Discovery of very-high-energy $\gamma$-ray emission from the vicinity of PSR J1831-952 with H.E.S.S.

F. Sheidaei

Unit for Space Physics, North-West University, Potchefstroom 2520, South Africa, Astroparticule et Cosmologie (APC), CNRS, Université Paris 7 Denis Diderot, 10, rue Alice Domon et Léonie Duquet, F-75205 Paris Cedex 13, France

A. Djannati-Ataï

Astroparticule et Cosmologie (APC), CNRS, Université Paris 7 Denis Diderot, 10, rue Alice Domon et Léonie Duquet, F-75205 Paris Cedex 13, France

&. H. Gast

Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany

For the HESS Collaboration

We report on the latest discovery of an extended Very High Energy (VHE) $\gamma$-ray source near the 67 ms pulsar PSR J1831-0952 during the H.E.S.S. Galactic Plane Survey (GPS). The dispersion measure distance of the pulsar (4.3 kpc) would imply that less than $\sim 1\%$ of its spin-down energy is required to provide the observed VHE luminosity of the source. No other plausible counterparts have yet been found through preliminary multi-wavelength searches. The most likely scenario is that the VHE emission originates from the – yet unseen at other wavelengths – wind nebula of PSR J1831-0952. If so this would constitute another case of a $\gamma$-ray discovered pulsar wind nebula.

I. OBSERVATIONS AND ANALYSIS

The H.E.S.S. (High Energy Stereoscopic System, an array of four imaging atmospheric Cherenkov telescopes located in the Khomas Highland in Namibia) has revealed more than 60 sources of very-high-energy (VHE) $\gamma$-rays through its Galactic Plane Survey (GPS) since 2004. Thanks to the use of advanced multivariate analysis techniques and the accumulation of exposure, H.E.S.S. has achieved a sensitivity of better than 2% of Crab in the core region of the GPS (i.e. $l = 282^{\circ}$ to $60^{\circ}$) [1]. Pulsar Wind Nebulae (PWNe) constitute by far the dominating source population as compared to that of young shell-type Supernova Remnants (SNRs), or to that of older and/or interacting remnants. About one third of H.E.S.S. sources have still either no known counterparts in other wave-lengths, or lack any clear emission scenario.

The data on HESS J1831-098 consist of observations either dedicated to nearby sources such as SNR 21.5-0.9/HESS J1833-105, or from the extension of H.E.S.S GPS near $l = 21^{\circ}$. These data were taken in 2004 (May-Oct.), 2005 (June and July), 2007 (Apr.-July), and 2009 (Apr.-July), for a total observation time on HESS J1831-098 of $\sim 52$ hours. After application of the H.E.S.S. standard data quality criteria [2] based on hardware and weather conditions, the data set for HESS J1831-098 amounts to a total live-time of 40 hours with average zenith angle and average offset (to the FoV center) of $22.8^{\circ}$, and $1.30^{\circ}$, respectively. The mean offset is rather large because observations were not specifically targeted at this source.

The standard Hillas H.E.S.S. event reconstruction scheme was applied to the data after calibration[3]. The rejection of cosmic-ray showers was done by application of a recently developed multivariate analysis [4]. The sky maps were produced with an image size cut of 80 photo-electrons (p.e.) and using the Ring Background method [5] where the background at each test position on the sky is derived from a ring surrounding it with a mean radius of $0.7^{\circ}$. To derive the spectrum, the same cut on image size was applied together with the a Reflected-Region procedure to estimate the Background, followed by the application of a forward-folding method[6].

II. RESULTS

The excess count map of the $0.4^{\circ} \times 0.4^{\circ}$ region around HESS J1831-098 is shown on Figure 1. The map is smoothed with a Gaussian of $\sigma \sim 0.12^{\circ}$. An extended $\gamma$-ray emission to the south-east of PSR J1831-0952 is observed with a peak pre-trials significance of $7.9\sigma$ for the standard integration radius of $\theta = 0.22^{\circ}$, used for generation of the GPS maps when searching for extended sources. The significance level of the source after a conservative correction for trials is $5.8\sigma$. The fit of the excess map with a two dimensional symmetrical Gaussian function, convolved with the H.E.S.S Point-Spread Function (PSF), results in a source centroid position of $\alpha \sim 18^{h}31^{m}25^{s}, \delta \sim -9^{\circ}54^{\prime}$, with a width of $\sigma \sim 0.15^{\circ}$ and a $\chi^2$ of 593.4/525. The fit of an asymmetrical Gaussian function does not improve significantly the $\chi^2$ nor the
FIG. 1: The excess map for HESS J1831-098, smoothed with a Gaussian of $\sigma \sim 0.12^\circ$. The white curves show the significance contours at 5, 6 and 7 $\sigma$ for an integration radius of 0.22$^\circ$. The white cross shows the fitted position of the source. The position of PSR J1831-0952 is shown as a black triangle. Neighbouring SNRs are shown in green. Note that the fitted centroid does not coincide with the emission peak due to its departure from a Gaussian shape.

residuals. A circular region of 0.3$^\circ$ radius, chosen as a compromise between optimal signal-to-noise ratio and independence of source morphology, was used to determine the energy spectrum. The differential spectrum, based on the 484 excess events in the circular region, is shown in Fig. 2. The best fitted shape is a power-law ($d\phi/dE = \phi_0(E/1\text{TeV})^{-\Gamma}$) with no significant indication of a cut-off up within the fitting energy range which extends up to 30 TeV. The fitted flux (uncorrected for events falling outside the integration disk) is $\phi_0 = (1.1 \pm 0.1) \times 10^{-12}\text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$ and the photon index $\Gamma = 2.1 \pm 0.1$. The integrated flux for $E > 1$ TeV corresponds to about 4% of the flux of the Crab nebula in the same energy range [2].

FIG. 2: Differential energy spectrum of HESS J1831-098, fitted with a power-law function after extraction of events from a circular region of 0.3$^\circ$ radius, centered on the best-fitted position. The arrow shows the Fermi differential U.L. at 30 GeV.

III. SEARCH FOR COUNTERPARTS

A preliminary multi-wavelength search for energetic counterparts to HESS J1831-098 resulted in the sole pulsar PSR J1831-0952 [7], which lies at a small angular offset of $\sim 0.05^\circ$ from the H.E.S.S. source’s best fit position (see Fig. 1). Some X-ray data from Chandra and XMM-Newton are available, but the observations have been done at large offsets with respect to PSR J1831-0952 and hence are not very useful. The search in the GeV energy was carried out using $\sim 33$ months of public data from the Large Area Telescope (LAT) on board of Fermi (collected from 2008 August 4 (MJD 54682) to 2011 April 10 (MJD 55661)). A region of interest (ROI) of 6$^\circ$ was used to select events in the [10-100] GeV range. The ROI radius was chosen such as to be large enough to get a reliable value for the normalization of the diffuse model and to be several times greater than the LAT PSF in the selected energy range. Events were analysed by applying the standard Fermi Science Tools to events of class 4 which is recommended for studies of faint
diffuse sources and which go beyond 20 GeV (in order to to minimize the non-photon background contami-
nation). The corresponding instrument response func-
tion used for this event class is P6.V3.DATACLEAN [8]. Other standard cuts were also applied (e.g. zenith
angle larger than 105° in order to reduce the contri-
bution from terrestrial albedo γ-rays [9]).

A hot-spot, at a pre-trials TS=25, was found within
the boundaries of the H.E.S.S. source on a map gen-
erated by gttsmap (Fig. 4). The hot-spot consists of
one 0.01deg² pixel at TS=25 and few neighbouring
pixels at lower TS values. To account for the trials factor a conservative approach was adopted,
namely the ratio of the predefined HESS source circle
of radius 0.15° to one Fermi sky map pixel area was
used. This yields a post-trial significance of ∼ 4.5σ
for the hot-spot. Investigating a slightly higher en-
ergy band of [30-100] GeV, the hot-spot significance
drops to less than 3.4σ. Hence an upper limit (U.L.)
on flux of U.L. ∼ 5 × 10⁻¹¹phcm⁻²s⁻¹ was derived by
assuming a spectral index equal to that of the HESS
source (Γ = 2.1). This U.L. is higher than the ex-
trapolated flux of the H.E.S.S. source into the LAT
range: (∼ [30 - 100] GeV) ∼ 3.5 × 10⁻¹¹ph cm⁻²s⁻¹,
and therefore does not exclude the existence of a GeV
counterpart.

IV. DISCUSSION AND SUMMARY

PSR J1831-0952 is an energetic pulsar exhibiting a
spin-down luminosity of 1.1 × 10³⁶erg s⁻¹, spin-down
age of τc ∼ 128 kyr, spin period of ∼ 67 ms and a dis-
tance estimated from dispersion measurements of 4.32
kpc [10]. To power the H.E.S.S. source, a conversion
efficiency from rotational energy to 1-20 TeV γ-rays
of ε ∼ 1% would be required, i.e. a value compar-
able to those inferred for other VHE PWN can-
didates such as HESS J1420-609/HESSJ1418-607 in
the wings of Kookaburra [11], HESS J1718-385 or HESS
J1809-193 [12]. The angular offset of ∼ 0.05°, trans-
lating into a projected distance of ∼ 4(d/4kpc) pc, is also
well within the range of offsets observed for crushed
PWN, as is the projected size of HESS J1831-098
(~ 20(d/4kpc) pc) when compared to the size of known
VHE γ-ray PWN.

These values and the fact that the offset-type mor-
phology is rather common to VHE emitting PWNs
(e.g. HESS J1825-137, MSH 15-52, HESS 1718-385
and HESS J1809-193) favour an interpretation of the
VHE emission as originating from a PWN associated
to PSR J1831-0952. In this scenario γ-rays are pro-
duced through Inverse Compton (IC) scattering of
ambient radiation fields (2.7 K Cosmic Microwave
Background Radiation (CMBR), dust and star-light)
by electrons injected by the pulsar into the nebula and
re-accelerated at the wind terminal shock. The offset
of the VHE-peak from the pulsar position can be due
to the expansion of the SNR/PWN into an inhomoge-
nous medium (e.g. [13]) and/or the proper motion of
the pulsar. In the latter case, and if the system age is
indeed equal to the characteristic age of 128 kyr, the
implied pulsar projected velocity of ∼ 300 km s⁻¹ re-
mains reasonable and well within the bimodal veloc-
ity distribution derived in [14].

On the other hand, the extension of the maximum
measured energy up to 30 TeV would imply a rather
low magnetic field of 1 μG in the IC scenario (see
e.g., Eq. (6) in [15]). However, the inferred value of
the magnetic field intensity depends on the system
age, which could suffer from large uncertainties (over-
estimation) given that the pulsar characteristic age
is calculated assuming that the initial spin period is
negligible and remarking this is not always the case
(e.g. PSR J1400-6326, where the true age of 1-2 kyr,
is much smaller than the characteristic age of 12.7 kyr
[16]).

To summarize, although no PWN has been detected
so far at other wavebands, the interpretation of HESS
J1831-098 in terms of a wind nebula remains the most
likely scenario, given the spatial coincidence with the
ergentic PSR J1831-0952, the reasonable efficiency
and offset, and the observed abundance of such PWN-
type VHE sources. If the association is confirmed,
HESS J1831-098 would constitute a gamma-ray discovered PWN. If so and if the true age of the system is close to the characteristic age of the pulsar, this source would be among the oldest known TeV PWNe. However, given the uncertainties on the source morphology due to limited statistics, other scenarios (e.g. a SNR shell emission) can not be excluded. X-ray observations an additional data in the VHE $\gamma$-ray band are necessary to better understand the origin of the VHE emission.

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.

[1] Gast, H., et al., for the H.E.S.S. Coll., Proceedings of the 32nd International Cosmic Ray Conference, 2011, Beijing
[2] Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al., (HESS Collaboration), A&A, 2006, 457:899
[3] Aharonian, F., Akhperjanian, A. G., Aye, K. M., et al. (HESS Collaboration), APh, 2004, 22:109
[4] Becherini, Y., et al., Astroparticle Physics, 2011, 34:858-870
[5] Berge, D., et al., A&A, 2007, 466:1219
[6] Piron, F., Djannati-Ataï, A., Punch, M., et al. A & A, 2001, 374:895
[7] Lorimer, D. R., Faulkner, A. J., Lyne, A. G., MNRAS, 2006, 372:777-800
[8] Abdo, A. A., et al., Phys. Rev. Lett., 2009, 103, 25, 1101
[9] Abdo, A. A., et al., Phys. Rev. D, 2009, 80,12 , 2004
[10] Manchester, R. N., Hobbs, G. B., Teoh, A. & Hobbs, M., AJ, 2005, 129:1993-2006
[11] Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al., (HESS Collaboration), A&A, 2006, 456:245-251
[12] Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R, et al. (H.E.S.S. Collaboration), A&A, 2007, 464:235
[13] Blondin, J. M., Chevalier, R. A. & Frierson, D. M., ApJ, 2001, 563:806
[14] Arzoumanian, Z, Chernoff, D. F., Cordes, J. M. , The Astrophysical Journal, 2002, 568:289
[15] de Jager, O. C., & Djannati-Ataï, A. 2009, Neutron Stars and Pulsars, ed. W. Becker (Springer ASSL), XV, 357, 451
[16] Renaud, M., et al., ApJ, 2010, 716:663