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Monitoring the first candidate host for the merger of a Supermassive Black Hole Binary with H.E.S.S.

D. Kostunin,[a,*] S. Ohm,[a] F. Schüssler,[b] M. Zacharias,[c] F. Brun,[b] J.-F. Glicenstein,[b] H. Rueda,[b] R. Konno,[a] F. Bradascio[b] and A. Jaitly[a] for the H.E.S.S. collaboration

[a] *Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany*

[b] *Institute for Research on the Fundamental Laws of the Universe (IRFU), Commissariat à l'énergie atomique (CEA), Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*

[c] *Landessternwarte, Universität Heidelberg, Königstuhl 12, D 69117 Heidelberg, Germany*

E-mail: contact.hess@hess-experiment.eu

Supermassive black hole binary (SMBHB) is a result of galaxies coalescing, when two supermassive black holes form a hard binary with distances from kpc to pc. If the system reaches milliparsec separation, the black holes eventually merge. There are a growing number of few sub-pc SMBHB candidates, one of which according to Jiang et al (2022). will merge within three years. We have performed the monitoring of the host galaxy SDSSJ143016.05+230344.4 during its visibility with H.E.S.S. in April–July 2022. Given that subsequent follow-up observations with optical and X-ray instruments have not confirmed some of the predictions initially presented, and time constraints for the merger beyond 2022 are less precise, we changed our monitoring and follow-up strategy for further observations. In this work we present our results of the monitoring and discuss the prospects of these kind of observations with imaging atmospheric Cherenkov telescopes.

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*Speaker

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1. Introduction

Galaxy mergers are believed to potentially produce supermassive black hole binaries (SMBHB), which may form parsec-scale bound systems by losing energy due to dynamical friction [1]. Further energy losses will eventually lead to a collision, which produces low-frequency gravitational waves detectable by orbital antennas [2]. SMBHB within milliparsec separation is of a special interest due to their imminent merger in less than Hubble time, however, direct detection of such candidates is challenging due to limited angular resolution of modern experiments and therefore only be achieved for nearby galaxies, e.g. in NGC 6240 [3].

There are a number of indirect methods for the detection of SMBHB based on studying light curves from optical and X-ray observations. Recently, a SMBHB candidate with unique signature in optical and X-ray bands was detected [4] in the Seyfert 1 galaxy SDSS J143016.05+230344.4 (hereafter called SDSS J1430+2303) at redshift $z = 0.08$. In the original detection [4] the lightcurve was interpreted as an indication of an "Imminent Merger of a Supermassive Black Hole Binary" to happen sometime between 2022–2025, which triggered follow-up monitoring and observations with different instruments, including The High Energy Stereoscopic System (H.E.S.S.).

2. Follow-up studies of SDSS J1430+2303

Currently there are more than a dozen works citing the original paper [4], including both theoretical and observational results. In this section we summarize the most significant ones in chronological order:

- Ref. [5] performed VLBI imaging and detected a compact source with unresolved morphology of size smaller than 0.8 pc and a flat radio spectrum.
- Ref. [6] performed an optical follow-up of the source with the Rapid Eye Mount telescope, and compared the new data with the model provided in the original paper, showing discrepancies with the SMBHB hypothesis. The observed light curves are explained with relativistic Lense-Thirring precession of an accretion disc around a single massive black hole.
- Ref. [7] continued the investigation of the X-ray lightcurves from original study [4] and measured a strong variability in this domain, thus confirming the original hypothesis. However, it does not fully exclude a clumpy wind scenario.
- Ref. [8] performed an X-ray follow-up with NICER and detected unusually hard X-Ray flares during high-cadence monitoring. A number of interpretations are given, including the SMBHB scenario with self-lensing. However, the authors prefer the variable corona model.
- Ref. [9] performed a polarization study of the source and rejected the binary scenario with a probability of 85% stating that a single black hole is able to reproduce the observed spectrum and polarization.

H.E.S.S. started monitoring this source in the first half of 2022 before the appearance of the aforementioned works.

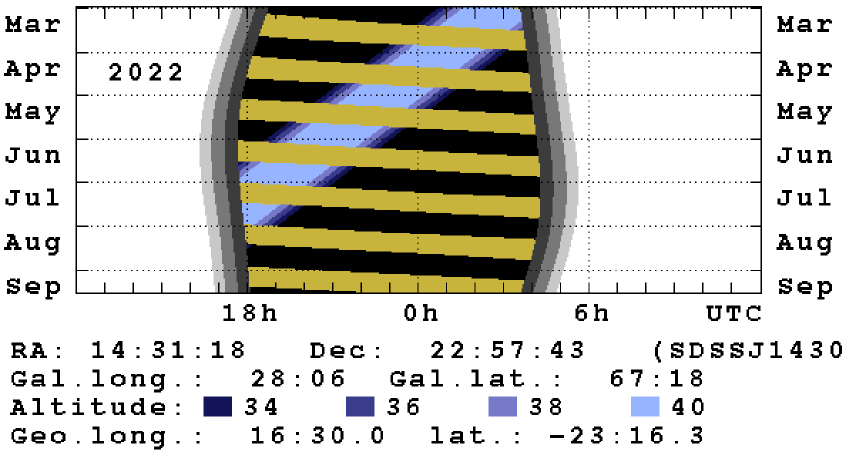

Figure 1: Visibility of SDSS J1430+2303 at H.E.S.S. Black and yellow vertical bands indicate dark and moonlight periods during nights, respectively. Diagonal band indicate appearance of the source with altitude higher than 35°.

3. H.E.S.S. observations of SDSS J1430+2303

H.E.S.S. is an array of four 12-m and one 28-m Imaging Atmospheric Cherenkov Telescopes (IACTs) located in the Khomas Highland in Namibia at an altitude of 1835 m. It is sensitive to gamma-rays from energies of a few tens of GeV to 100 TeV [10].

H.E.S.S. had developed a sophisticated program for the gravitational wave follow-up [11]. Although no very-high energy gamma-ray counterpart has yet been detected after gravitational wave bursts, H.E.S.S. observations of GW170817 allowed for constraining the magnetic field in the merger outflow [12].

Given a unique opportunity of observation supermassive black hole merger, monitoring of SDSS J1430+2303 started shortly after the appearance of initial merger prediction [4]. The visibility window at the H.E.S.S. site lasts from March to July, thus covering the period predicted in the original model as the most probable time of merger (see Fig. 1).

Date	Exposure (min)	Date	Exposure (min)
2022-03-26	28	2022-04-09	140
2022-04-01	28	2022-05-20	122
2022-04-02	168	2022-05-21	140
2022-04-03	196	2022-05-22	56
2022-04-04	336	2022-06-16	56
2022-04-05	224	2022-06-20	84
2022-04-06	112	2022-07-02	84
2022-04-07	28	2022-07-03	56
2022-04-08	196	2022-07-04	84

Table 1: H.E.S.S exposure for SDSS J1430+2303

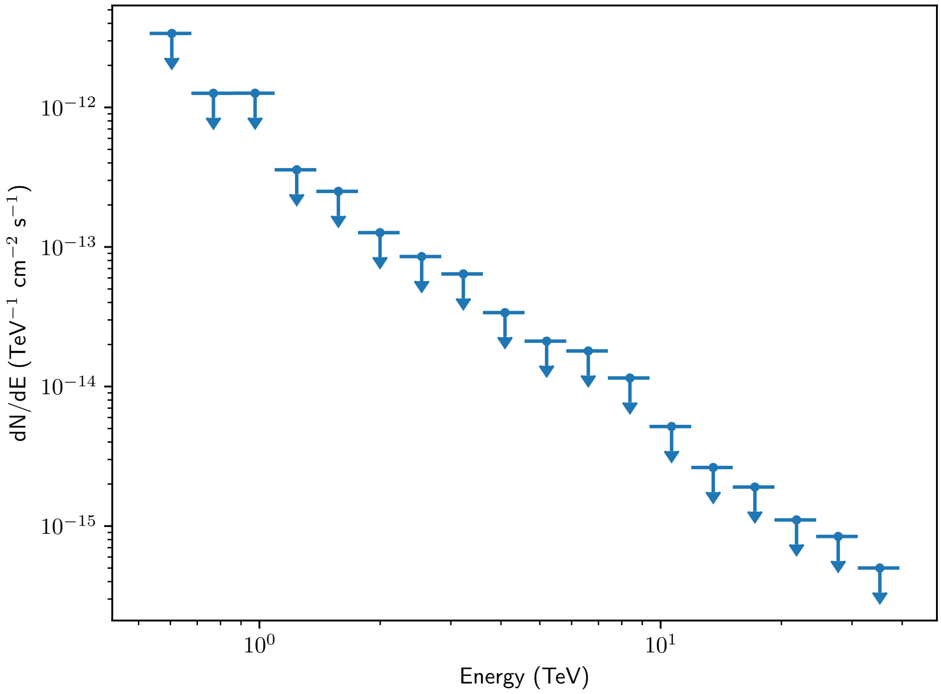

Figure 2: Differential 99% C.L. upper limits derived for SDSS J1430+2303 assuming a E^{-2} gamma-ray spectrum.

We were able to obtain 35 h of observations in April – July 2022. The allocated observations are grouped within one week per month, with about half of them taken a the beginning of April (see Table 1).

Given that SDSS J1430+2303 does not feature any known gamma-ray source, we do not expect any contamination from other gamma-ray sources in our observations. Thus, assuming serendipitous merger, the real-time analysis (RTA) software [13] would trigger further observations if a significant signal (more than 4σ) would have been observed.

The final analysis is performed for the four 12 m telescopes, with both the *Model Analysis* [14] and *ImPACT* [15] software packages providing consistent results in confirmation of non-detection of gamma-ray emission. The differential flux upper limits are given in Fig. 2, and the derived integral flux upper limit is 3.5×10^{-13} cm^{-}2 s^{-1} above 0.5 TeV at 99% confidence level (C.L.).

There were good reasons for the monitoring of SDSS J1430+2303 over several months: serendipitous observation of the merger if it happened, and getting the pre-merger state of source in the very-high energy domain. Although the prediction in Ref. [4] allows for a merger to happen beyond 2022 (when X-ray data are not included in the model), is it much more uncertain and cover a 2-year period. Moreover, follow-up observations in other domains performed parallel to H.E.S.S. monitoring did not provide a firm proof of the SMBHB scenario. Thus, we changed the observation strategy for this source into a target-of-opportunity program, i.e. the observations will be triggered by third-party detection of any unusual activity from this region.

4. Discussion

Monitoring of the “Tick-Tock” source SDSS J1430+2303 is a unique attempt of observation of a potential occurance of a not yet detected phenomenon of a SMBHB merger. After having been published as preprint, the prediction of a SMBHB merger triggered a number of observations in a broad frequency range.

The H.E.S.S. observatory acquired and analyzed sufficient data on SDSS J1430+2303 and covered several months of the year in which the source was visible to H.E.S.S. Despite the non-detection, the raw data is conserved and can be revisited in case of an increased interest of the community in the future. In this proceeding we provide the observation times on SDSSJ1430+2303 with the H.E.S.S. telescopes.

Unlike short-notice target-of-opportunity observations, predictions of SMBHB mergers do not require prompt reaction. More important is efficient monitoring while waiting for the event to happen, maximizing the probability of simultaneous observations. The observations done with H.E.S.S. can serve as starting point for developing such pipelines in the future Cherenkov Telescope Array (CTA) [16] Science User Support System and Science Operations Support System[1].

Acknowledgments

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