TeV}}/\dot{E}$ denotes the efficiency as the ratio of the $\gamma$-ray luminosity of the VHE source to the pulsar spin-down power. Properties of the three pulsars were taken from the online ATNF Pulsar Catalogue (version 1.33). Distance estimates given below (in units of kpc) were calculated according to the Galactic electron distribution model of Cordes & Lazio [28]. The uncertainties shown in parentheses are statistical errors only. Systematic errors on spectral indexes are typically 0.2.

| H.E.S.S. source | R.A. (J2000) | Dec. (J2000) | Source rms (deg.) | Offset (deg.) | Norm(1 TeV) (cm$^{-2}$s$^{-1}$TeV$^{-1}$) | Slope | $L_{1-10\text{TeV}}/\dot{E}$ (%) |
|----------------|-------------|-------------|-------------------|--------------|-----------------------------|-------|--------------------------|
| J1809-193      | 18$^{h}$09$^{m}$52$^{s}$ | -19$^{\circ}$23$^{\prime}$42$^{\prime\prime}$ | 0.25(0.02) | 0.11(0.02) | 6.4(3.0)$\times$10$^{-12}$ | 2.23(0.05) | 1.5(0.8)$\times$d$^{-2}$ |
| J1912+101      | 19$^{h}$12$^{m}$49$^{s}$ | 10$^{\circ}$09$^{\prime}$06$^{\prime\prime}$ | 0.26(0.03) | 0.15(0.05) | 3.5(0.6)$\times$10$^{-12}$ | 2.7(0.2) | 0.5(0.2)$\times$d$^{-2}$ |
| J1356-645      | 13$^{h}$56$^{m}$00$^{s}$ | -64$^{\circ}$30$^{\prime}$00$^{\prime\prime}$ | 0.22(0.02) | 0.11(0.03) | 2.7(0.9)$\times$10$^{-12}$ | 2.2(0.2) | 0.2(0.1)$\times$d$^{-2}$ |

DISCUSSION

The main characteristics of the three H.E.S.S. sources, in relation with their respective pulsars, are summarized in Table 1. The most uncertain pulsar-VHE association is certainly that between PSR J1913+1011 and HESS J1912+101, since no X-ray emission has been found neither from the pulsar itself nor from any putative PWNe. For the two others, indications of such an association exist, through the extended X-ray emission towards HESS J1809-193, and through the extended radio structure coincide with HESS J1356-645. The VHE efficiencies of these three H.E.S.S. sources are of the same order as that measured in other VHE PWNe, i.e. around one percent. This qualitative argument shows that these pulsars are energetic enough to power the observed VHE extended sources, thought to be the relic PWNe probing their past evolution. Deeper follow-up observations, mainly in radio and X-rays, are necessary in order to reveal the nature of these sources. As discussed in [1], PWNe have now emerged as the largest population of galactic VHE sources. The three H.E.S.S. sources presented here will certainly benefit population studies [29, 30], which may provide new insights on these complex sources.

ACKNOWLEDGMENTS

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the U.K. Science and Technology Facilities Council (STFC), the IPNP of the Charles University, the Polish Ministry of Science and Higher Education, the South African Department of Science and Technology and National Research Foundation, and by the University of Namibia. We appreciate the excellent work of the technical support staff in Berlin, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment.

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