Observations of Binary Systems with the H.E.S.S. Telescopes

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Abstract. Observations of binary systems obtained recently with the High Energy Stereoscopic System (H.E.S.S) of Cherenkov telescopes are reported. The outcomes of a detailed observation campaign on PSR B1259-63 during its periastron passage in 2014 will be presented. This system was observed for the first time with H.E.S.S. II, providing spectra and light curves down to 200 GeV, which will be compared with observations conducted during previous periastron passages and with results from an analysis of contemporaneously taken Fermi-LAT data. Also long-term observations of LS 5039 with H.E.S.S in phase I and phase II are reported. This source was monitored at very high energies (VHEs) in a period of time spanning more than ten years. Its spectral energy distribution measured with H.E.S.S. II extends down to 120 GeV. Spectral results from the Fermi-LAT observations are shown as well, and the compatibility with H.E.S.S. results in the overlapping energy range is discussed. The identification of the new gamma-ray binary candidate HESS J1832-093 will also be presented. Furthermore, the search for VHE emission from the microquasars GRS 1915+105, Circinus X-1 and V4641 Sgr based on data from H.E.S.S. observations conducted contemporaneously with the RXTE satellite experiment will be reported. These data provide constraints on the integral gamma-ray flux at different X-ray states of the three sources.

Introduction

A majority of 70% of all stars in our galaxy are part of binary systems [1]. Depending on the orbital parameters, the nature of the individual objects and properties of the emission, these systems can be grouped into several categories. The following sections will focus on results from observations of gamma-ray binaries and microquasars (MQs) in the VHE (very high energy, with photon energies above \( \sim 100 \text{ GeV} \)) gamma-ray domain. The former are binary systems whose non-thermal radiative output is dominated by gamma rays, i.e. photons with energies above \( \sim 1 \text{ MeV} \). They consist of a compact object, either a neutron star or a stellar-mass black hole, and a massive O- or B-type star. Only seven of such systems are known to date. MQs are binary systems which emit X-rays and exhibit extended radio emission. High-energy (HE, 100 MeV \(< E < 100 \text{ GeV}\)) gamma-ray emission has been reported from at least two such systems, Cyg X-1 and V4641 Sgr based on data from H.E.S.S. observations conducted contemporaneously with the RXTE satellite experiment.
The results presented here are derived from observations performed with the High Energy Stereoscopic System (H.E.S.S.) telescopes. In phase I of the H.E.S.S. experiment, regular observations were conducted with four telescopes with 107 m$^2$ reflectors each arranged in a square with a side length of 120 m started in 2004. In 2012, a much larger fifth telescope with a reflector area of 596 m$^2$ called CT 5 was placed into the centre of the array, marking the beginning of phase II of the H.E.S.S. experiment. In these proceedings, results from observations conducted with both the H.E.S.S.-I and the H.E.S.S.-II configurations are reported. For more information about the experimental setup, see e.g. Aharonian et al. [2].

In the following sections, results from observations of PSR B1259-63/LS 2883 around the 2014 periastron are presented. Furthermore, results from long-term observations of LS 5039 are reported. Lastly, the discovery of a gamma-ray binary candidate is discussed and results from observations of three microquasars are presented.

Observations of PSR B1259-63/LS 2883

PSR B1259-63/LS 2883 is a binary system comprising a massive O9.5Ve star with a circumstellar disk and a pulsar with a rotational period of 48 ms and a spin-down luminosity of $8 \cdot 10^{35}$ erg/s. The orbit of the pulsar around the central star is very eccentric, with an eccentricity of $e = 0.87$, and has a period of 3.4 yr. The system is located at a distance of 2.3 kpc. It is the only gamma-ray binary system for which the nature of the compact object is known [3, 4].

At VHEs, PSR B1259-63/LS 2883 was discovered with the H.E.S.S. telescopes around the 2004 periastron [5]. Since then, observations with the H.E.S.S. telescopes were conducted around all periastron passages since then [6, 7]. In case of the 2014 periastron passage, data equivalent to 60 h of live time were collected with the five-telescope H.E.S.S.-II array. Both the pre- and post-periastron phases were covered as well as, for the first time, the time of periastron itself. Gamma rays from this system were detected with a statistical significance of $>30 \sigma$.

The differential photon spectrum obtained from a monoscopic analysis of the 2014 data performed with the MonoReco algorithm [8] is shown in Fig. 1 together with results from an extension of the Hillas reconstruction presented in Aharonian et al. [2] enabling analyses of data recorded with the H.E.S.S. II array. Spectral indices as given in the figure are compatible with each other. Also the flux normalisations at 1 TeV are compatible within systematic uncertainties assumed to be 20% of the flux. For comparison, also spectra from re-analyses of archival data from observations around previous periastra are shown. These spectra are obtained from analyses with the ImPACT algorithm [9]. While all spectral indices are compatible with each other within errors, the flux normalisation differs from one year to the other. This is expected, as different parts of the orbit were sampled each year. It should be noted that the safe energy threshold of the re-analyses of archival data are significantly lower than the published thresholds due to refined analysis techniques. The monoscopic safe energy threshold is expected to be lowered by several tens of GeV in the future, since the current value of approximately 200 GeV is chosen arbitrarily to guarantee robust results.

Fluxes above 200 GeV are shown in the left panel of Fig. 2 with a night-wise and a monthly binning. In the night-wise light curve, several interesting features can be identified. A rising flux well before the first disk crossing

![FIGURE 1. Differential photon spectra obtained from monoscopic and stereoscopic analyses of the 2014 data set. Also spectra resulting from re-analyses of archival data from previous periastra are shown. Spectral indices are given in the legend.](image-url)
is observed, with maximum fluxes compatible to the flux level observed around the actual disk crossings. After the first disk crossing, the flux decreases towards periastron. Finally a high flux, again with fluxes similar to the fluxes observed during the disk crossings, is seen at the time of the GeV flare occurring between 32 d and approximately 60 d after periastron. For comparison also light curves obtained from all years are shown on the right panel of Fig. 2 for energies above 1 TeV. The general features previously discussed remain the same. It should be noted, though, that the high flux before the first disk crossing is followed by a low flux at the time of the nominal disk crossing. This behaviour is still under investigation. Furthermore it can be seen that also above 1 TeV the flux is high at the central part of the GeV flare, which may constrain current theoretical models of the origin of the periodic HE flare.

Data from measurements with Fermi-LAT corresponding to the release version Pass 8 were analysed as well. The obtained light curve is shown in Fig. 3. Apart from the fact that the prominent flares observed approximately 30 d after periastron in both 2010 and 2014 can be reproduced it should be noted that, for the first time, several flux points with a significance of at least 3σ were obtained for the times around the disk crossings in both years. There is no indication of a high flux state at the time of the high flux state at VHEs before the first disk crossing.

### Observations of LS 5039

The gamma-ray binary LS 5039 consists of an O6.5Ve star with a mass of 23 $M_\odot$ and a compact object of unknown nature with a mass of 3.7 $M_\odot$. These two objects are in a very close orbit with a period of only 3.9 d. In this section,
results from ten years of H.E.S.S. observations are presented. The data set comprises 104 h and 19 h of live time recorded with the H.E.S.S. array in phase I and phase II, respectively.

Analyses of all available data yield the spectral energy distributions (SEDs) shown on the left side of Fig. 4. Both an SED resulting from a monoscopic analysis of the data taken with the H.E.S.S. II array and an SED obtained from a stereoscopic analysis of H.E.S.S. I data are shown. The analyses were performed with the Model Analysis [10]. In case of the monoscopic analysis, the energy threshold is approximately 120 GeV. Together with the H.E.S.S. curves, also an SED obtained from a re-analysis of Fermi-LAT data in the Pass 8 release is shown. For the first time the energy ranges of LS 5039 SEDs resulting from the two experiments significantly overlap. The data points in this region are compatible with each other within statistical uncertainties.

On the right side of Fig. 4, two other SEDs resulting from an analysis of the H.E.S.S.-I data set are shown. The two SEDs correspond to either the inferior or the superior conjunction phase of the orbit. While the latter SED is well-fit by a power law, the former one exhibits a curvature and is therefore fit with a power law with an exponential cut-off at approximately $(6.6 \pm 1.6)$ TeV. This cut-off energy is approximately 1000 times the cut-off energy of $(5.3 \pm 0.6)$ GeV observed in the HE gamma-ray spectrum shown on the left side of the figure. The indices of the spectra are $\Gamma = 2.41 \pm 0.06$ and $\Gamma = 1.84 \pm 0.07$ for the superior and inferior conjunctions, respectively. At 1 TeV, the normalisations of the differential photon fluxes are $(1.01 \pm 0.05) \times 10^{-12}$ ph/TeV/cm$^2$/s and $(2.58 \pm 0.10) \times 10^{-12}$ ph/TeV/cm$^2$/s.

For more information, the reader is referred to Mariaud et al. [11].

**Observations of HESS J1832-093**

HESS J1832-093 was detected at VHEs during the galactic plane scan performed with the H.E.S.S. experiment [12]. The observed gamma-ray excess in the direction of object source is compatible with the excess from a point-like source of VHE gamma rays. The differential photon spectrum is well described by a power law with an index of $2.6 \pm 0.3$. Several scenarios about the nature of this object are discussed in the literature. Here the tentative identification as one of the seven aforementioned gamma-ray binaries is presented.

Recent measurements with the Chandra satellite experiment reveal that the apparent angular distance of the star 2MASS J18324516–0921545 and the X-ray source XMMU J183245–0921539 is only 0.3”, suggesting an association of these two objects due to the low chance coincidence of 0.3 %. Also the high column density inferred from a spectral fit of the X-ray data, which is approximately ten times higher than the total galactic value, supports the hypothesis that the objects form a binary system. The fact that HESS J1832-093 is compatible with a point-like source at VHEs disfavours the identification as a pulsar wind nebula or a supernova remnant, since such objects appear, in general, as extended sources. Furthermore, the flux observed at X-ray energies is variable, with a factor of approximately six between the low and high flux states, which is similar to the value obtained from the gamma-ray binary HESS J0632+057. Another similarity to the latter system is the fact that no significant HE gamma-ray emission could be detected with current-generation instruments. Despite the lack of such emission, the spectral energy distribution is dominated by the VHE emission, which is a necessary requirement for the identification as a gamma-ray binary.
Based on the above arguments, HESS J1832-093 has been catalogued as a gamma-ray binary system. For further information and the discussion of associations with different object classes, the reader is referred to Eger et al. [13].

**Observations of Microquasars**

As mentioned earlier, HE gamma rays have been detected from MQs already. VHE gamma rays are predicted to be emitted by MQs during transient outbursts by various theoretical models, but have not been detected yet. In this section, results from H.E.S.S. observations of three MQs conducted contemporaneously to observations with the RXTE satellite experiment are presented. All observations were performed with the H.E.S.S. I array in 2004, aiming to cover times of expected broadband flaring events. One target of the observations was GRS 1915+105. Observations of this object were performed after a flux decrease in the radio band at frequencies of approximately 15 GHz between April 28 and May 3, 2004 as shown in Fig. 5. Cir X-1 was observed around the time of periastron between June 18 and June 20. V4641 Sgr was observed after a rapid increase of the intensity was measured in the radio, optical and X-ray domains between July 7 and July 9. None of the observations yielded the detection of a significant flux in the VHE gamma-ray regime. Thus flux upper limits at the 99 % confidence level were calculated after an analysis of the data with the Hillas reconstruction algorithm. The results are displayed in Tab. 1.

For more information, the reader is referred to Abdalla et al. [14].

**Summary**

In these proceedings, results from observations of binary systems with the H.E.S.S. telescopes have been presented. The gamma-ray binary PSR B1259-63/LS 2883 was observed around the 2014 periastron, exhibiting a high flux state at the time of the GeV flare. A high flux state before first disk crossing is currently under investigation. There are no clear signatures for inter-orbital variation of the spectral index or the flux level at VHEs. The spectrum could be extended down to an energy of 200 GeV. In case of LS 5039, results from ten years of observations with both the H.E.S.S.-I and H.E.S.S.-II arrays have been presented. Significant spectral variation is observed between orbital phases corresponding to the inferior and superior conjunctions, respectively. The phase-averaged SEDs obtained from analyses of both H.E.S.S.-I and H.E.S.S.-II data agree well with each other and also with the phase-averaged SED resulting from a re-analysis of Fermi-LAT data. The identification of the VHE gamma-ray emitter HESS J1832-093

![FIGURE 5. Top panel: Integrated flux between 2 keV and 20 keV as a function of time as measured by RXTE. Central panel: Hardness, defined as the ratio of the fluxes in the higher and lower energy band of the X-ray flux as indicated on the ordinate as a function of time. Bottom panel: Radio flux at 15 GHz as a function of time as measured by the Ryle experiment. Colours denote the times during which H.E.S.S. observations were performed. Adapted from Abdalla et al. [14].](image-url)
TABLE 1. Flux upper limits at the 99 % confidence level. Limits were calculated assuming a power-law shape of the spectrum with an index of 2.6 or 2.0 for the std and hard cut configurations defined in Aharonian et al. [2], respectively. The live time \( T_L \), the energy threshold \( E_{\text{thr}} \) and the flux \( I \) are listed in the table. Adapted from Abdalla et al. [14].

|                | Cuts | \( T_L [/\text{h}] \) | \( E_{\text{thr}} [/\text{GeV}] \) | \( I (> E_{\text{thr}}) [/\text{ph/cm}^2/\text{s}] \) |
|----------------|------|-----------------|-----------------|-----------------|
| GRS 1915+105   | std  | 6.9             | 562             | < 7.338 \cdot 10^{-13} |
|                | hard | 6.9             | 1101            | < 1.059 \cdot 10^{-13} |
| Circinus X-1   | std  | 5.4             | 562             | < 1.172 \cdot 10^{-12} |
|                | hard | 5.4             | 1101            | < 4.155 \cdot 10^{-13} |
| V4641 Sgr      | std  | 1.8             | 237             | < 4.477 \cdot 10^{-12} |
|                | hard | 1.8             | 422             | < 4.795 \cdot 10^{-13} |

as a gamma-ray binary is discussed as well. This identification is mostly based on features of the spectral energy distribution, flux variability and the source morphology. Lastly, also observations of MQs are presented. These observations yield no significant detection of VHE gamma ray photons, but competitive upper limits for the emission of such photons from microquasars have been computed.

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