

X-ray and γ -ray orbital variability from the γ -ray binary HESS J1832–093

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ABSTRACT

Context. γ -ray binaries are systems composed of a massive star and a compact object whose interaction leads to particle acceleration up to relativistic energies. In the last fifteen years, a few binaries have been found to emit at high energies, but their number is still low. The TeV source HESS J1832–093 has been proposed as a binary candidate, although its nature is unclear. Neither a GeV counterpart nor a period was detected.

Aims. The purpose of this work is to search for a GeV counterpart to understand the origin of the TeV signal detected by H.E.S.S. For an unambiguous identification of its binary nature, finding an orbital modulation is crucial.

Methods. We analysed data spanning more than 10 years from the *Fermi* Large Area Telescope (*Fermi*-LAT), together with *Swift* archival observations taken between 2015 and 2018, using both the X-Ray Telescope and UV/Optical Telescope. We searched for periodicities in both X-ray and GeV bands.

Results. We find a periodic modulation of ~ 86 days in the X-ray source candidate counterpart XMMU J183245–0921539, together with indications of γ -ray modulation with a compatible period in the GeV candidate counterpart 4FGL J1832.9–0913. Neither an optical nor a UV counterpart is found at the X-ray source location. The overall spectral energy distribution strongly resembles the known γ -ray binary HESS J0632+057.

Conclusions. Both the spectral energy distribution and the discovery of an orbital period allow the identification of the TeV source HESS J1832–093 as a new member of the γ -ray binary class.

Key words. X-rays: binaries – gamma-rays: stars – acceleration of particles – binaries: general – stars: individual: HESS J1832–093

1. Introduction

The search for binaries emitting γ -rays resulted in the discovery of a few systems at high energies, the γ -ray binaries (see [Dubus 2013](#) for a review). These systems are unique because their spectral energy distribution (SED) peaks at γ -rays, while they show orbitally modulated emission across the electromagnetic spectrum – including their high-energy (HE; $E > 100$ MeV) and very-high-energy (VHE; $E > 100$ GeV) components. Almost all the systems known are located in the Galactic plane – PSR B1259–63 ([Aharonian et al. 2005](#)), LS 5039 ([Aharonian et al. 2006](#)), LSI+61 303 ([Albert et al. 2006](#)), HESS J0632+057 ([Aharonian et al. 2007](#)), 1FGL J101 8.6–5856 ([Fermi LAT Collaboration 2012](#)), PSR J2032+4127 ([Abeysekara et al. 2018](#)), and 4FGL J1405.1–6119 ([Corbet et al. 2019](#)) – with the notable exception of LMC P3 in the Large Magellanic Cloud (LMC; [Corbet et al. 2016](#)).

γ -ray binaries are composed of a massive star (O or Be) and a compact object whose nature is in most cases unknown. PSR B1259–63 and PSR J2032+4127 are the only systems for which a pulsar has been identified, but it is believed that the rest of such binaries may also host a neutron star. It is generally accepted that these systems are direct precursors of high-mass X-ray binaries, before the neutron star enters an accretion state. Their intriguing multi-wavelength nature, together with their periodic behaviour makes them optimal laboratories for studying particle acceleration processes in astrophysical sources – for a review, see [Dubus \(2013\)](#) and

references therein. Therefore, even if the geometrical conditions for the systems differ significantly, the search for new binaries may contribute to a better understanding of the general features observed and improve the current evolutionary and population models. One of the main issues within the present status is the number of Galactic γ -ray binaries whose signal at VHE has not been associated because of their low brightness at HE or other wavelengths – for instance, HESS J0632+057-like systems ([Dubus et al. 2017](#)).

HESS J1832–093 is an unidentified point-like source located in the Galactic plane, discovered by [H.E.S.S. Collaboration \(2015\)](#) and confirmed in the H.E.S.S. Galactic plane survey ([H.E.S.S. Collaboration 2018](#)). It is partially coincident with the radio shell of the supernova remnant (SNR) G22.7–0.2. At a distance of $d = 4.4 \pm 0.4$ kpc ([Su et al. 2014](#)), this SNR might be associated with the γ -ray signal, since it shows faint non-thermal radio emission and an extension of $26'$ ([Shaver & Goss 1970](#)). Previous systematic studies on SNRs as seen by the *Fermi* Large Area Telescope (*Fermi*-LAT) considered G22.7–0.2 as a possible HE emitter in the 1–100 GeV range ([Acero et al. 2016](#)). This SNR was initially classified as a candidate for detection, but the strong dependence of the signal significance on the interstellar emission model used for the analysis made its detection uncertain. For this reason, G22.7–0.2 was included in the list of non-detected SNRs – see Table 3 in [Acero et al. \(2016\)](#). At VHE, [H.E.S.S. Collaboration \(2015\)](#) argued that the spatial separation between HESS J1832–093 and G22.7–0.2, together with the existence of infra-red (IR) and X-ray sources spatially

compatible with the γ -ray signal (2MASS J18324516–0921545 and XMMU J183245–0921539, respectively), pointed strongly against an SNR origin. However, the absence of optical and GeV counterparts prevented a clear identification of its nature. Its point-like signal and its significant spatial deviation from the SNR led to ambiguous scenarios for the VHE emission: a pulsar wind nebula (PWN), an active galactic nucleus (AGN) seen through the Galactic plane, a γ -ray binary or the interaction between protons accelerated in the SNR and a nearby molecular cloud (MC). An interacting MC origin would require slow diffusion, an extended source at TeV and a single hadronic component which should also be seen at HE, while an AGN nature was also disfavoured due to the absence of GeV emission and a soft spectral index at VHE (H.E.S.S. Collaboration 2015). This possibility cannot be completely discarded yet, since it could be an unusual host galaxy. On the other hand, the γ -ray binary scenario seems to be preferred over the PWN origin because of the variability observed in X-rays (Eger et al. 2016) and the candidate IR counterpart (Mori et al. 2017). Unfortunately, no pulsations from a pulsar have been found, no orbital period has been established, and no star has been found as the optical counterpart. Identifying a GeV source in this multi-wavelength picture could provide crucial information about the origin of the γ -ray signal. This situation resembles the discovery of HESS J0632+057, where no periodicity nor HE counterpart was discovered at first, but in later studies (Aharonian et al. 2007; Bongiorno et al. 2011; Caliendo et al. 2013; Li et al. 2017).

Motivated by the hints in favour of the binary scenario for HESS J1832–093, we performed a multi-wavelength study of this candidate. In this work, we notice the presence of a HE source close to the binary candidate associated with it, and the SNR shell G22.7–0.2 in the 4FGL catalogue (Abdollahi et al. 2020). We analyse more than ten years of *Fermi*-LAT data as well as archival X-ray and ultraviolet (UV) data from *Swift* (Sects. 2 and 3). Later, we present the spectral results obtained (Sect. 4) and the discovery of an orbital period (Sect. 5). Finally, we discuss the binary interpretation for XMMU J183245–0921539/4FGL J1832.9–0913/HESS J1832–093, and its implications (Sect. 6), finally summarising our conclusions (Sect. 7).

2. *Fermi*-LAT observations and data analysis

The LAT is the main γ -ray detector on board the *Fermi* Gamma-ray Space Telescope (Atwood et al. 2009), covering the energy range between 30 MeV to more than 500 GeV. Its energy-dependent point-spread function (PSF) goes from several degrees at low energies ($\sim 5^\circ$ at 100 MeV) to less than 0.1° above 10 GeV at 68% containment. In this paper, observations from 2008 August 4 to 2018 November 3 were included, using ~ 10.25 years of data. The analysis was performed using *Fermitools*-1.0.1¹ on P8R3 reprocessed data (Bruehl et al. 2018). SOURCE event class (evclass=128) and FRONT+BACK event type (evtype=3) were employed, together with the P8R3_SOURCE_V2 instrument response functions (IRFs). All photons within a $20^\circ \times 20^\circ$ region of interest (ROI) centred on XMMU J183245–0921539 and in the energy range between 100 MeV and 500 GeV were selected. Earth limb contamination was handled by selecting events with zenith angles $< 90^\circ$. The

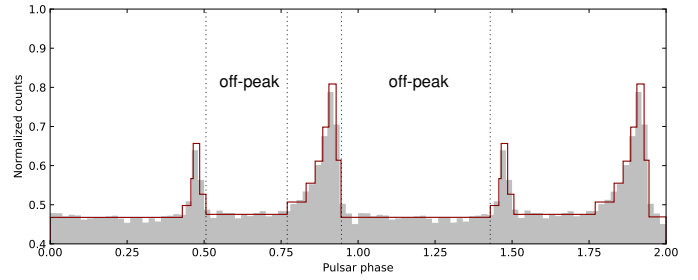


Fig. 1. Pulse profile of PSR J1833–1034 with an ROI of 1° above 100 MeV binned with 100 bins per period (grey). Its Bayesian block representation is shown by the red profile. The off-peak phases are delimited by the vertical black lines.

low energy threshold is motivated by the large uncertainties in the arrival directions of the photons below 100 MeV, leading to confusion between point-like sources and the Galactic diffuse component. See Principe et al. (2018) for a different analysis implementation to solve this and other issues at low energies.

Fluxes presented in this work were obtained performing a binned maximum likelihood fit (Mattox et al. 1996) using *fermipy* 0.17.4² (Wood et al. 2017), with a pixel size of 0.1° and 8 energy bins per decade. The spectral-spatial model employed includes all sources from the 4FGL catalogue *gll_psc_v18* (Abdollahi et al. 2020) within a $30^\circ \times 30^\circ$ region centred on our target. The Galactic and isotropic diffuse components used are “*gll_iem_v07.fits*” and “*iso_P8R3_SOURCE_V2_v1.txt*”, respectively. To evaluate the significance of the detection of each source, the test statistic $TS = -2 \ln(L_{\max,0}/L_{\max,1})$ was used, where $L_{\max,0}$ is the log-likelihood value for the null hypothesis (i.e. model without the source) and $L_{\max,1}$ the log-likelihood for the complete model. The larger the value of the TS, the less likely $L_{\max,0}$ is. A TS of at least 25 ($\sim 5\sigma$ evaluated from a χ^2 distribution with 1 degree of freedom) is required to claim detection of a source (Abdollahi et al. 2020).

The catalogue source 4FGL J1832.9–0913 is spatially close to HESS J1832–093, as well as the X-ray and IR counterparts ($\sim 0.14^\circ$). We consider it as the possible γ -ray counterpart of XMMU J183245–0921539. However, 4FGL J1832.9–0913 is in a crowded region of the Galactic plane, and contamination from bright pulsars might be significant. We searched for known pulsars close to our target and found PSR J1832–0836 (at $\sim 0.6^\circ$) and PSR J1833–1034 (at $\sim 1^\circ$). While the first one is very faint, PSR J1833–1034 is bright at low energies (Abdo et al. 2010). Its emission might be significant and gating it assures no contamination in our ROI. A similar analysis was performed by Li et al. (2017) in their study of HESS J0632+057. Therefore, we split our analysis in two energy bands, gating its emission only below 10 GeV.

In order to attribute a pulsar phase to each event in the ROI, we used TEMPO2 (Hobbs et al. 2006; Edwards et al. 2006) and the *Fermi* plug-in³ (Ray et al. 2011). We adopted an updated ephemeris obtained using the method from Kerr et al. (2015). The pulse profile of PSR J1833–1034 for photons within 1° of the source above 100 MeV is shown in Fig. 1. Its off-peak phase reported in the second *Fermi*-LAT pulsar catalogue (Abdo et al. 2013) does not accurately describe its updated pulse profile. In

¹ This is the nomenclature for the new *Fermi* Science Tools released through Conda. See <https://github.com/fermi-lat/Fermitools-conda/wiki>

² A Python package for the *Fermitools*. See <https://fermipy.readthedocs.io/en/latest/>

³ https://fermi.gsfc.nasa.gov/ssc/data/analysis/user/Fermi_plugin_doc.pdf

order to improve it, we decomposed the pulsed light curve using a Bayesian blocks algorithm as detailed in [Scargle et al. \(2013\)](#). This was the method used by [Abdo et al. \(2013\)](#) in the pulsar catalogue. We redefine the off-peak phases as $\Delta\phi = [0.946–0.429]$ and $\Delta\phi = [0.506–0.770]$. Fluxes were re-scaled by a factor 0.747 to account for the different exposure time.

A maximum-likelihood fit was performed on this reduced dataset using the described source model and binning. Firstly, the iterative `optimize` method from *fermipy* was applied. In a second step, normalization was left free for all sources fewer than 7° from our target. The smaller PSF at higher energies allowed us to perform an analysis above 10 GeV, with an ROI of $8^\circ \times 8^\circ$ and a zenith angle $<105^\circ$. In this case, normalisation for sources within 3° of 4FGL J1832.9–0913 was left free, as well as all parameters for those within 1° .

3. Swift observations and data analysis

The *Neil Gehrels Swift* Observatory ([Gehrels et al. 2004](#)) is one of most versatile missions at X-ray wavelengths. Although its primary goal is to provide detailed information about γ -ray bursts (GRBs), it is widely used to monitor sources using Target of Opportunity (ToO) observations. This satellite has three instruments on board: the Burst Alert Telescope (BAT; [Barthelmy et al. 2005](#)), the X-Ray Telescope (XRT; [Burrows et al. 2005](#)), and the UV/Optical Telescope (UVOT; [Roming et al. 2005](#)). We used 54 archival on-target observations of XMMU J183245–0921539 with *Swift* (see Appendix A), plus about ten serendipitous observations of the region that might be useful for extracting the flux of our binary candidate. In this paper, only XRT and UVOT data have been used: according to the fluxes previously reported in other works ([Eger et al. 2016](#); [Mori et al. 2017](#)), the source is substantially fainter at hard X-rays than the sensitivity limit of the BAT instrument.

3.1. Swift-XRT analysis

The XRT is a grazing-incidence focusing X-ray telescope covering energies between 0.3 and 10 keV, whose ToO programme allows the monitoring of variable X-ray sources. Four observations of XMMU J183245–0921539 with this instrument were included in [Eger et al. \(2016\)](#) but have been re-analysed here. For the analysis of the observations, we used the HEASOFT v6.26 package with the newest calibration database (CALDB) available. Data were reprocessed using XRTPIPELINE, generating CLEANED level 2 events from grades 0–12. All PC data from the 54 observations of XMMU J183245–0921539 (i.e. more than 120 ks of exposure) were selected for the spectral extraction. Using XSELECT, a spectrum was obtained from a circular region of $46.6''$ centred on the binary candidate position. For the background, an annular region between $98.8''$ and $188.8''$ was defined. To account for the detector response, a custom effective area file was produced using XRTMKARF, with the CALDB⁴ file `swxpc0to12s6_20130101v014.rmf`. Additionally, the exposure file generated with XRTPIPELINE was used for the correction. The resulting spectrum was binned with a minimum of 20 counts per energy bin using `grppha`, and later fitted using XSPEC through its `pyxspect` 2.0.2 interface. A χ^2 fit was performed assuming an absorbed power-law model with the hydrogen column density N_H , the spectral index Γ , and normalisation as free parameters.

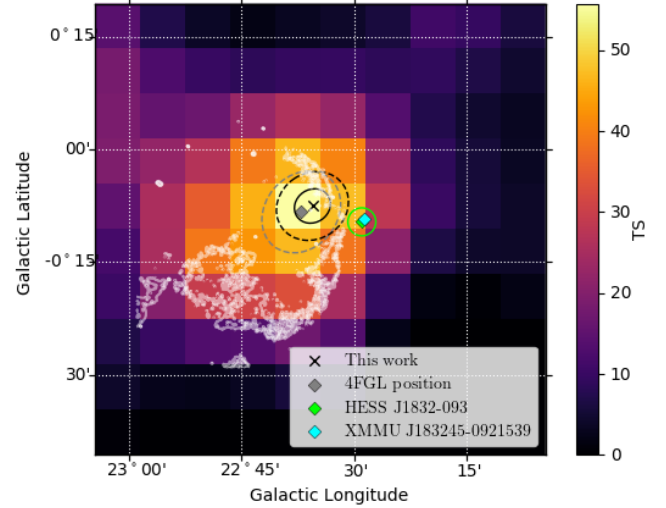


Fig. 2. TS map between 100 MeV and 10 GeV of the region around HESS J1832–093 after gating off PSR J1833–1034. The map includes the positions of the X-ray, GeV and TeV counterparts, as well as the radio contours of SNR G22.7–0.2 ([Helfand et al. 2006](#)). Confidence contours at 67% (solid) and 99% (dashed) levels are added for the 4FGL and the updated source. Additionally, the 95% confidence contour for the TeV counterpart is included.

Adding the serendipitous observations, a similar analysis was performed to obtain an unabsorbed light curve between 0.3 and 10 keV. All observations were analysed separately, obtaining the spectra using XRTPRODUCTS with the same calibration described above. Due to the low number of counts, we imposed the condition of one count per energy bin with `grppha`. Finally, the fluxes were obtained from XSPEC performing a C-Stat fit. For this analysis, an absorbed power-law model was assumed again, but fixing N_H and Γ to the values obtained in the overall spectral analysis described above.

3.2. Swift-UVOT analysis

The UVOT is a diffraction-limited 30 cm Ritchey-Chrétien reflector telescope on board *Swift*, with a $17' \times 17'$ field of view with several filters at UV and optical wavelengths. Apart from the XRT observations, the UVOT telescope also observed the location of XMMU J183245–0921539. V, U, UVM2, UVW1, and UVW2 filters were used to study the region. In this work, all ToO images with the same filter were summed using UVOTISUM. Absolute photometry was applied using both UVOTSOURCE to search for the source and UVOTDETECT to obtain the values for the upper limits. For this purpose, a circular region of $5''$ was selected for the source and an annular region from $8''$ to $13''$ defined for the background to avoid the presence of other sources in the background subtraction. Exposure correction was taken into account.

4. Spectral results

In this section, we present a study of the potential binary spectrum in different energy bands, from the UV to the HE regime.

4.1. GeV energies

4FGL J1832.9–0913 is a γ -ray source included in the 4FGL catalogue ([Abdollahi et al. 2020](#)), close to the position of

⁴ Version 20190412.

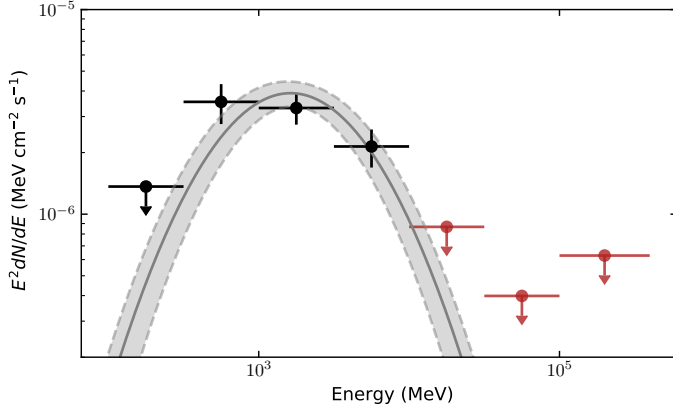


Fig. 3. SED for 4FGL J1832.9–0913 (black) and best fit (grey) from the analysis below 10 GeV after gating off pulsed emission from PSR J1833–1034. In red, upper limits from the analysis above 10 GeV.

HESS J1832–093, and spatially compatible with the SNR G22.7–0.2. It is detected in the catalogue at 7.6σ , with an integrated energy flux between 100 MeV and 100 GeV of $1.88 \pm 0.72 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (here and hereafter, uncertainties are defined at 1σ confidence level). Its spectrum is modelled with a log-parabola,

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_b} \right)^{-(\alpha + \beta \log(E/E_b))}, \quad (1)$$

where E_b is a scale parameter fixed to 1.8 GeV. While it is associated in the catalogue with the SNR and HESS J1832–093, 4FGL J1832.9–0913 is located only 0.14° from the position of the X-ray counterpart (slightly beyond the 95% confidence limit – see Fig. 2). This source is qualified with Flag 2, meaning its position moves beyond the 95% ellipse when changing the diffuse model (Abdollahi et al. 2020).

Following the analysis described in Sect. 2 (i.e. two energy bands, PSR J1833–1034 gated), 4FGL J1832.9–0913 is detected with $TS = 85.72$ (9.26σ) below 10 GeV. We evaluated its spectrum performing an extra fit with all its spectral parameters free, as well as the normalisation of sources within 3° of our target. An integrated energy flux of $1.60 \pm 0.25 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Table 1) is obtained between 100 MeV and 10 GeV, with $\alpha = 2.1 \pm 0.2$ and $\beta = 0.435 \pm 0.007$. Its SED can be seen in Fig. 3, and it is compatible with the results from the 4FGL catalogue. Additionally, we refined its position employing the *localize* function from *fermipy*. The updated location of the γ -ray signal is $(l, b) = (22.593^\circ \pm 0.026^\circ, -0.125^\circ \pm 0.025^\circ)$, reducing the distance between the X-ray and GeV sources to 0.12° .

The analysis above 10 GeV using the whole dataset and a zenith angle $>105^\circ$ does not yield significant emission from the source ($TS = 3.1$), leading to an upper limit of $6.13 \times 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}$ at 95% confidence level. This result confirms the non-detection of any γ -ray source with *Fermi*-LAT in H.E.S.S. Collaboration (2015), when an analysis above 10 GeV was performed with only four years of data.

4.2. UV and X-ray wavelengths

XMMU J183245–0921539 spectrum at keV energies is better described by a power law than using a single thermal component (Eger et al. 2016). The best fit with XSPEC to the archived data between 0.3 and 10 keV provides an unabsorbed integrated energy flux of $5.9^{+0.3}_{-1.6} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, a column density

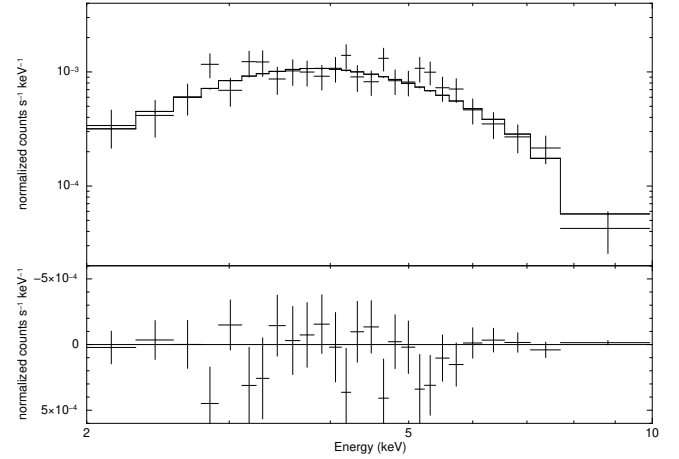


Fig. 4. *Top:* X-ray spectrum for XMMU J183245–0921539 using all observations centred on the binary, fitted to an absorbed power law and zoomed between 2 and 10 keV. *Bottom:* residuals of the fit.

$N_H = (7.3 \pm 1.4) \times 10^{22} \text{ cm}^{-2}$ and a spectral index $\Gamma = 1.46 \pm 0.33$ (Fig. 4). Both N_H and Γ are fully compatible with previous results (Mori et al. 2017), but the flux is lower. From a binary system, we expect variability along an orbit, thus this value would correspond to an average flux if the orbit is completely covered.

The analysis from UVOT data provides for the first time upper limits of the source at UV wavelengths (see Appendix A). The non-detection at optical wavelengths (filter V) down to $2.03 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ at 95% confidence level constrains the flux of the companion star to lower levels than the previous upper limits from surveys (see Sect. 6.2).

5. Search for periodicity

In order to confirm the binary nature of XMMU J183245–0921539 and unambiguously associate it to 4FGL J1832.9–0913, we need to find an orbital period. Therefore, we searched for a periodic modulation of their flux.

5.1. X-ray orbital modulation

X-ray orbital modulation has been observed for all the known γ -ray binaries. Eger et al. (2016) suggested, for the first time, X-ray variability from XMMU J183245–0921539; however, this assessment is insufficient to establish the binary nature without periodicity. Using the observations analysed in this work and the fluxes reported by Mori et al. (2017), we searched for a periodic variability through a Lomb-Scargle periodogram (Lomb 1976; Scargle 1982). To reduce the noise, only observations with more than 1 ks of exposure were selected, and observations earlier than 57200 MJD were discarded due to their poor sampling of the time space. A peak is found at 86.28 ± 3.77 days, with a false alarm probability (FAP) smaller than 5σ (Fig. 5). This FAP is computed using the analytical approximation from Baluev (2008) implemented in *astropy* (Astropy Collaboration 2018). The peak is still detected with $p < 0.01$ using the more conservative bootstrap method (VanderPlas 2018). We arbitrarily define $\phi = 0$ at $T_0 = 54524.9979255$ (the oldest observation performed with *Swift*-XRT of the source). Phase-folding the light curve with this period shows orbital variability (Fig. 6). We can see how the *NuSTAR* and *Chandra* observations (Mori et al. 2017) correspond to the peaks of the light curve. Similar results are

Table 1. Summarised spectral properties of HESS J1832–093.

	Integrated flux	Luminosity	Γ	α	β
VHE ($E > 0.1$ TeV)	$5.1 \pm 1.8 \times 10^{-12}$ erg cm $^{-2}$ s $^{-1}$	1.2×10^{34} erg s $^{-1}$	2.6 ± 0.3	–	–
HE (0.1–100 GeV)	$1.6 \pm 0.3 \times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$	3.7×10^{34} erg s $^{-1}$	–	2.1 ± 0.2	0.435 ± 0.007
X-ray (0.3–10 keV)	$5.9^{+0.3}_{-1.6} \times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$	1.4×10^{33} erg s $^{-1}$	1.46 ± 0.33	–	–

Notes. Luminosities are computed assuming $d = 4.4 \pm 0.4$ (Su et al. 2014). VHE data are from H.E.S.S. Collaboration (2015).

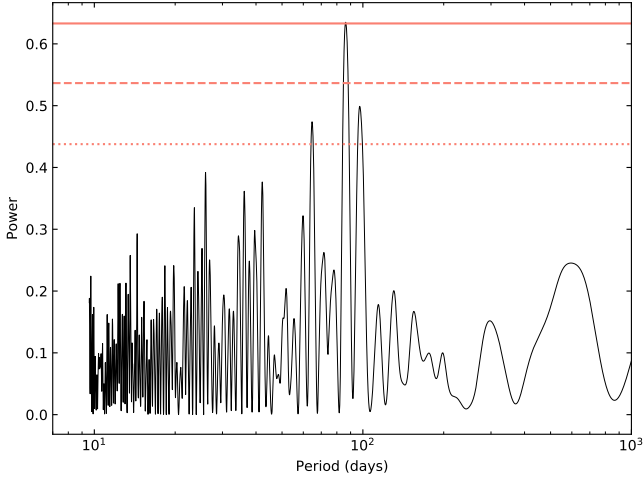


Fig. 5. Lomb-Scargle periodogram for the unbinned light curve in X-rays. A peak is found at $P = 86.28 \pm 3.77$ days. FAP levels are represented in red at 3σ (dotted), 4σ (dashed), and 5σ (solid).

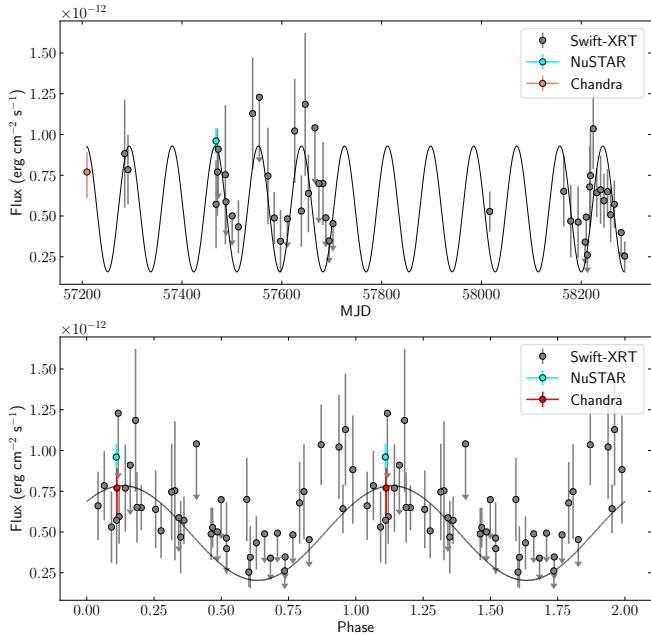


Fig. 6. *Top:* X-ray light curve for XMMU J183245–0921539 in time space, including all observations performed after 57200 MJD. A sinusoidal function with fixed period to 86.28 days is fitted to the data. *Bottom:* phase-folded light curve of the same observations with that period. XMM re-analysis from Mori et al. (2017) has been added for completeness. Data are duplicated in two orbits for visualization purposes.

found if the *Swift* observations are binned assuring at least 1.5 and 2.5 ks per bin, with peaks at 85.94 ± 3.94 and 85.40 ± 3.93 days, respectively. Similar background subtractions to the

one described in Sect. 3.1 have been tested and provide compatible results. Failure modes or other defects (VanderPlas 2018) cannot describe the signal found. Additionally, an epoch-folding method is employed (Leahy 1987). This was successfully used to establish the period of the binary 1FGL J1018.6–5856 with *Swift* observations (An et al. 2013). This methodology allows us to use all observations regardless of individual exposures. The broad peak found is compatible with the previous result, but it is not an improvement compared with the Lomb-Scargle algorithm.

Two other non-negligible peaks are found in Fig. 5, at ~ 96 and ~ 65 days, respectively, and both of them have a non-physical origin. The first one can be explained as a resonance of the window function, meaning it is an artefact produced by the sample of times t_i of the observations. The second one is an effect of the deviation from a sinusoid of the light curve. If a second mode is added to the regular Lomb-Scargle periodogram, a peak is found at 85.37 days and the light curve is well represented by the fit. In this case, no peak is found at ~ 65 days, confirming its origin as an artefact of the residual. γ -ray binaries show a non-symmetric peak in their X-ray light curve peaks (Bongiorno et al. 2011; Dubus et al. 2015; Barkov & Bosch-Ramon 2018; Corbet et al. 2019); thus we do not expect an exact sinusoidal modulation.

5.2. Search for GeV orbital modulation

If 4FGL J1832.9–0913 is associated with XMMU J1832 45–0921539, a similar periodicity should be found in the γ -ray data. Period searches using Fourier series in *Fermi*-LAT data are described by Corbet & Kerr (2010), and blind searches using this method on γ -ray sources led to the discovery of the γ -ray binaries LMC P3 and 4FGL J1405.1–6119 (Corbet et al. 2016, 2019). Using all events within 2° of the binary candidate, we assigned a probability to each of them using the model obtained from the analysis described in Sect. 2. Time bins of 1500 ks were used and weighted with the exposure. No signal is found in the power spectrum obtained. Similar results are obtained if a larger binning is used (e.g. three days).

Additionally, we explored the possibility of adapting the epoch-folding method mentioned before to the γ -ray data. Leahy (1987) proposed an epoch-folding method to determine the period P and the amplitude A of signals with a sinusoidal nature. All the data are phase-folded for a grid of periods P' and binned in the phase space in n bins. Finally, all phase-folded light curves are compared with the average flux using a χ^2 test to search for variability, and those values are plotted in a χ^2 vs. P' plot. This plot should show a peak for the true value of P and white noise for other P' . This method contemplates a χ^2 test for count rates, but we can use the summed probabilities per bin weighted with the exposure, using $n = 10$. A peak is found at 87.106 days (see Fig. 7). Unfortunately, the S statistic defined in Leahy (1987) does not converge, and varying the number of bins used also enhances the smaller peaks found nearby, reaching

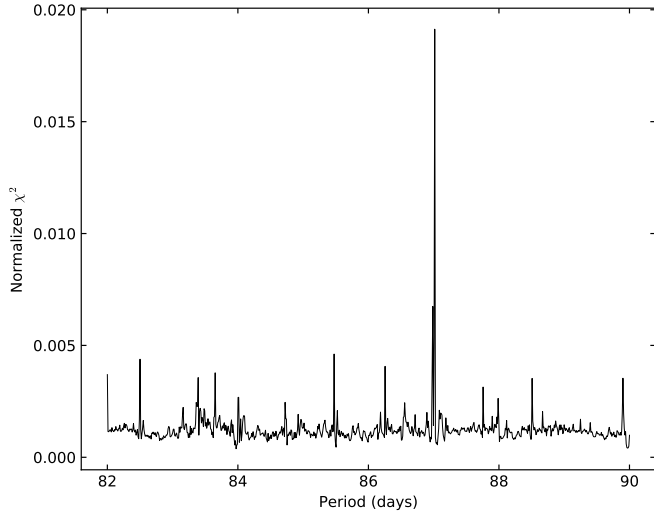


Fig. 7. χ^2 vs. period for the *Fermi*-LAT data. A peak is found at 87.016 days.

similar levels. This makes the result uncertain and might indicate the existence of variability, but it cannot confirm the true period.

These methods for period searches make use of the aperture photometry analysis using all events. A different approach would be to explore the variability of the system performing a maximum likelihood analysis in a phase-binned analysis. We phase-folded the γ -ray data with the 87.106 day period. When an analysis is performed as described in Sect. 2, variability can be appreciated (Fig. 8). However, due to the large flux uncertainties, a χ^2 test cannot discard the hypothesis of non-variability ($\chi^2_{\text{d.o.f.}} \approx 1$). Similar results are found when phase-folding the data with the periods obtained using the binned light curves in X-rays. Searches for variability by phase-folding the results with periods much larger or smaller than 86 ± 3 days do not indicate any variability.

6. Discussion

Given the spatial coincidences of the sources at different wavelengths (Fig. 2) and the flux variability at GeV and keV energies (Fig. 8), the association between XMMU J183245–0921539, 4FGL J1832.9–0913 and HESS J1832–093 is reinforced. Its composite SED using the results obtained in previous sections together with the VHE data (H.E.S.S. Collaboration 2015, 2018) peaks in γ -rays (Fig. 9). Radio upper limits are obtained from MAGPIS (Helfand et al. 2006) and NVSS (Condon et al. 1998). Interestingly, the TeV and GeV components do not arise from a single PL, since the upper limits at intermediate γ -rays prevent such connection. This behaviour is typically observed in γ -ray binaries, where a cut-off between GeV and TeV components is present. This phenomenology showing two separate components has been understood as synchrotron and inverse Compton (IC) emission produced by two different populations of electrons accelerated in the shocked pulsar wind and the Coriolis turnover, respectively (Zabalza et al. 2013), being a consequence of the orbital motion. Actually, the SED observed in Fig. 9 strongly resembles the spectrum from HESS J0632+057, with an excess in the GeV component that might arise from particularities of HESS J1832–093, like the geometry of the system, or a contribution from the nearby SNR G22.7–0.2.

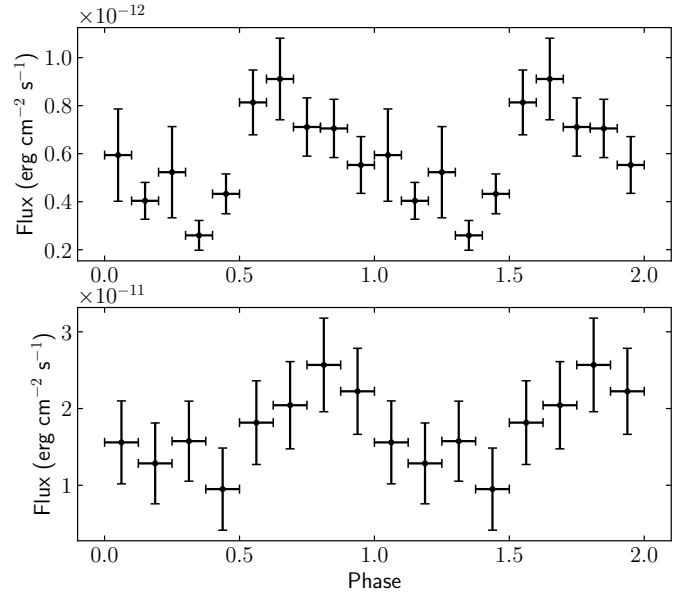


Fig. 8. Light curves folded with $P = 87.016$ days. *Top*: X-rays from *Swift*-XRT. *Bottom*: *Fermi*-LAT data. All fluxes are significantly detected above 2σ per bin. Data are duplicated in two orbits for visualisation purposes.

Regarding the HESS J1832–093 orbital variability, the hints of periodicity in γ -rays allow a comparison between both light curves. In Fig. 8, we see how the peak shifts to later phases from X-ray to GeV. This is a common phenomenon in γ -ray binaries (Chang et al. 2016). Therefore, the relation between GeV and TeV sources for HESS J1832–093 is strengthened. On the other hand, for all γ -ray binaries known, the X-ray and TeV light curves are correlated (Dubus 2013; Aliu et al. 2014). Thus, we expect the TeV component to peak at the same phase as in X-rays. However, it should be noted that these relations between γ -ray and X-ray light curves might change over several orbits for some binary systems (Hadasch et al. 2012).

6.1. A new GeV-faint γ -ray binary

In light of the new results presented in this work, we can finally identify HESS J1832–093 as a new member of the γ -ray binary class. Corbet et al. (2016) suggested that the discovery of LMC P3 in the LMC could be interpreted as an indication that almost all the observable population of γ -ray binaries in our Galaxy had been already discovered. However, the confirmation of the binary nature of HESS J1832–093, and the recent discovery of 4FGL J1405.1–6119 (Corbet et al. 2019), do not support this interpretation.

Early works predicted an overall population of ~ 30 γ -ray binaries in the Milky Way (Meurs & van den Heuvel 1989). However, in a more recent study performed by Dubus et al. (2017), the population of Galactic γ -ray binaries was estimated to be 101^{+89}_{-52} . The main factor of uncertainty in this model is the TeV unassociated sources whose GeV component might be faint (i.e. systems similar to HESS J0632+057 and HESS J1832–093). According to Dubus et al. (2017), such systems have extremely low probabilities of being detected in *Fermi*-LAT or H.E.S.S.-like surveys ($\sim 0.8\%$), but the detection of HESS J0632+057 as a faint GeV source (Li et al. 2017) placed an upper limit to the number of similar systems as 231.

The resemblance between HESS J1832–093 and HESS J0632+057 might be an indication of a population of γ -ray

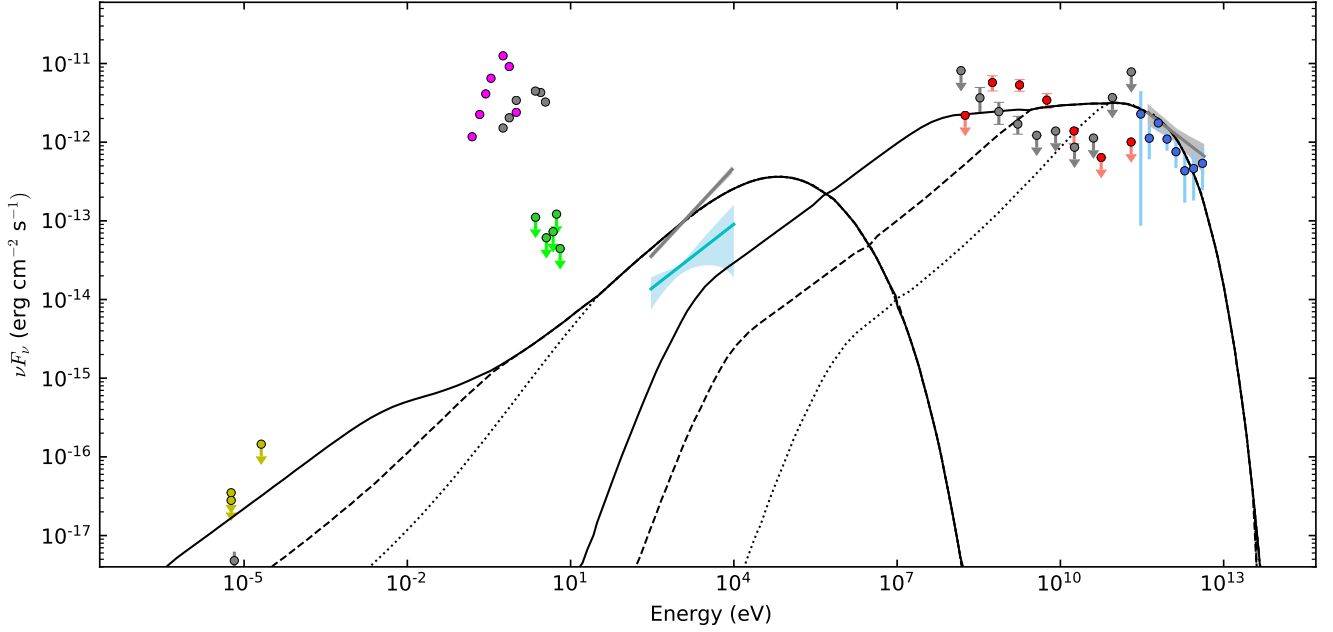


Fig. 9. SED of HESS J1832–093: radio upper limits (yellow) (Condon et al. 1998; Helfand et al. 2006), IR (magenta) (Skrutskie et al. 2006), UV (green), X-rays (cyan), HE (red), and VHE (blue) γ -rays (H.E.S.S. Collaboration 2015). In grey, SED from HESS J0632+057 is shown for comparison, including radio (Moldón et al. 2011), IR re-scaled a factor 10^{-3} (Skrutskie et al. 2006), X-ray (Hinton et al. 2009), and γ -rays (Li et al. 2017; Aharonian et al. 2007). In black, synchrotron and IC emission models for HESS J0632+057 with $E_{\min}$ of 1 GeV (solid), 10 GeV (dashed) and 100 GeV (dotted) (Hinton et al. 2009).

binaries which have not been identified due to observational biases. While other steady binaries have $L_{\text{GeV}} \approx 10^{35} \text{ erg s}^{-1}$, HESS J1832–093 is one order of magnitude fainter at HE but similarly bright at VHE – see Table 2 in Dubus (2013). The detection threshold in systematic searches for periodicity performed by Corbet et al. (2019) is consistent with the non-identification of HESS J1832–093 due to its lack of detection above 10 GeV. Given the low probability of serendipitous detections of new binaries, new observational approaches are required. Multi-wavelength synergies between observatories at all frequencies are necessary, especially between X-rays and VHE. Dubus et al. (2017) estimated that the CTA (Cherenkov Telescope Array Consortium 2019) will be able to detect a few of these systems within the first two years of observations, but as is seen in the case of HESS J1832–093, X-ray surveys such as eROSITA (Merloni et al. 2012) could be used to properly identify the systems once they are detected.

6.2. On the optical counterpart issue

Apart from period searches, resolved spectra from a faint source would unambiguously distinguish between a binary containing a massive star or an AGN. Unfortunately, no optical counterpart is found in the sky surveys performed at visible wavelengths, even in *Gaia* DR2⁵. After finding an orbital modulation at other wavelengths, the absence of an optical counterpart has to be properly understood.

Since G22.7–0.2 is in a complex region with MCs, H_{II} regions, and the GLIMPSE9 stellar cluster (Su et al. 2014), we consider the possibility of having a binary object related with those systems, thus at a distance of $d = 4.4 \pm 0.4 \text{ kpc}$. Assuming this distance and using previous observations from the literature

of the IR candidate counterpart 2MASS J18324516–0921545, Mori et al. (2017) derived a spectral type between B8V and B1.5V, fully compatible with the stars found in other γ -ray binaries (Dubus 2013). They obtained an optical absorption of $A_V = 7.7$ using the hydrogen column density from radio surveys $N_H = 1.7 \times 10^{22} \text{ cm}^{-2}$ (Gorenstein 1975; Willingale et al. 2013; Mori et al. 2017). Using this extinction and the typical luminosities of spectral types B0–B8 (Binney & Merrifield 1998), we obtain a range of V magnitudes between 16.7 and 20.7. We note that this is only a lower limit, since the hydrogen column density obtained from X-rays is significantly higher ($N_H = 7.3 \times 10^{22} \text{ cm}^{-2}$). The result is consistent with its non-detection, taking into account that *Gaia* DR2 completeness is affected for sources fainter than $G = 17 \text{ mag}$ due to systematics, especially in crowded regions in the Galactic plane.

However, our upper limit in the V filter of 20.5 mag is more restrictive, and the source should have been observed. Therefore local dust absorption is required if the assumption of $d = 4.4 \pm 0.4 \text{ kpc}$ is correct. As Mori et al. (2017) suggested, high absorption would also allow an O primary star, since we obtain an upper limit for the optical absorption of $A_V = 33.2$ using the X-ray measurement. New data releases from *Gaia* or dedicated photometric and spectroscopic observations are necessary to identify the stellar type of the companion and obtain a proper distance to the system.

7. Summary

We used *Fermi*-LAT data and *Swift* archival observations to understand the origin of the TeV source HESS J1832–093. The spectral and temporal analysis performed in the present work led to the following results:

1. 4FGL J1832.9–0913 is a γ -ray source spatially compatible with the binary candidate HESS J1832–093. We update its

⁵ <https://gea.esac.esa.int/archive/documentation/GDR2/> (Gaia Collaboration 2016).

position, reducing the distance to 0.12° , which is smaller than our PSF at 1 GeV (0.8° at 68% containment).

2. This source is only detected below 10 GeV with *Fermi*-LAT.
3. A period of ~ 86 days is obtained from the X-ray *Swift*-XRT data, confirming the existence of a binary system. Indications of a similar periodicity are found in the *Fermi*-LAT γ -ray data.
4. The SED shows a bimodal component at high energies, a feature characteristic of γ -ray binaries. In particular, the SED from HESS J1832–093 strongly resembles that of the binary HESS J0632+057.
5. The population of γ -ray binaries might be larger than expected due to the existence of further faint-GeV binaries like HESS J1832–093 and HESS J0632+057.

HESS J1832–093 is therefore identified as a new γ -ray binary. Subsequent multi-wavelength observations will be able to establish the geometrical, thermal and high-energy properties of the system⁶.

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⁶ During the publication process of this work, Tam et al. (2020) reported a multi-wavelength study of HESS J1832–093.

Appendix A: *Swift* observations**Table A.1.** continued.**Table A.1.** *Swift*-XRT observations of XMMU J183245–0921539 in PC mode.

OBS_ID	MJD	Exposure (s)
00010378001	58203	4707.4
00010378002	58210	2414.9
00010378003	58212	1920.4
00010378004	58217	2230.1
00010378005	58218	2622.2
00010378006	58224	3860.9
00010378007	58231	4849.7
00010378008	58238	4585.0
00010378009	58245	4859.7
00010378010	58252	4732.3
00010378011	58259	4124.1
00010378012	58266	4615.0
00010378014	58280	4759.8
00010378015	58287	4659.9
00034056001	57285	2599.7
00034056002	57291	2826.9
00034056003	57471	1795.6
00034056004	57472	1168.7
00034056005	57486	1158.8
00034056006	57488	1478.7
00034056007	57500	3281.0
00034056008	57513	2197.6
00034056009	57518	549.4
00034056010	57529	159.8
00034056011	57530	1858.0
00034056012	57538	641.8
00034056014	57541	1855.5
00034056015	57555	1186.2
00034056016	57557	626.8
00034056017	57561	0.0
00034056018	57572	1445.9
00034056019	57576	894.0
00034056020	57578	317.2
00034056021	57584	3066.7
00034056022	57597	3596.1

OBS_ID	MJD	Exposure (s)
00034056023	57611	3728.4
00034056024	57625	2122.7
00034056025	57626	357.1
00034056026	57631	472.0
00034056027	57639	1910.4
00034056028	57644	174.8
00034056029	57646	1423.5
00034056030	57653	2250.1
00034056031	57658	1311.1
00034056032	57666	2554.7
00034056034	57674	1256.1
00034056035	57682	2130.2
00034056036	57685	5.0
00034056037	57688	2899.3
00034056038	57694	3710.9
00034056039	58165	1780.6
00034056040	58179	1770.6
00034056041	58193	1947.9
00034056042	58207	2005.4
00034056031	57658	1311.1
00036174001	54524	2320.1
00036174002	56974	252.2
00036174004	57702	1028.9
00044299001	56242	524.4
00044307001	56244	489.5
00081776001	57468	1730.6
00087484001	58016	4490.1
00087484003	58177	474.5
00087518004	58174	397.1

Table A.2. UVOT upper limits at 95% confidence level in $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$.

Filter	V	U	UVM2	UVW1	UVW2
Flux	2.03×10^{-17}	1.76×10^{-17}	5.42×10^{-17}	2.80×10^{-17}	2.30×10^{-17}