Discovery of the Binary Pulsar PSR B1259−63 in VHE Gamma Rays

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Abstract. The detection of the binary system PSR B1259−63 / SS 2883 with the High Energy Stereoscopic System (H.E.S.S.) of four imaging atmospheric Cherenkov telescopes is reported. PSR B1259−63, a radio pulsar with a highly eccentric orbit around a very luminous, massive star was observed around its periastron passage in February/March 2004. Very high energy (VHE) gamma-ray emission has been predicted to be produced in the interaction region of the pulsar wind and the photon field of the star, where accelerated electrons are believed to undergo Inverse Compton scattering. The flux of the gamma-ray emission should then depend on the pulsar orbital phase. Gamma-ray signals with a significance $> 10\sigma$ were detected above an energy threshold of ~ 380 GeV. The measured flux varies significantly on timescales of days. The spectrum derived from the pre-periastron data has a flux level of 7% of the Crab Nebula flux and a photon index of $\Gamma = 2.7 \pm 0.3_{\rm stat}$.

INTRODUCTION

PSR B1259−63 / SS 2883 is a binary system consisting of a ∼48ms pulsar in orbit around a massive B2e companion star [1, 2]. The highly eccentric orbit of the pulsar places it just $26R_* \approx 10^{12}$ cm from the companion with radius R_* during periastron every ∼3.4 yrs. This makes PSR B1259−63 a unique laboratory for the study of pulsar winds interacting with a changing environment in presence of an extremely intense photon field.

Electrons with multi-TeV energies are believed to be present in the ultra-relativistic pulsar wind or to be produced by shock acceleration in the termination region of the wind [3]. The *ROSAT* and *ASCA* satellites [4–6] detected unpulsed non-thermal X-rays extending up-to soft gamma rays [7] which likely originate from the synchrotron emission of these electrons. High energy γ-rays can be produced by the interaction of the intense photon field and the accelerated electrons through Inverse Compton (IC) scattering [8–11]. This emission depends on the distance of the pulsar from its companion and on the angle between the line of sight and the connecting line of both objects, and is therefore predicted to vary with the pulsar orbital phase.

Additionally, radio observations indicated that the companion has a dense equatorial disc, a common feature among B2e stars. The disc was found to be inclined with respect to the orbital plane [12, 13] emphasising the unique character of the system. The pulsed radio emission from the pulsar was found to be eclipsed near the periastron passage (τ) [14, 15]. Simultaneously, continuous radio emission was detected with two maxima around $\sim \tau - 10$ and $\sim \tau + 20$ days, when the pulsar is thought to interact with the disc, and remaining detectable beyond $\tau + 100$ days. In addition to IC γ-rays, one may therefore expect an additional component of gamma-radiation associated with interactions of accelerated electrons and possibly hadrons with the dense ambient gas of the disc [16].

In the following we present preliminary analysis results from very high energy (VHE) γ-ray observations of PSR B1259$-$63 around its 2004 periastron passage.

OBSERVATIONS AND RESULTS

Dataset and Analysis

The observations of PSR B1259$-$63 in February and March 2004 were performed with the High Energy Stereoscopic System (H.E.S.S.), consisting of four imaging atmospheric Cherenkov telescopes [17–22] operated in coincidence and located in Namibia, at $23°16'$ S $16°30'$ E at 1800 m a.s.l. All observations were carried out in moonless nights tracking sky positions with an alternating offset of $\pm 0.5°$ in declination relative to the source (the so-called *wobble* mode). This allows to determine the background from the same field of view and omit off-source observations, effectively doubling the observation time.

The dataset, selected according to standard quality criteria, has a dead-time corrected exposure (live-time) of 25.7 h and a mean zenith angle of $43.4\,°$. The corresponding mean threshold energy defined by the peak of the γ-ray detection rate for a Crab-like spectrum after selection cuts was estimated to be 380 GeV. In the phase prior to the periastron passage (7.8 h live-time), data from only three telescopes were considered and for the post-periastron phase (17.8 h live-time) data from the full telescope array were used.

Recorded air showers were reconstructed by parameterising each telescope image by its center of gravity and second moments followed by the stereoscopic reconstruction of the shower geometry, providing an angular resolution of $\approx 0.1°$ for individual γ rays. The γ-ray energy was reconstructed with a typical resolution of $\sim 15\%$ by comparing the image intensity and shower geometry with Monte Carlo simulated showers. γ-ray candidates were selected using cuts on image shape optimised on simulations for sources with a flux level of 0.1 Crab, allowing to retain 41.2% of γ rays while rejecting 99.9% of cosmic-ray air showers. A more detailed description of the analysis techniques can be found in [23].

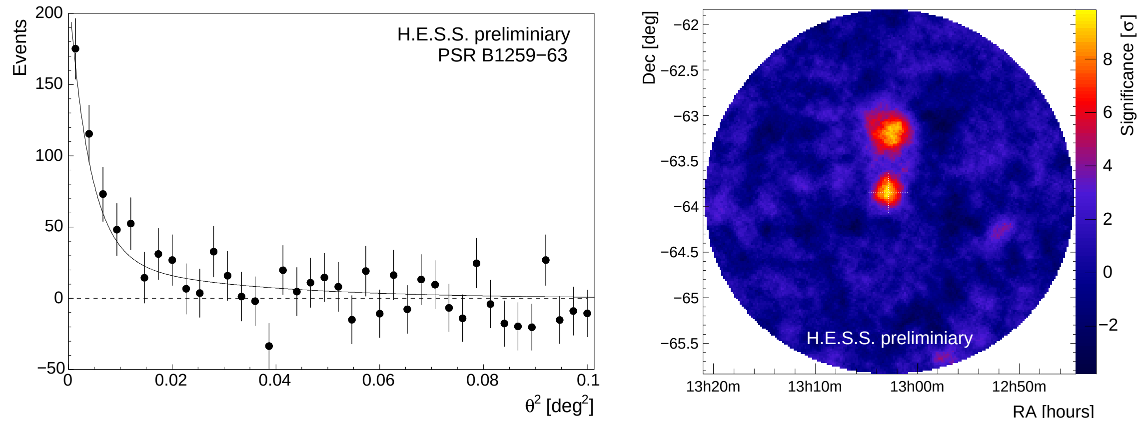

FIGURE 1. *Left*: Distribution of background-subtracted γ-ray candidates in θ^2 for the complete dataset, where θ is the angular distance between the reconstructed shower direction and the position of PSR B1259−63. The solid line indicates the distribution expected for a point source of γ rays. *Right*: Significance sky-map (correlated bins) of the H.E.S.S. field of view centered on the position of PSR B1259−63 for the pre-periastron dataset. The excess $\sim 0.6°$ north of the pulsar is the newly discovered unidentified TeV source HESS J1303−631 [24]. The background for each position in the field of view was estimated from a ring around this position correcting for the radial acceptance of the instrument within the field of view and background contamination from the two γ-ray sources.

Results

Figure 1 (left) shows the distribution of the squared angular distance θ^2 of excess events relative to the position of PSR B1259−63 for the whole dataset. The clear excess in direction of the pulsar has a significance of 10.8 σ and is consistent with a distribution obtained from a simulated γ-ray point source. The background was estimated from several non-overlapping control regions with the same distance to the center of the field of view [25]. The results for the considered darkness periods are summarized in Table 1.

A 2D-analysis of the H.E.S.S. field of view around PSR B1259−63 (see Fig. 1, right) revealed a new unidentified VHE γ-ray source HESS J1303−631 [24]. The resulting bias in the background estimation was corrected in the analysis.

The measured energy spectrum for the pre-periastron phase is shown in Fig. 2. A

TABLE 1. Results of H.E.S.S. observations on PSR B1259−63. For each darkness period the number of telescopes used in the analysis $N_{\rm tel}$, the live-time $t_{\rm live}$, the significance S of the excess, the number of counts within the on-source ($N_{\rm On}$) and off-source ($N_{\rm Off}$) region(s), the background normalisation α, and the number of detected γ-rays ($N_{\rm Excess}$) are listed.

Darkness period 2004	$N_{\rm tel}$	$t_{\rm live}$ [h]	S [σ]	$N_{\rm On}$	$N_{\rm Off}$	α	$N_{\rm Excess}$
February	3*	7.8	9.4	691	3 181	0.144	233±25
March	4	17.8	7.1	1 763	10 247	0.143	299±42
Total		25.7	10.8	2454	13428	0.143	532±49

* due to technical problems with one of the telescopes

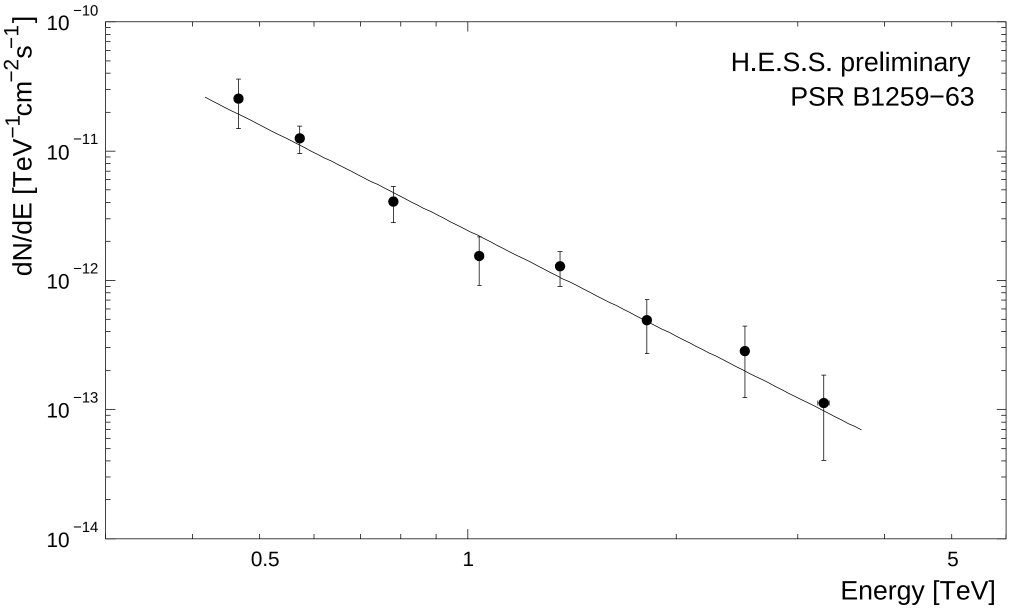

FIGURE 2. Energy spectrum dN/dE of γ-rays from PSR B1259−63 determined from H.E.S.S. pre-periastron data. The solid line indicates the power-law fit $F(E) = F_0 E_{\mathrm{TeV}}^{-\Gamma}$ to the spectrum with a photon index of $\Gamma = 2.7 \pm 0.3_{\mathrm{stat}}$, and $F_0 = (2.4 \pm 0.3_{\mathrm{stat}}) \cdot 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$.

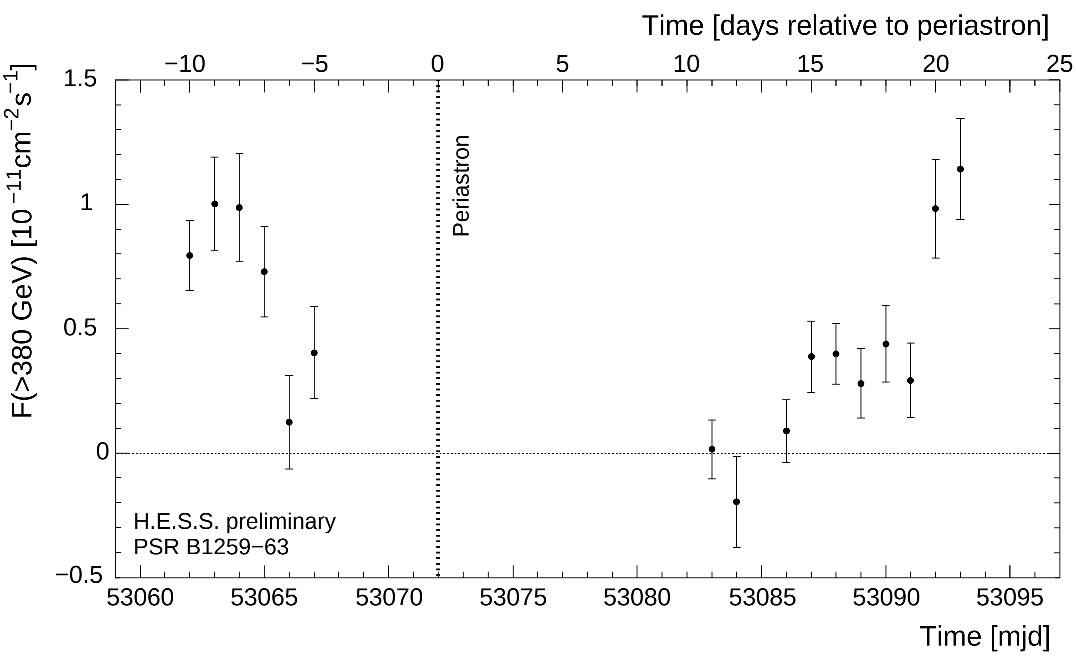

FIGURE 3. VHE γ-ray light curve of PSR B1259−63 around its 2004 periastron passage (dotted vertical line) showing the daily integral flux above 380 GeV as measured by H.E.S.S. Only statistical errors are shown. A possible decline of the flux before and a rise after periastron can be recognized.

power-law fit of the differential energy spectrum $F(E) = F_0 E_{\mathrm{TeV}}^{-\Gamma}$ yields a photon index $\Gamma = 2.7 \pm 0.3_{\mathrm{stat}}$ and $F_0 = (2.4 \pm 0.3_{\mathrm{stat}}) \cdot 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$ with a χ^2 of 2.6 per 6 degrees of freedom. The integral flux above the mean threshold energy is $F(E > 380\,\mathrm{GeV}) = (7.3 \pm 1.0_{\mathrm{stat}}) \cdot 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, equivalent to $\sim 7\%$ of the Crab Nebula flux at this threshold. Within statistical errors, there is no indication of significant time variability of the photon index in the whole dataset. Systematic errors are still under investigation.

The daily integral flux of γ-rays above the mean threshold of 380 GeV is shown in Fig. 3. The data clearly indicate a variable flux. This can be quantified by a fit of a constant flux to the data yielding a χ^2 of 82 per 35 degrees of freedom corresponding to a probability of $3.6 \cdot 10^{-11}$. Although only statistical errors are shown, the conclusion of evident source variability is not expected to change after inclusion of systematical errors on the flux. Unfortunately, the periastron passage is not covered by our data due to the full moon, but it is apparent that a low flux state after periastron is followed by a distinct rise towards $\sim \tau + 20$ days indicating flux variability on the order of days.

SUMMARY AND CONCLUSIONS

The detection of VHE γ-ray emission from the binary pulsar PSR B1259−63 by H.E.S.S. provides the first model-independent evidence of particle acceleration in this object. A power law fit to the measured spectrum yields a photon index $\Gamma = 2.7 \pm 0.3_{\mathrm{stat}}$ similar to the photon index of the Crab Nebula VHE γ-ray spectrum. The measured flux at the level of a few percent of the Crab Nebula flux is clearly variable on timescales of days. The emission is enhanced towards the date where the pulsar crosses the equatorial disc at $\tau + 20$ days, similar to the unpulsed radio emission profile. This feature makes it difficult to explain the origin of γ-ray emission by IC cooling of electrons accelerated by the shocked or unshocked pulsar wind only.

A more detailed analysis of the complete H.E.S.S. 2004 dataset will be the subject of an upcoming paper [26].

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. Particle Physics and Astronomy Research Council (PPARC), the IPNP of the Charles University, 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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