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

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**Abstract:** The H.E.S.S. Galactic Plane Survey (GPS), undertaken since 2004, has revealed more than 60 Very High Energy (VHE) $\gamma$-ray sources. We report on the latest discovery of an extended source near the 67 ms pulsar PSR J1831-0952. Adopting the dispersion measure distance of the pulsar (4.3 kpc), less than $\sim 1\%$ of its spin-down energy would be required to provide the observed luminosity of the VHE source. Multi-wavelength searches have not revealed any other plausible counterpart yet. If the VHE emission originates within a wind nebula around PSR J1831-0952 this would constitute another case of a $\gamma$-ray discovered pulsar wind nebula. The morphology and spectrum of the extended emission, assumed as a single source, are presented and discussed.

**Keywords:** HESS J1831-098, PSR J1831-0952, Pulsar Wind Nebula

## 1 Introduction

Since 2004, more than 60 sources of very-high-energy (VHE) $\gamma$-rays have been revealed by the H.E.S.S. (High Energy Stereoscopic System) GPS. Emission associated with Pulsar Wind Nebulae (PWNe) constitutes 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. At the same time a significant fraction, of about one third, of H.E.S.S. sources remains unidentified as there are no known counterparts in other wavelengths, or because of lack of any clear emission scenario. With the accumulation of exposure and the use of advanced multivariate analysis techniques, H.E.S.S. now achieves a sensitivity of better than 2% of Crab in the core region of the GPS (i.e. $l = 282°$ to $60°$) [1]. Here we report on the discovery of a new extended VHE source, HESS J1831-098, near Galactic longitude $l = 21°$. We will discuss its morphology, spectrum and possible counterparts in the following sections.

## 2 Observations and Analysis

H.E.S.S. is an array of four imaging atmospheric Cherenkov telescopes located in the Khomas Highland in Namibia at an altitude of 1800 m above sea level. Each telescope has a mirror area of $107m^2$ [2] and is equipped with a camera consisting of 960 photomultiplier tubes for a the total (FoV) of $5°$ [3]. The system works in a stereoscopic mode allowing a high angular resolution of $\sim 0.1°$ per event, a good energy resolution of $15\%$ (on average) and an effective background rejection. Its large FoV and good off-axis sensitivity make it suitable for the study of extended sources such as the one discussed here. For more information on H.E.S.S. the reader is referred to [4]. 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 $l = 21°$. They were taken in 2004 (May-Oct.), 2005 (June and July), 2007 (Apr. and July), 2008 (Sept.) 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 [5] based on hardware and weather conditions, the data set for HESS J1831-098 amounts to a total live-time of $40$ hours with an average zenith angle of $22.8°$, and an average offset (to the FoV center) of $1.30°$. 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 and tail-cuts cleaning of the camera images [6]. In order to reject the background of cosmic-ray showers, a newly developed multivariate analysis [7] was used. The sky maps were produced with an image size cut of 80 photo-electrons (p.e.) and using the so-called Ring Background method [8] where the background at each test position on the sky is derived from a ring surrounding it with a mean radius of $0.7°$. For spectral studies the same cut on image size is applied together with the a Reflected-Region procedure to estimate the Background, before application of a forward-folding method yielding the parameter estimates [9].

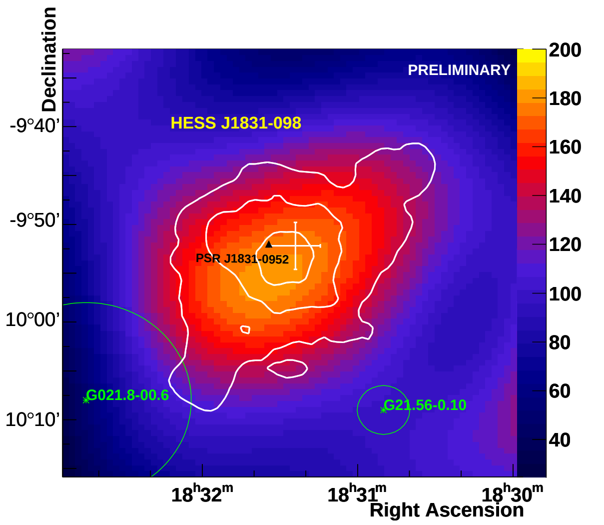


Figure 1: Excess map of HESS J1831-098. The map is smoothed with a Gaussian of $\sigma \sim 0.12°$. The white curves show the significance contours at 5,6 and 7 $\sigma$ for an integration radius of $0.22°$. The white cross shows the fitted position of the source (it does not coincide with the peak emission because of its departure from a Gaussian shape.). The position of PSR J1831-0952 is shown as a black triangle. Neighbouring SNRs are shown in green.

## 3 Results

Figure 1 shows the excess count map of the $0.4° \times 0.4°$ region around HESS J1831-098. The map is smoothed with a Gaussian of $\sigma \sim 0.12°$. An extended $\gamma$-ray emission to the south-east of PSR J1831-0952 is observed with a peak pre-trials significance of $7.9\sigma$ when using an integration radius of $\theta = 0.22°$ (i.e. the standard value 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 $\alpha \sim 18^{\rm h}31^{\rm m}25^{\rm s}, \delta \sim -9° \, 54'$, with a width of $\sigma \sim 0.15°$ and a $\chi^2$ of 593.4/525. The fit of an asymmetrical Gaussian function does not improve significantly $\chi^2$ nor the residuals. The energy spectrum was determined within a circular region of $0.3°$ radius, chosen as a compromise between optimal signal-to-noise ratio and independence of source morphology. The total number of excess events is 484 corresponding to a significance of $8.4\sigma$. The differential spectrum is shown in Fig. 2. It has been fitted by a pure power law ($\mathrm{d}\phi/\mathrm{dE} = \phi_0(\mathrm{E}/1\mathrm{TeV})^{-\Gamma}$) with no hint of a cut-off up to an energy of 30 TeV. The fitted flux (uncorrected for events falling outside the integration disk) is $\phi_0 = (1.1 \pm 0.1) \times 10^{-12}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the photon index $\Gamma = 2.1 \pm 0.1$. The integrated flux for $\mathrm{E} > 1$ TeV

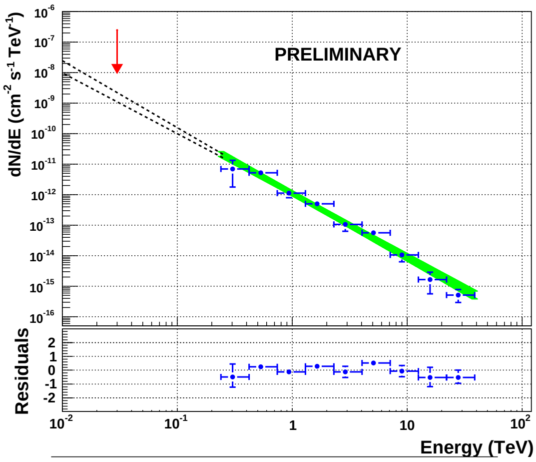


Figure 2: Differential energy spectrum of HESS J1831-098, extracted from the circular region with integration radius of $0.3°$ fitted with a power-law function. The arrow shows the Fermi differential UL at 30 GeV.

corresponds to about 4% of the flux of the Crab nebula in the same energy range [5].

## 4 Search for counterparts and discussion

A multi-wavelength search was carried out to look for possible counterparts to HESS J1831-098. The most plausible counterpart candidate to HESS J1831-098 is the energetic pulsar PSR J1831-0952 [10], lying at a small angular offset of $\sim 0.05°$ from the H.E.S.S. source's best fit position (white cross in Fig. 1). The association is discussed further below. The available X-ray data from *Chandra* and XMM-*Newton* are all at large offsets with respect to PSR J1831-0952 and hence not very useful. The search in the neighbouring energy domain of the Large Area Telescope (LAT) on board of Fermi was carried out using $\sim 33$ months of data collected from 2008 August 4 (MJD 54682) to 2011 April 10 (MJD 55661). Photons in the [10-100] GeV range were selected within a region of interest (ROI) of $6°$ which is large enough to get a reliable value for the normalization of the diffuse model and is several times greater than the PSF of the LAT in the selected energy range. These photons were analysed using event class 4 which is recommended for studies of faint diffuse sources and studies that go beyond 20 GeV in order to to minimize the non-photon background contamination. The corresponding instrument response function for this event class is P6_V3_DATACLEAN [11]. Other standard cuts were also applied (e.g. zenith angle larger than $105°$ in order to reduce the contribution from terrestrial albedo $\gamma$-rays [12]). By using the standard *Fermi* Science Tool *gttsmap* a hotspot at a pre-trials TS=25 is found within the boundaries of the H.E.S.S. source (Fig. 4). This hot-spot consists of one $0.01\mathrm{deg}^2$ pixel at TS=25 and few neighbouring pixels at lower TS values. When accounting for the trials factor (which is derived conservatively here as the ratio of the predefined HESS source circle of radius $0.15°$ to one Fermi sky map pixel area) the significance level drops from $\sim 5.5\sigma$ to $\sim 4.5\sigma$. In a higher energy band ( [30-100] GeV), the hot-spot significance drops to less than $3.4\sigma$ and hence an upper limit on flux of UL $\sim 5 \times 10^{-11}\mathrm{phcm^{-2}s^{-1}}$ was derived by assuming a spectral index equal to that of the HESS source ($\Gamma = 2.1$). This UL is higher than the extrapolated flux of the H.E.S.S. source into the Fermi range: $([30-100]\,\mathrm{GeV}) \sim 3.5 \times 10^{-11}\mathrm{ph\,cm^{-2}s^{-1}}$, and therefore does not exclude the existence of a GeV counterpart.

PSR J1831-0952 is a rather energetic pulsar with spin-down luminosity of $1.1 \times 10^{36}\mathrm{erg\,s^{-1}}$, spin-down age of $\tau_c \simeq 128$ kyr, spin period of $\sim 67\,\mathrm{ms}$ and a distance estimated from dispersion measurements of 4.32 kpc [13]. It is then sufficiently energetic to power the H.E.S.S. source with an implied conversion efficiency from rotational energy to 1-20 TeV $\gamma$-rays of $\epsilon \sim 1\%$, i.e. a value comparable to the efficiency inferred for other VHE PWN candidates such as HESS J1420-609/HESSJ1418-607 in the wings of Kookaburra [14], HESS J1718-385 or HESS J1809-193 [15]. The angular offset of $\sim 0.05°$ translates into a projected distance of $\sim 4(\frac{\mathrm{d}}{4\mathrm{kpc}})\,\mathrm{pc}$, a value well within the range of what is observed for other offset-type PWNe. The projected size of HESS J1831-098 is also comparable to the size of known VHE $\gamma$-ray PWNe ( $\sim 20(\frac{\mathrm{d}}{4\mathrm{kpc}})\,\mathrm{pc}$). The above numbers and the fact that the offset-type morphology is rather common to VHE emitting PWNe (e.g. HESS J1825-137, MSH 15-52, HESS 1718-385 and HESS J1809-193) plead in favour of interpreting HESS J1831-098 as a PWN associated to PSR J1831-0952. In this scenario the VHE emission is produced through Inverse Compton (IC) scattering of target photons (2.7 K Cosmic Microwave Background Radiation (CMBR), dust and starlight) by electrons injected by the pulsar into the nebula reaccelerated of the wind terminal shock. The VHE-peak to pulsar offset can be explained in terms of the expansion of the SNR/PWN into an inhomogeneous medium (e.g. [16]) and/or the proper motion of the pulsar. If we consider here that the observed offset is due to the proper motion of the pulsar, and that the system age is equal to the characteristic age of 128 kyr, the implied pulsar projected velocity of $\sim 300\,\mathrm{km\,s^{-1}}$ remains reasonable and well within the bimodal velocity distribution fitted in [17].

On the other hand, by assuming the association with the pulsar and an IC emission produced by electrons, the extension of the maximum measured energy to 30 TeV would imply a rather low magnetic field of  1 $\mu$G (see e.g., Eq. (6) in [18]). The latter value depends however on the estimate of the system age, which could suffer from large overestimates, as the pulsar characteristic age is calculated assuming that the initial spin period is negligible (i.e. for high spin-down energy loss rate of pulsar), e.g. in the case of PSR J1400-6326, the true age of the system is 1-2 kyr whereas the characteristic age calculation yields 12.7 kyr

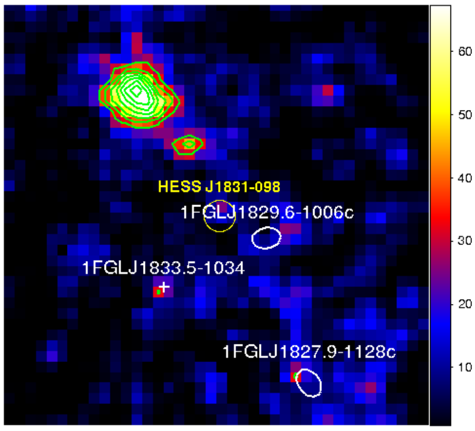


Figure 3: Fermi TS Map in the 10-100 GeV range (FoV = 2°) with contours for TS $> 30$ corresponding to $\sim 5.5\sigma$ (pre-trials). HESS J1831-098 is shown by the yellow circle of radius $0.15°$.

[19].

In summary, although no PWN has been detected so far at other wavebands, the spatial coincidence of HESS J1831-098 with the energetic PSR J1831-0952, the reasonable efficiency and offset, and the abundance of PWN-type VHE sources make the interpretation in terms of a wind nebula likely. If this is confirmed, HESS J1831-098 would constitute a gamma-ray discovered PWN; if so and if the true age is close to the characteristic age, this source would be among the oldest TeV PWNe. It should however be noted that there is still insufficient information on the source morphology due to limited statistics, and hence other scenarios such as SNR shell emission can not be excluded. To confirm the interpretation above, X-ray observations are crucial together with additional data in the VHE $\gamma$-ray band.

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