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A Very High Energy γ-ray Survey of X-ray Binaries with H.E.S.S.

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Abstract: Since the discovery of TeV emission from the LS 5039/RX J1826.2-1450 binary system, microquasars are an established class of Very High Energy γ-ray sources. Nonetheless, the current catalogue of γ-ray binaries remains somewhat limited, with only four examples known. We present the results of a systematic search for TeV emission from known X-ray binaries with similar properties to LS 5039/RX J1826.2-1450 using the H.E.S.S. atmospheric Cherenkov telescope array.

Introduction

Galactic binary systems were established as a new class of TeV γ-ray sources when the pulsar-Be star binary PSR B1259-63 was detected by the H.E.S.S. Collaboration [1]. In this system very high energy γ-rays are likely generated as a result of the interaction of a strong pulsar wind with the dense equatorial wind of the Be star companion.

Subsequent H.E.S.S. observations of the microquasar LS5039/RX J1826.2-1450 provided the first known example of an orbitally modulated TeV γ-ray signal [2]. Furthermore, the association of bipolar milliarsecond radio structures with the LS 5039 system [3] permits consideration of jet-powered scenarios of VHE γ-ray emission [4] suggesting possible parallels with the supermassive cousins of microquasars - the Active Galactic Nuclei (AGNs) (See however [5]). The companion star in the LS 5039 system has been spectroscopically identified as a massive O6.5V((f)) star [6]. The nature of the compact primary is somewhat ambiguous, with the recent ephemeris of [7] indicative of a black hole, but only when combined with the assumption of pseudo-synchronicity of the companion star. Neglecting this assumption, the derived lower mass limit of $\approx 1.5 M_\odot$ is consistent with a neutron star primary. [7] also derive an somewhat short orbital period for the system of 3.9 days, combined with a rather low eccentricity of 0.35. In the X-ray band, LS 5039 is an unremarkable source albeit with a somewhat hard spectrum [8]. The system was also associated with the soft γ-ray EGRET source 3EG J1824-1514 [9].

The most recently discovered γ-ray binary is the northern hemisphere object LS I +61°303, detected by the MAGIC collaboration [10]. Like LS 5039, this system exhibits a variable VHE γ-ray flux, although the existence of any orbital modulation is yet to be established. The orbital period of ≈ 26.5 days [11, 12] is somewhat longer than that of LS 5039 but a higher eccentricity of 0.72 gives a similar periastron distance of ~ 0.1 AU. [13] identified the optical counterpart of LS I +61°303 as a B0 V star with an equatorial disk. At radio frequencies LS I 61°+303 also exhibits jet-like structure on milliarcsecond scales [14], although recent observations by [15] suggest that these "jets" may in fact result from interactions of a pulsar wind with the stellar wind of the companion. The X-ray charcteristics of LS I 61°+303 are remarkably similar to those of LS 5039 [16], and also reminiscent is the tentative association with the EGRET source 2CG 135+01 [17].

These three systems constitute the entire VHE γ-ray binary catalogue. [18] performed a search for TeV signals coincident with the positions of known X-ray binaries using a sample containing a wide range of donor masses, compact primary types, radio, X-ray and soft γ-ray behaviours. Nonetheless no significant detections were obtained.

Instead of this blind search approach, a more sensible methodology might be to use the characteristics of the known γ-ray binaries as selection criteria for a more targeted survey. Indeed it is apparent that the objects in the existing catalogue share several physical and observational characteristics, some or all of which may be prerequisites for detectable TeV emission. In deriving our selection criteria we focus on the shared characteristics of LS 5039 and LS I 61°+303 , since PSR B1259-63 is only detectable during a very small fraction of its 1237 day orbit and the probability of detecting a similar long period system is consequently rather low. We then use the generated criteria to construct a sample of likely VHE γ-ray binaries.

Source Selection

The final sample of 11 X-ray binaries is shown in Table 1, together with an outline of the selection criteria employed, and the degree to which each object in the sample fulfils these criteria. Five characteristics common to both LS 5039 and LS I 61°+303 were chosen as selection criteria. Based upon the observed similarities we should select short period ($P \sim 3 - 20$ days) systems with high mass donors, feeding neutron star or pulsar primaries, displaying extended milliarcsecond radio structure and carrying associations with known soft γ-ray sources.

Unfortunately, there are only two known systems which fulfil all of these criteria, and these are LS 5039 and LS I +61°303. In fact, choosing targets which do not precisely match the γ-ray binary template gives a useful diagnostic of which system properties or combinations thereof are important for the generation of a detectable TeV flux. Suitable targets were identified using the X-ray binary catalogues of [19] and [20] together with references therein. Ultimately, seven of the targets in our sample were chosen because they share at least some of the characteristics of our idealised γ-ray binary. The remaining four systems, GRS 1915+105, Circinus X-1, GX 339-4 and V4641 Sgr are known superluminal sources. The possibility of observing a transient VHE γ-ray flare during a superluminal outburst event was seen as sufficient justification for their inclusion in the survey.

Analysis and Results

Data reduction and analysis were carried out using the standard H.E.S.S. analysis procedure outlined in [21]. The event selection cuts placed on image size, θ^2 and the mean reduced scaled parameters are identical to those described as standard in [21], and are consistent with the expected point-like nature of the target objects. The γ-ray background was estimated using a 'reflected' background model with several run dependent *off* regions defined the same distance from the camera centre as the on region. Areas of the sky containing known TeV γ-ray sources are precluded from being chosen as *off* regions to ensure that the background estimate remains as uncontaminated as possible. Nonetheless, contamination can occur when the *on* region coincides with a known γ-ray source. Despite having excellent angular resolution for an instrument of its type, the H.E.S.S. point spread function is somewhat extended, with a 68% containment radius of $\sim 0.1°$. For this reason it can be impossible to disentangle the signals from nearby objects. This is particularly difficult when the expected target spectrum and flux are unknown.

As reported in [22] the region exposed by the galactic plane scan is somewhat crowded with VHE γ-ray sources, and it is therefore unsurprising that some contamination of our targets did indeed occur.

Table 2 outlines the results of the survey. Upper limits to the photon flux above 1 TeV have been derived for 10 of the 11 targets. These upper limits represent 99% confidence intervals derived using the unified Feldman-Cousins method [23]. The remaining target OAO 1657-415, was too close to the known TeV emitter HESS J1702-420 for a reliable upper limit or flux estimate to be obtained.

Conclusions

99% confidence upper limits to the VHE γ-ray flux above 1TeV have been derived for seven X-ray binaries with properties similar to LS 5039 and four superluminal microquasars. No significant detections were obtained. For the LS5039-like systems this could be due to orbital modulation of the TeV flux and observations contemporaneous with a low

Name	Companion Type	Compact Object	Radio Structure	Orbital Period (d)	γ-ray Emission
Vela X-1	OB	NS	No	8.96	TeV?
Cen X-3	OB	NS	No	2.09	GeV/TeV?
GX339-4	LM	BH	Yes	?	No
Cir X-1	LM	NS	Yes	16.6	No
GRO J1665-40	LM	BH	Yes	2.62	GeV
OAO 1657-415	B0-B6 Supergiant	NS	No	10.4	No
4U 1700-37	O6.5Iaf^{+}	NS?	No	3.96	No
4U 1538-52	B0I	NS	No	4	GeV?
V4641 Sgr	LM	BH	Yes	2.81	No
4U 1907+097	OB/Be	NS	No	8.38	No
GRS 1915+105	LM	BH	Yes	35	No

Table 1: The targets for our X-ray binary survey are shown in the table below. In the Companion Type column the spectral type of the donor is listed unless LM is specified, indicating a low-mass companion. The compact object type is either a black hole (BH) or neutron star (NS). Question marks indicate ambiguity in the quoted values or an absence of data.

Target Name	Significance [σ]	Excess [counts]	Livetime [hours]	Flux Upper Limit ($E_\gamma > 1$ TeV) [ph cm^{-2}s^{-1}]
Vela X-1	-1.407	-73.000	4.360	3.550×10^{-12}
Cen X-3	0.778	21.589	5.283	5.845×10^{-12}
GX339-4	1.349	106.640	8.495	6.657×10^{-12}
Cir X-1	-0.942	-106.704	27.906	1.406×10^{-13}
GRO J1665-40	0.939	46.390	9.536	1.625×10^{-11}
OAO 1657-415	7.197	604.597	26.744	1.440×10^{-11}
				(**Contaminated by HESS J1702-420**)
4U 1700-37	2.929	289.137	38.708	1.058×10^{-11}
4U 1538-52	-0.4256	-22.339	7.524	2.741×10^{-12}
V4641 Sgr	1.215	62.175	2.554	1.271×10^{-12}
4U 1907+097	-0.567	-13.490	14.997	1.372×10^{-12}
GRS 1915+105	0.156	4.566	19.692	7.803×10^{-13}

Table 2: The preliminary results of the survey are shown below. The region exposed by the galactic plane scan is crowded with VHE γ-ray sources, and it is therefore unsurprising that some contamination of our targets occurred due to overlap with known VHE sources. Where the target region is contaminated by the flux from a known TeV source, the derivation of an upper limit is not possible, but there is no way to safely associate the observed flux with the X-ray binary system. In this case the contaminating object is indicated in the Flux Upper Limit column. Negative excesses and significances result purely from fluctuations in the γ-ray background and should not be interpreted as a genuine deficit in the photon flux.

flux state. In some cases a rather short exposure time might also explain the lack of a detection. However, it may be that all the specific conditions found in the LS 5039 and LS I 61°+303 are required to produce a detectable VHE γ-ray signal. For the superluminal sources, failure to observe during a flaring event is the most likely explanation for a non-detection.

In the absence of a significant detection, it seems conspicuous, given that nearly 300 X-ray binaries are known, that only three should be detectable in the VHE γ-ray band. It may be that LS 5039, LS I 61°+303 and PSR B1259-63 are unique systems in our galaxy, or perhaps with the advent of more sensitive instruments such as H.E.S.S. II combined with the high energy γ-ray coverage of *GLAST* will reveal a much larger population of faint γ-ray binaries.

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