A Multiwavelength Study of the $\gamma$-Ray Binary Candidate HESS J1832–093

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Received 2019 November 17; revised 2020 June 13; accepted 2020 June 17; published 2020 August 13

Abstract

We investigate the nature of the unidentified very-high-energy $\gamma$-ray object, HESS J1832–093, in a multiwavelength context. Based on X-ray variability and spectral index ($\Gamma_X \sim 1.5$), and its broadband spectrum, which was remarkably similar to that of HESS J0632+057—a confirmed $\gamma$-ray binary—HESS J1832–093 has been considered a strong $\gamma$-ray binary candidate in previous works. In this work, we provide further evidence for this scenario. We obtained a spectrum of its IR counterpart using Gemini/Flamingo, finding absorption lines that are usually seen in massive stars, in particular O stars. We also obtained a rather steep ATCA spectrum of its IR counterpart using Gemini/Flamingo, finding absorption lines that are usually seen in massive stars, in particular O stars. Based on spatial-spectral analysis and variability search, we found that 4FGL J1832.9-0913 is possibly associated with SNR G22.7−0.2 rather than with HESS J1832–093 only.

Unified Astronomy Thesaurus concepts: High mass x-ray binary stars (733); Gamma-ray sources (633); Spectroscopy (1558); Galactic radio sources (571); Massive stars (732)

1. Introduction

$\gamma$-ray binaries are a class of high-mass X-ray binaries that radiates predominantly in the $\gamma$-ray energy band in the $\nu\nu_{\gamma}$ representation (Dubus 2013). Comprised of a neutron star or a black hole, and a O/Be companion, $\gamma$-ray binaries consisted of only several well-established members until 2019: PSR B1259−63, LS I 61 303, LS S039, HESS J0632−057, 1FGL J1018−5658 (Dubus 2015; Li et al. 2017), PSR J2032+4127 (Lyne et al. 2015; Ho et al. 2017; Abeysekara et al. 2018), a point source “P3” in the Large Magellanic Cloud (Corbet et al. 2016; HESS Collaboration et al. 2018), and 4FGL J1405.1-6119 (Corbet et al. 2019). All of them have been detected above 100 GeV by ground-based Cerenkov telescopes and/or at 100 MeV to 100 GeV by the Large Area Telescope (LAT) on board the Fermi satellite.

The Cerenkov telescope array, the High Energy Stereoscopic System (H.E.S.S.), was used to discover HESS J1832−093 in the vicinity of supernova remnant (SNR) SNR G22.7−0.2. It is seen as a point source by H.E.S.S., and its 0.4−5 TeV spectrum is well fit by a single power law with a photon index of $\Gamma_{\text{TeV}} = 2.6 \pm 0.3_{\text{stat}} \pm 0.1_{\text{syst}}$. Its flux is around 1% that of the Crab Nebula above 1 TeV. The observations were carried out from 2004 to 2011, comprising 67 hr live time, and no variability was found in the data (HESS Collaboration 2015). Based on its proximity to SNR G22.7−0.2 and spatially coincident CO emission, an SNR–molecular cloud interaction scenario was suggested. HESS Collaboration (2015) also used >10 GeV data from the Fermi/LAT and did not find any significant emission. HESS J1832−093 has been observed with various X-ray instruments since 2008. An X-ray source, XMMU J183245−0921539, consistent with the location of HESS J1832−093, was found in a dedicated XMM-Newton observation in 2011 (HESS Collaboration 2015). While the X-ray column density of $N_{\text{H}} \sim 10^{23}$ cm$^2$ toward the source is high (Eger et al. 2016; Mori et al. 2017), its X-ray flux is at the level of $10^{22}$ erg cm$^{-2}$ s$^{-1}$ with a hard photon index of $\sim 1.5$. A Chandra observation in 2015 July (MJD 57209) was used to refine the XMM-Newton source location and it is fully consistent with an infrared (IR) source, 2MASS J18324516−0921545 (Eger et al. 2016). It is very likely that the IR, X-ray and TeV sources are associated with each other based on the spatial coincidence. The Chandra observation also constrained the X-ray source size to be $<0\prime\prime.28$ with 90% confidence. NuSTAR detects X-rays up to 30 keV with a $\Gamma_X = 1.5 \pm 0.1$ spectrum, showing particle acceleration typically seen in Galactic $\gamma$-ray binary systems. No X-ray periodicity from 4 ms to 85.7 ks was found in the NuSTAR data (Mori et al. 2017).

Eger et al. (2016) reported that Chandra saw XMMU J183245−0921539 at an elevated X-ray flux state (on MJD 57209; about a factor of 6 above other measured X-ray flux), while the X-ray flux at other epochs (obtained by Swift/XRT and XMM-Newton observations) are consistent with being constant (Eger et al. 2016). However, this level of variability is disputed (Mori et al. 2017), who instead suggest an X-ray variability at the level of 50% based on the XMM-Newton and NuSTAR flux at two different epochs. If confirmed, such a variability almost certainly rules out scenarios that predict steady emission, including SNR–molecular cloud interaction or a putative pulsar wind nebula. Instead, as discussed in Eger et al. (2016), we seem to left with two scenarios: a $\gamma$-ray binary or an active galactic nucleus (AGN).

There is no known optical counterpart, and it is likely because of high level of absorption revealed by the X-ray data. Spitzer detected the IR counterpart, 2MASS J18324516−0921545, up to 8 $\mu$m (from the catalog; source name SSTGLMC G022.4768-00.1539). Pan-STARRS (DR2) have a few measurements in the $i_-$ (= 21.52 ± 0.16), $z_-$ (= 20.32 ± 0.11), and $y_-$ (= 19.70 ± 0.06) bands.

To further probe the origin of HESS J1832−093, we obtained Gemini-south NIR spectroscopic observations and...
investigate the Fermi-LAT data obtained over the first 10.6 yr. We also obtained data by ATCA (2016 June 2) and Swift/XRT (up to MJD 58287). Based on the multiwavelength data sets, we argue that HESS J1832−093 is indeed a γ-ray binary.

2. Gemini Near-infrared Observation

We obtained a Fast Turnaround (FT) mode of observation using the FLAMINGOS-2 (long-slit spectrograph) instrument at the Gemini-south Observatory on 2016 June 2. The data reduction was done using the IRAF\(^8\) software. The spectra that we obtained are shown in the upper panel of Figure 1. The data quality is not particularly high and we note several strong telluric absorption lines due to water vapor.

To quantify the signal-to-noise ratio of any stellar lines among the telluric lines, we define \( r \) to be (area of the absorption lines measured—Area of the telluric absorption lines)/(area of the telluric absorption lines), and identify four lines with \( r > 4 \), which are shown in Table 1, together with their equivalent widths. The region longer than 1.72 \( \mu \)m in the \( H \) band is severely contaminated, and the contamination is more severe in the \( H \) band than in the \( K \) band. To make the situation more explicit, we depict in the bottom panel of Figure 1 the IR transmission spectra taken from the Gemini website.\(^9\)

We found evidence of the lines related to Br\(\gamma\), Br\(11\), H\(e\) I, and H\(e\) II, many of which are seen in massive stars only:

1. The H\(e\) II 2.189 \( \mu \)m line is seen in O stars but not B stars (Martins et al. 2019).
2. He\(e\) II (1.6923 \( \mu \)m) line appears only in the O-type star (Hanson et al. 1998; Roman-Lopes et al. 2018).
3. The equivalent width of H\(e\) I (1.7007 \( \mu \)m) line shows that the spectral type should be before O8 or after B2 (Blum et al. 1997).
4. The equivalent width of Br\(11\) (1.6811 \( \mu \)m) line would indicate that the star is an O-B1 star (Roman-Lopes et al. 2018).

Therefore, combining all the information above, we suggest that the IR counterpart of XMMU J183245−0921539 to be an O- or, less likely, early B-type star. The lack of prominent emission line in NIR also rules out a circumstellar disk normally associated with a Be star. Therefore, we conclude that

\[^{8}\text{IRAF is distributed by the National Optical Astronomy Observatories.}\]
\[^{9}\text{https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-transmission-spectra}\]
the NIR counterpart is a massive star, and not an AGN. This conclusion is consistent with the photometric considerations (in the J and K bands) reported in Mori et al. (2017).

3. Fermi/LAT observations of HESS J1832−093

The LAT detector is an all-sky monitor at energies from several tens of MeV to more than 300 GeV (Atwood et al. 2009). The γ-ray data used in this work were obtained using the Fermi/LAT between 2008 August 4 and 2019 March 13. We used Fermi Tools 1.0.0 to reduce and analyze the data. Pass 8 data with energy 100 MeV to 500 GeV classified as “source” events were used. To reduce the contamination from Earth albedo γ-rays, events with zenith angles greater than 90° were excluded. The instrument response functions “P8R3_SOURCE_V2” were used.

3.1. Maximum-likelihood Analysis

We carried out a binned maximum-likelihood analysis (gtlike) of a rectangular region of 15° × 15° centered on the position of HESS J1832−093. We subtracted the background contribution by including the Galactic diffuse model (gll_iem_v07.fits) and the isotropic background (iso_P8R3_SOURCE_V2_v1.txt) as well as the 4FGL (Abdollahi et al. 2020) sources within 20° away from HESS J1832−093. FL8Y sources were also employed (instead of 4FGL sources) for cross-check purposes. In the FL8Y/4FGL catalog, one source, 4FGL J1832.9-0913 (i.e., FL8Y J1832.5-0921), is said to be associated with HESS J1832−093/SNR G22.7−0.2, in accordance with HESS Collaboration (2015). Moreover, both catalog sources were located very close to HESS J1832−093, hence we did not treat FL8Y J1832.5-0921/4FGL J1832.9-0913 as a background source in our analysis. The γ-ray pulsars PSR J1831-0952 and PSR J1833-1034 are within one degree from HESS J1832−093. The former γ-ray pulsar was reported in Laffon et al. (2015) and no timing ephemeris has been given. Considering also that the current available timing ephemerides of the latter is valid until 2013 October only, we did not perform pulsar gating in the likelihood analysis. However, we include 4FGL J1831.5-0935 (associated with PSR J1831-0952) in the background model, as this pulsar is within 0.4 degrees from HESS J1832−093. The recommended spectral model for each source in the corresponding catalog was used, while we modeled a putative source exactly at the position of HESS J1832−093 with a power law (PL):

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma},$$

where the normalization $N_0$ and spectral index $\Gamma$ were allowed to vary. The normalization parameter values for the Galactic and isotropic diffuse components, and for the sources within 6° from HESS J1832−093, the normalization $N_0$, and spectral index $\Gamma$ were allowed to vary as well.

HESS J1832−093 was detected with $TS = 95.8$ in this analysis. The best-fit power-law index is $2.46 \pm 0.70$, and the photon flux is $(5.10 \pm 1.48) \times 10^{-8} \text{ photons cm}^{-2} \text{ s}^{-1}$. We repeated the analysis using photons within narrower energy bands (i.e., 0.1–0.3 GeV, 0.3–1.0 GeV, 1–3 GeV, 3–15 GeV, and 15–300 GeV), and the flux obtained is plotted in the spectral energy distribution (see Figure 6). We also attempted to use a power-law with an exponential cutoff (PLE), and the best fit of PLE gives a spectral index of $\Gamma = 1.58 \pm 0.29$ and a cutoff energy of $E_c = 650 \pm 140 \text{ MeV}$. However, PLE shows no statistical improvement. To produce the TS map shown in Figure 2, we use 1–500 GeV clean, front-converted photons to avoid low-energy photon contamination from nearby sources.

As the SNR G22.7-0.2 is only 11°/5 from XMMU J183245−0921539, and the former can potentially contribute to the γ-rays that we see (e.g., by SNR–molecular cloud interaction), we subtract the contribution of HESS J1832−093 by inserting HESS J1832−093 into the background source model, and recompute the TS map. We find that residual emission (besides those from HESS J1832−093) exists with a TS value of about 25, and is located at R.A. = 18°33′01.3″, decl. = −09°12′00″± 6′ (J2000), which is fully embedded within the radio contours of SNR G22.7-0.2.

Another diagnosis to unveil the origin of 4FGL J1832.9-0913 is to search for spatial extension of the source. For this purpose, we insert uniform disks of various radius, from 0.05 to 0.45, centered on the TS peak position in Figure 2. In this analysis, we used spatial bins of 0.02 to increase spatial resolution, while allowing the spectral parameters of sources within 3° from HESS J1832−093 to vary. Figure 3 shows how the TS value of the source varies with increasing radius. It can be seen that a uniform disk with a radius of 0.2±0.03 is preferred over a point source. The difference in TS indeed indicates spatial extension for 4FGL J1832.9-0913 at the 3.6σ level.

3.2. Periodicity and Variability Search

One distinguishing feature of γ-ray binaries is their orbital periodicity. We tried a box-fitting algorithm (Kovács et al. 2002) and did not find any significant periodicity for timescales from 10−1 to 103 s. We also created a γ-ray light curve using a bin size of 1 day and searched for periodicity with a Lomb–Scargle algorithm (Lomb 1982; Scargle 1982). We further used the REDFIT algorithm to estimate the red noise level (Schulz & Muzelsee 2002). Only a peak located at ~53.4 days, which is the precession period of the Fermi orbit, is clearly above the red noise level.

To probe any possible variability in GeV γ-rays, we produced light curves using the likelihood analysis for time bins of sizes 173.5 days, which is a balance between small photon statistics and the desire to probe variability on timescales shorter than about a year. The background source model used in the previous section is also used here. We do not see any significant change in flux nor spectral index in different time bins. A 88 day binned light curve is also produced and again no strong variability can be seen.

To formally assess whether HESS J1832−093 varies at GeV energies, we follow the same treatment for variability as in 2FGL (Nolan et al. 2012), as well as in the 3FGL (Acero et al. 2015) catalog, by comparing the difference of the likelihood in the null hypothesis (the flux of HESS J1832−093 is stable over the full time range) and that in the alternative hypothesis (the source flux is allowed to vary). The variability index thus obtained is 26.9, which for 21 degrees of freedom corresponds to a variability confidence level just below 90% (which would have a variability index 29.6). Therefore, we do not detect any significant variability.

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10. Provided by the FSSC at http://fermi.gsfc.nasa.gov/sci/.
11. https://fermi.gsfc.nasa.gov/sci/data/access/lat/FL8Y/
12. http://www.slac.stanford.edu/~kerrm/fermi_pulsar_timing/
4. ATCA Radio Observations

We conducted radio continuum observations with ATCA under project CX359, when the array was in 1.5B configuration. These were carried out on 2016 June 2, 14:56 to 19:04 UT, for a total of 3.6 hr on source. The Director’s Discretionary Time observations were prompted by the large X-ray flux variability reported by Eger et al. (2016). We simultaneously observed two frequency windows, centered at 5.5 and 9 GHz, each with a bandwidth of 2 GHz. We used the source PKS 1934-638 as a bandpass and flux calibrator, and 1829−106 as a phase calibrator. The data were flagged and calibrated in Miriad v1.5 (Sault et al. 1995) using standard procedures. We imaged the data in CASA 4.5 (McMullin et al. 2007) using Briggs weighting of robustness 1, which balances sensitivity and spatial resolution.

Resolutions of 44′′ × 15′′ at 5.5 GHz and 25′′ × 12′′ at 9 GHz were achieved. We detected significant unresolved emission near the X-ray position of HESS J1832−093, which we characterized by fitting a point source in the image plane using the CASA IMFIT task. In the higher signal-to-noise image (5.5 GHz), the position of this source was R.A. (J2000) = 18:32:45.154 ± 0.009 s or 0′′.13, decl. (J2000) = −09:21:57.6 ± 2′′.6, which is fully consistent with the Chandra position (Eger et al. 2016). At 5.5 GHz, we obtained the flux density of $S_{5.5} = 211 ± 31$ μJy. At 9 GHz, $S_9 = 118 ± 37$ μJy. Taking the conventional form of the spectral index $\alpha$ as in $S_{\nu} \propto \nu^{\alpha}$, one obtains $\alpha = -1.18^{+1.04}_{-0.88}$.

The steep spectrum does not suggest the radio source is an AGN, which should have a rather flat spectrum. Within the γ-ray binary scenario, this radio counterpart may be due to the synchrotron radiation from shocked electrons or a putative radio pulsar.

5. Swift/XRT Observations of HESS J1832−093

Long-term X-ray monitoring is essential to check for any flare-like emission or variability of the source in X-rays. Eger et al. (2016) reported X-ray observations up to MJD 57291. We obtained 41 additional measurements from MJD 57460 to
MJD 58287. The exposures ranges from <1 ks to 5 ks. Most of them are useful to build a long-term X-ray light curve, but the data qualities are not good enough for meaningful spectral analyses. In particular, the photon index ($\Gamma_X$) and column density ($N_H$) are not constrained by the Swift data, therefore we take the value of $N_H$ to be $\approx -9.5 \times 10^{22}$ cm$^{-2}$ and $\Gamma_X = 1.5$, which is obtained from a joint fit of the Chandra, XMM-Newton, and NuSTAR spectra (Mori et al. 2017). This gives a count-to-energy flux ratio of one count to $1.382 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV). This is a bit different from that presented in Martí-Devesa & Reimer (2020), who performed a spectral analysis of each data set and calculated the unabsorbed flux.

To extract the XRT light curve, we used the Swift online analysis tool\(^{13}\) (Evans et al. 2007, 2009) to take good care of bad pixels, vignetting, and point-spread function (PSF) corrections of the data. All parameters were left at program default values with the option binning by observation chosen.

The light curve (Figure 4, beyond MJD 57200) is shown together with the Chandra and NuSTAR data as presented in Mori et al. (2017). Fitting the full XRT count rate (including those before MJD 57200) with a constant flux returns a $\chi^2$(d.o.f.) value of 38.5(40). Therefore, no significant variability can be inferred solely from the Swift/XRT data due primarily to the large error bars.

We also searched for periodicity at timescales $>0.5$ day. In both cases, no significant signal is seen. The highest peak is located at 86 days if the three data points before MJD 57200 are included, but if we exclude those three data points, the highest peak will be located at 7.4 days, followed by 95 days (see Figure 5). The normalization of our Lomb–Scargle power spectra are based on that in Scargle (1982) and the false alarm probability is calculated based on the number of independent frequency from formula (13) in Horne & Baliunas (1986). Our algorithm is rewritten from this IDL program developed by Joern Wilms.\(^{14}\) We note that the significance of this peak varies by adding/removing a few data points (or by adding new observations).

\(^{13}\) http://www.swift.ac.uk/user_objects/

\(^{14}\) http://astro.uni-tuebingen.de/software/idl/aitlib/timing/scargle.html
~86 day orbital variability using a similar set of X-ray data. However, we obtained only a marginal detection (∼2σ) of the 86 day period. We note that both results are subject to the low count rate and thus large errors and insufficient sampling seen by Swift/XRT. X-ray observations including data from sensitive X-ray instruments will help to resolve this discrepancy.

6. Discussion

Among the five firmly identified TeV γ-ray binaries so far, PSR B1259−63, LS 5039, LS I+61 303, and 1FGL J1018.6−5856 all exhibit a peak in their SED at MeV−GeV energies, while HESS J0632+057 may also have been detected in this energy band (Li et al. 2017). A MeV−GeV peak may be due to synchrotron emission; see, e.g., PSR B1259−63 by Abdo et al. (2011), Tam et al. (2015). For HESS J0632+057, with its SED peak possibly in TeV, an inverse Compton (IC)-dominated model has been considered (Hinton et al. 2009; Yi & Cheng 2017; Barkov & Bosch-Ramon 2018).

Based on our Fermi analysis results shown in Figure 6, the SED, i.e., the GeV band, of HESS J1832−093 looks like neither the four former binaries nor HESS J0632+057. Assuming the GeV emission is indeed due to HESS J1832−093, it would suggest that HESS J1832−093 is spectrally different from those previous identified TeV γ-ray binaries. We test two simplified one-zone models to explain its SED, a synchrotron-dominated model (not shown) and an IC-dominated model (shown as in Figure 6), both of which face difficulties to explain the spectrum of 4FGL J1832.9−0913. The GeV spectrum possibly includes a contribution from unrelated sources, such as the SNR G22.7-0.2. This possibility is supported by the possible extended morphology of 4FGL J1832.9−0913 (Section 3.1). If this is the case, the rather low break energy found (∼650 MeV in the PLE fit, see Section 3.1) is similar to those found for middle-aged SNRs, e.g., W44 (Uchiyama et al. 2012) and W51C (Abdo et al. 2009). Future planned missions, including eastrogam (De Angelis et al. 2017) and AMEGO,15 with their better PSF below 1 GeV, will certainly help.

7. Conclusion

The X-ray and TeV spectra of HESS J1832−093 are similar to those of other γ-ray binaries, e.g., HESS J0632+057, as noted before, suggesting HESS J1832−093 is also a γ-ray binary. In this work, we present several additional observations to further support this scenario:

1. We present the first NIR spectroscopy of the IR counterpart of HESS J1832−093, which identifies it as an O-, or less likely, an early B-type star; this result is consistent with a photometric measurement (Mori et al. 2017);
2. A radio source coincident with the massive star is a strong case for a γ-ray binary. The rather steep ATCA spectrum is consistent with the synchrotron radiation from shocked electrons or a radio pulsar residing in the binary.
3. The GeV source—4FGL J1832.9−0913 is located just ∼10′ from HESS J1832−093, and well within the radio emission of the SNR G22.7-0.2. There is no significant evidence for variability of this source. Evidence of extension at a radius of 12′ and the unique GeV spectrum, which is difficult to explain with conventional γ-ray binary models, seem to support the SNR scenario. In this case, HESS J1832−093 remains one of the only γ-ray binaries (candidates) without a Fermi-LAT counterpart. Future missions with better PSF will help verify the nature of 4FGL J1832.9−0913.

4. Mori et al. (2017) found a ∼50% X-ray flux variability based on XMM-Newton and NuSTAR observations. However, no significant variability can be inferred from the Swift/XRT data due primarily to the large error bars. This indicates that regular monitoring using sensitive X-ray instruments is needed to constrain the real X-ray light curve. Finding such a light curve could possibly help identify the orbital period of HESS J1832−093, as was the case for HESS J0632+057.

To conclude, we find that the radio, IR, X-ray, and TeV point sources are associated with each other based on positional coincidence. Moreover, they all support this γ-ray binary hypothesis, while 4FGL J1832.9−0913 involves alternative

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15 https://asd.gsfc.nasa.gov/amego/
sources, i.e., SNR G22.7-0.2. Further radio observations with more accurate spectral measurements and dedicated radio pulsar timing searches are needed to understand the nature of the radio source. Monitoring observations in the radio and X-ray will be key to better characterize the binary system, including its orbital period and the nature of the compact object.

This research made use of data supplied by the High Energy Astrophysics Science Archive Research Center (HEASARC) at NASA’s Goddard Space Flight Center, and the UK Swift Science Data Centre at the University of Leicester. We thank ATNF for the rapid scheduling of the ATCA observations. The Australia Telescope Compact Array is part of the Australia Telescope National Facility which is funded by the Australian Government for operation as a National Facility managed by CSIRO. This work is supported by the National Natural Science Foundation of China (NSFC) through grants 11633007 and U1731136. A.K.H.K. is supported by the Ministry of Science and Technology (MOST) of the Republic of China (Taiwan) through grant 105-2119-M-007-028-MY3. K.L.L. is supported by the MOST of the Republic of China (Taiwan) through grant 108-2112-M-007-025-MY3.

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