Detection of very-high-energy γ-ray emission from the vicinity of PSR B1706−44 with H.E.S.S.

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***Abstract*. The high spin-down luminosity pulsar PSR B1706−44 together with the adjacent supernova remnant candidate G343.1−2.3 have been observed by H.E.S.S. in dedicated observations in 2007. A new source of very-high-energy (VHE; E > 100 GeV) γ-ray emission was detected in these observations with its centroid at $\alpha_{2000} = 17^h 8^m 10^s$ and $\delta_{2000} = -44°21'$, with a statistical error of 3′ on each axis (HESS J1708−443). The VHE γ-ray source is significantly more extended than the H.E.S.S. point spread function, with an intrinsic Gaussian width of 0.29°±0.04°. Its energy spectrum can be described by a power law with a photon index of $\Gamma = 2.0 \pm 0.1_{\rm stat} \pm 0.2_{\rm sys}$. The integral flux measured between 1−10 TeV is ∼17% of the Crab Nebula flux in the same energy range.**

***Keywords*: HESS J1708−443, PSR B1706−44, G 343.1−2.3**

I. Introduction

The pulsar PSR B1706−44 was first detected in a high-frequency radio survey by Johnston et al. [25]. With a spin period of 102 ms, a characteristic age of 17,500 years and a spin-down luminosity of $3.4 \cdot 10^{36}$ erg s^{-1}, it belongs to the class of relatively young and very energetic pulsars. Its distance estimate ranges from 1.8 kpc ([25], [36]) to 3.2 kpc [29]. The positionally-coincident γ-ray source 2CG342−02 [35] was firmly identified as PSR B1706−44 when the EGRET instrument observed pulsation with a period also seen in the radio waveband [37]. PSR B1706−44 is therefore one of the very first pulsars from which pulsed emission was detected not only in radio [25] and X-rays [22], but also in high-energy γ-rays.

PSB B1706−442 is surrounded by a synchrotron nebula with an extension of 3′ at radio wavelengths ([19], [21]). The observed polarization and the flat spectrum of the radio emission (with a photon index of 0.3) suggest a pulsar wind nebula (PWN) origin. The synchrotron nebula is also visible in X-rays, first reported by Finley et al. [17] using the ROSAT satellite. Employing the superior resolution of the Chandra satellite, Romani et al. [32] were able to map the morphology of the PWN at the arcminute scale. Their findings suggest a diffuse PWN with a spectral index of 1.77, surrounding a more complex structure comprising a torus and inner and outer jets. The diffuce PWN has a radius of ∼110″ and exhibits a fainter, longer extension to the West. The non-deformed X-ray jets support the low scintillation velocity of the pulsar of less than 100 km/s as reported by Johnston et al. [26].

PSR B1706−44 is located at the southeast end of an incomplete arc of radio emission [31] suggested to be the shell of a faint supernova remnant (SNR) (G 343.1−2.3). The arc itself is embedded in weak, broad-scale radio emission [19] for which polarization measurements suggest an association with synchrotron radiation from the SNR [16]. No X-ray emission was detected from the radio structure (see e.g. [10]). The question of a possible association between PSR B1706−44 and G 343.1−2.3 could not be answered unambiguously so far. The dispersion distance for the pulsar of 2.3 ± 0.3 kpc ([32] and references therein) using the electron distribution model by Cordes and Lazio [14] is compatible with the $\Sigma - D$ distance of ∼3 kpc for the SNR [31]. However, the off-center position of the pulsar relative to the radio-arc implies a rather high proper motion velocity (∼700 km/s) which is incompatible with the measured scintillation velocity. Bock et al. [12] suggested a scenario of an off-centered cavity explosion which would release the restrictions on the implied velocity and invalidate the age estimate for the SNR of 5000 years [31], which is based on a Sedov-Taylor model. In this scenario, the radio arc is identified with the former boundary of the wind-blown cavity that was overtaken and compressed by the expanding SNR. The diffuse, broad-scale radio emission would then result from the interaction of the SNR with the parent molecular cloud.

At very-high energies (VHE; E > 100 GeV), the region of interest was observed using ground-based air-Cherenkov instruments. The CANGAROO experiment reported the detection of steady emission coincident with the pulsar. The measured flux was at a level of 50% of the Crab Nebula flux ([28], [30]). The H.E.S.S. collaboration—operating only two telescopes at the time, without a stereo trigger on the hardware level—did not

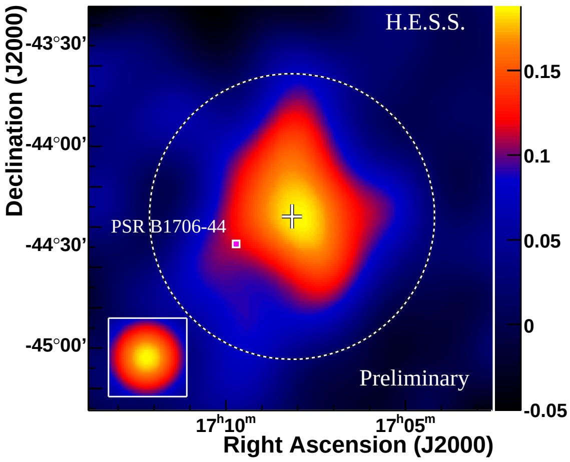

Fig. 1. Image of the VHE γ-ray excess from HESS J1708−443, smoothed with a Gaussian profile of $\sigma = 0.15°$along each axis. The white cross indicates the best fit position of the center-of-gravity of the emission together with its statistical errors. The white circle illustrate the region which was used for spectral analysis. The position of the pulsar PSR B1706−44 is marked by a square. The inset in the bottom left corner shows the point-spread function of the instrument for this particular data set smoothed in the same way as the excess map.

detect any significant VHE γ-ray emission from the vicinity of the PSR B1706−44/G 343.1−2.3 complex but derived flux upper limits as low as 1% (5%) of the Crab Nebula flux for the pulsar (SNR), in clear disagreement with the previous findings [1]. In 2007, additional data was taken on the pulsar, now utilizing the superior sensitivity of the fully-operational H.E.S.S. telescope array. Here we present the findings of this observation campaign. No point-like emission is detected at the pulsar position. However, an extended source of VHE γ-rays was detected in the region of interest. Its centroid position appears significantly displaced from the pulsar position, in contrast to the original findings of the CANGAROO collaboration. The now measured flux exceeds the previously published upper limits [1], but is still below the original CANGAROO claim ([28], [30]). A re-analysis of the old H.E.S.S. data set (originally published in [1]), using the up-to-date H.E.S.S. standard analysis framework, however, results in flux upper limits consistent with the currently detected flux.

II. The H.E.S.S. detector / analysis technique

The High Energy Stereoscopic System (H.E.S.S.) is an array of four, imaging atmospheric Cherenkov telescopes, dedicated to the observation of VHE γ-rays. The array is located in the Khomas Highlands of Namibia (23°16'17" S, 16°29'58" E). Each telescope is equipped with a tessellated, spherical mirror of 107 m^2 area and a camera comprised of 960 photomultiplier tubes, covering a field-of-view 5° in diameter. The telescopes are operated in coincidence mode, which requires a trigger of at least two telescopes for an air shower to be recorded. The stereoscopic approach allows a high angular resolution of $< 0.1°$ per event, a good energy resolution of 16% (on average) and an effective background rejection [3]. The H.E.S.S. array can detect point sources at flux levels of about 1% of the Crab Nebula flux near zenith with a statistical significance of $5\,\sigma$ in 25 hours of observations. Its large field-of-view and a good off-axis sensitivity make it ideally suited for studies of extended sources.

The region of interest, which includes PSR B1706−44 and the SNR G 343.1−2.3, was observed with the full H.E.S.S. telescope array in 2007. The observations were dedicated to search for VHE γ-ray emission from the pulsar and were therefore taken in *wobble* mode, centered at its radio position ($\alpha_{2000} = 17^h 9^m 42.73^s$, $\delta_{2000} = -44°29'8.2''$, [38]). In this observation mode, the array is pointed towards a position offset from the source of interest to allow for simultaneous background estimation.

The data set was analyzed using the Hillas second-moment method, as described by Aharonian et al. (H.E.S.S. Collaboration) [3]. For gamma-hadron separation, the so-called *hard cuts* were used, which require a minimum of 200 photon electrons (p.e.) recorded per shower image. Compared to *std cuts* (80 p.e.), this relatively hard requirement results in better background rejection and an improved angular resolution, but also in a slightly increased energy threshold of 560 GeV for this data set. The time-dependent optical response of the system was estimated from the Cherenkov light of single muons passing close to the telescopes [13].

III. Results

Figure 1 shows the excess count map of the $2° \times 2°$ region around the source smoothed with a Gaussian profile of width 0.15° to reduce statistical fluctuations. A clear excess of VHE γ-rays is observed with a peak statistical significance of 7.5 σ using an integration radius of $\theta = 0.4°$. Fitting the fine-binned and unsmoothed excess map with a radially symmetric Gaussian profile ($\phi = \phi_0 e^{-r^2/(2\sigma^2)}$) convolved with the point-spread function of the instrument leads to a best fit position of $\alpha_{2000} = 17^h 8^m 10^s$ and $\delta_{2000} = -44°21'$, with a statistical error of $3'$ on each axis, as indicated by the white cross in Figure 1. Consequently, the new VHE γ-ray source is called HESS J1708−443. The fit results in an intrinsic Gaussian width of $0.29° \pm 0.04°_{\rm stat}$.

A preliminary differential energy spectrum was determined within a circular region of 0.71° radius (indicated by a dashed circle in Fig. 1), chosen as a compromise between optimal signal-to-noise ratio and independence of source morphology. Within this region, 605 excess events were found, corresponding to a statistical significance of $6.7\,\sigma$ (pre-trials). The spectrum is well-described by a power law $\phi = \phi_{\rm 1TeV} \cdot E^{-\Gamma}$ with a spectral index of $\Gamma = 2.0 \pm 0.1_{\rm stat} \pm 0.2_{\rm sys}$ and a flux normalization at 1 TeV of $\phi_{\rm 1TeV} = (4.2 \pm 0.8_{\rm stat} \pm 1.0_{\rm sys}) \cdot 10^{-12}\,{\rm cm^{-2} s^{-1} TeV^{-1}}$. The integral flux between 1 and 10 TeV is about 17% of the Crab Nebula

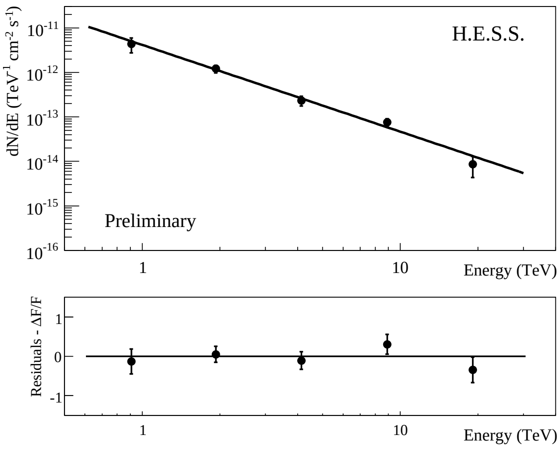

Fig. 2. Differential energy spectrum of HESS J1708−443, extracted from the circular region indicated in Fig. 1. The solid line shows the result of a pure power-law fit. The error bars denote 1-σ statistical errors; the bottom panel shows the residuals of the power law fit. Events with energies between 600 GeV and 28 TeV were used in the determination of the spectrum.

flux in the same energy range. The extracted flux points from the extended emission and the fitted power law are shown in Fig. 2.

IV. The Origin of the TeV emission

While a superposition of multiple sources cannot be excluded, each of the following objects could individually account for the observed VHE γ-ray emission.

A. A relic nebula from PSR B1706−44

With its high spin-down luminosity of $3.4{\cdot}10^{36}\,\mathrm{erg\,s^{-1}}$, the pulsar PSR B1706−44 is energetic enough to power the observed VHE γ-ray emission. Assuming a distance of 2.5 kpc for the pulsar, the energy flux from the H.E.S.S. source between 1 and 10 TeV is $1.2{\cdot}10^{34}\,\mathrm{erg\,s^{-1}}$. The implied apparent effective conversion efficiency from rotational energy to γ-rays in this energy range is then ∼0.4%, comparable to the efficiency of 0.8% inferred for PSR J1420−6048 [4]. This suggests the pulsar's wind nebula as a possible origin of the observed VHE γ-ray emission, similar to other PWN associations such as Vela X [5] and HESS J1825−137 [6]. In this scenario, the VHE γ-emission originates from accelerated electrons which up-scatter ambient photons to VHE energies (leptonic scenario).

The larger size of the TeV PWN compared to the 'bubble' nebula as seen in X-rays (radius $\sim 110''$) [32] can usually be explained by the different energies, and hence cooling times, of X-ray emitting and VHE γ-ray emitting electrons; such differences in size have already been observed in other PWN associations such as HESS J1825−137 [6]. However, in contrast to the PWN of PSR J1826−1334, where a magnetic field strength of $10\,\mu$G was inferred from X-ray observations [20], Romani et al. [32] estimated a magnetic field as strong as $140\,\mu$G within the $\sim 110''$ X-ray PWN of PSR B1706−44. In such high magnetic fields, electrons that emit keV X-rays and those that emit TeV γ-rays have comparable energies and hence comparable cooling times. Thus, the TeV PWN should appear almost point-like on the $5'$scale of the point-spread function of the H.E.S.S. instrument. Furthermore, given that the ratio of X-ray to VHE γ-ray energy flux ($dN/dE \cdot E^2$) is determined by the energy density in magnetic fields and Inverse Compton (IC) target photon fields (consider here only the CMB), the detected X-ray flux of $2.7{\cdot}10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ at 1.7 keV predicts a γ-ray flux of $1.4{\cdot}10^{-16}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ at 1.7 TeV, well below the level observable by H.E.S.S.

One way to reconcile the difference in size of the emission regions and the high flux level of the VHE emission is to assume that the size of the X-ray PWN is essentially governed by the extent of the high-field region, and that the magnetic field falls off by a large factor outside the X-ray PWN. Then, electrons can escape from the high-field region and—by accumulation over a significant fraction of the lifetime of the pulsar—form a larger nebula only visible in VHE γ-rays.

This scenario still does not explain the asymmetry of the VHE γ-ray nebula with respect to the pulsar location. Such asymmetries were observed before in other TeV PWNs, e.g. HESS J1718−385, HESS J1809−193 [9] and HESS J1825−137 ([2], [6]). They were explained either by the proper motion of the pulsar or by a density gradient within the ambient medium that either causes an asymmetry in the reverse shock of the original supernova or different expansion velocities of the TeV-emitting electrons ([11], [34]); in some of the simulations of Swaluw et al. [34], the displaced PWN is well-separated from its pulsar. Both explanations are in principle applicable in this situation. However, the measured scintillation velocity of less than 100 km/s for the pulsar renders the former explanation unlikely. The latter explanation would favor a displacement of the TeV PWN towards a low-density region, contrary to the observed offset, which brings the PWN closer to the higher density region of the Galactic Plane. It should be noted that a local density gradient, e.g. directly at the position of the pulsar, could affect the spatial distribution of the TeV PWN.

In this discussion it was assumed that the pulsar dominantly accelerates electrons. If a considerable fraction of the accelerated particles are hadrons, as discussed by Horns et al. [24], the constraints imposed by the large magnetic field within the X-ray PWN are removed. The TeV emission would then originate from π^0 meson decay produced in inelastic interactions of accelerated protons with ambient gas (hadronic scenario), and the VHE γ-ray emission would trace the distribution of the target material. The bright radio arc, which was interpreted by Bock et al. [12] as the compressed outer boundary of the former wind blown bubble, could act as such a region of enhanced target material density, which would explain its coincidence with the H.E.S.S. source.

B. SNR G 343.1−1.3

The H.E.S.S. source is partially coincident with the bright radio arc and the surrounding diffuse emission of the SNR, visible in the 1.4 GHz observations taken with the ATCA instrument [16]. The best-fit position of the H.E.S.S. source is consistent with the apparent center of the bright radio arc ($\alpha_{2000} = 17^h 8^m$ and $\delta_{2000} = -44^\circ 16' 48''$). However, due to low statistics in the VHE data, no further conclusions can be made about morphological similarities.

Similar to the potential association with the PWN of PSR B1706−44, both, leptonic and hadronic scenarios for VHE γ-ray production have to be considered. The leptonic scenario suffers from the non-detection of the SNR at X-ray energies. The VHE γ-ray spectrum reaches as far 20 TeV. Assuming IC scattering in the Thompson regime, the energy of the electrons upscattering CMB photons up to 20 TeV have an energy of roughly 80 TeV. For a reasonable magnetic field strength of 5 μG, such electrons would emit synchrotron photons with an energy of $\sim$1 keV, i.e. within the detectable energy range of current X-ray instruments. However, no stringent upper limit on the X-ray flux from within the H.E.S.S. source can be derived due to the vicinity of the luminous low-mass X-ray binary 4U 1705−440, whose stray light might bury any diffuse X-ray emission from the SNR.

In the hadronic scenario, where synchrotron radiation is expected only from secondary electrons, the lack of X-ray detection can easily be accounted for. In this scenario, the total energy within the whole proton population can be estimated to $W_{\rm P}(\rm tot) \approx 3.9 \times 10^{49} \rm erg \left(\frac{n}{cm^{-3}}\right)^{-1} \left(\frac{D}{kpc}\right)^2$, following the approach described in [23] (the proton spectrum was assumed to follow a power law with a spectral index of $\alpha = 2$ down to 1 GeV). For a total energy of 10^{51} erg released in the supernova explosion, an acceleration efficiency of $\epsilon = 0.15$ and a distance of 2.5 kpc, the necessary average proton density is $\rm n \sim 1.6\,cm^{-3}$, only slightly larger than the average Galactic ambient density.

However, an association of SNR G 343.1−2.3 with the pulsar PSR B1706−44, a scenario debated in the literature, (see e.g. [12], [32]), would make the SNR rather old (on the order of 10,000 years) and place it in the late Sedov-Taylor, or more likely, in the radiative phase. In this scenario, the SNR would be older than SNRs from which shell-morphology γ-ray emission has been unambiguously detected, such as RX J1713.7−3946 [7] and RX J0852.0−4622 [8] ($\sim$2000 years).

V. Summary

H.E.S.S. observations have led to the detection of a new VHE γ-ray source HESS J1708−443. The γ-ray signal is extended, but the exact morphology of the emission region is still under study. The flux from the source is $\sim 17\%$ of the Crab Nebula flux, but with a harder spectral index of 2.0. The possible associations of HESS J1708−443 with a relic PWN of PSR B1706−44 and the SNR G 343.1−2.3 have been discussed. Even though a possible association of the SNR with the pulsar PSR B1706−44 suggests that the SNR is in a later evolutionary stage than other previously-detected VHE SNRs, there is at present no ground to favor either of these two possible associations with the H.E.S.S. source.

VI. Acknowledgments

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