VERITAS observations of gamma-ray binaries

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VERITAS, an array of four 12-m imaging atmospheric Cherenkov telescopes, has been fully operational since April 2007. It is located at the Fred Lawrence Whipple Observatory in southern Arizona (31 40N, 110 57W, 1.3 km a.s.l.). One of the key VERITAS science programs have included the search for and monitoring of gamma-ray binaries. The gamma-ray binary systems are composed of a massive star and a compact object, black hole or neutron star. Their spectral energy distributions peak above 1 GeV. VERITAS archive consists of more than 200 hr of datasets for LS I +61° 303 and HESS J0632+057, having orbital periods of 316.7 days and 26.5 days, respectively. In this work the status and results from the VERITAS observations for these binary systems and the correlation studies between very high energy (VHE) γ-ray and X-ray emissions are discussed.

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1. Introduction

A new class of binary systems called "γ-ray binaries" was emerged from mid-200 due to new generation of γ-ray instruments [1, 2]. These systems were found to be emitting most of their radiated power beyond 1 MeV. Based on the composition of these systems and their energy output, they can be defined as systems consisting of a compact object orbiting a star (O or Be) with periodic release of large amounts of non-thermal emission at energies >1 MeV [3]. LS I +61 303 is the third γ-ray binary detected in VHE after LS 5039 [4] and PSR B1259-63 [5]. While HESS J0632+057 is the forth one serendipitously detected in VHE.

The γ-ray binary LS I +61° 303 consists of a rapidly rotating massive BeVe star (~12 $M_{\odot}$) located at 2.65 ± 0.09 kpc [6] and a compact object orbiting with a period of 26.5 days [7]. The recent detection of radio pulsations from the direction of this source by the the Five-hundred-meter Aperture Spherical radio Telescope suggests that the compact object is a rotating neutron star [8]. Moreover, the large uncertainty exists due to significantly different orbital solution derived from different optical measurements. The study of [7] suggests the passage of periastron and apastron at orbital phase (ϕ_{orb}) of 0.23 and 0.73, respectively. While, [9] suggests close to circular orbit with periastron passage at ϕ_{orb} of 0.62 and apastron passage at 0.12. In this work we assume the former orbital parameters.

Located at a distance of 1.1-1.7 kpc, HESS J0632+057 consists of an unknown compact object orbiting a Be star (MWC 148) with a period of 321 ± 5 days [10]. For HESS J0632+057 also, the different orbital solutions were founds by different studies, with main difference in the eccentricity of the orbit (ϵ) and orbital phase of periastron. The solution of [11] founds the ϵ=0.8 and perisatron passage at ϕ_{orb}=0.98, while [12] founds ϵ=0.6 and ϕ_{orb}=0.66.

2. Long-term VERITAS observations of LS I +61° 303 and HESS J0632+057

Each of the four telescopes of VERITAS has a Davies-Cotton-design segmented mirror dish of 345 facets and focuses the Cherenkov light from particle showers onto a pixelated camera having 499 PMTs and a total field of view of 3.5°. Since April 2007, it has undergone two major upgrades, during summer 2009 and summer 2012. The current configuration of the array can detect an object having 1% of the Crab Nebula flux in ~25 hours with a gamma-ray-photon energy resolution of 15-25%. For a 1 TeV photon, the 68% containment radius is ≤0.1°, with a pointing accuracy of <50". The details of the evolution of the performance of the VERITAS instrument with time are discussed in [13]. Recently, in order to account for the changing optical throughput and detector performance over time, signal calibration methods have been implemented to produce a fine-tuned instrument response functions [14].

The VERITAS archive includes one of the largest data sets for the sources of γ-ray binary class, which includes ~174 h and ~260 h and of good quality data (after applying weather-based time cuts) for LS I +61° 303 and HESS J0632+057, respectively. 174 h of observation of the LS I +61° 303 have been taken in different parts of its orbit. Figure 1 shows its superorbital vs. orbital phase space covered by the VERITAS observations since 2007. The total exposure in different orbital phase of HESS J0632+057 is shown in [15] (Table-4).

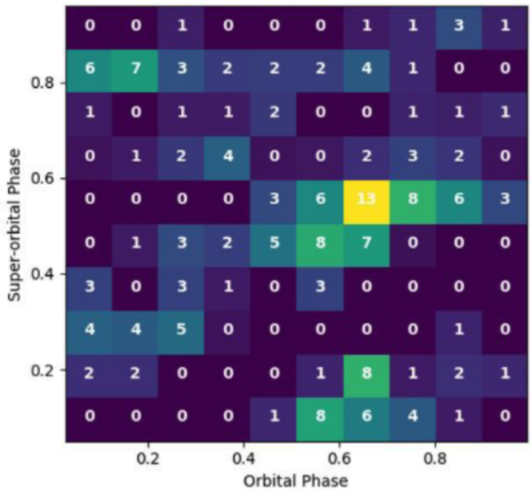

Figure 1: Superorbital and orbital phase space covered by VERITAS observation of LS I +61° 303. The number in each bin corresponds to exposure in hours.

3. Results

The orbital phase light curve binned in 0.1 phase bins from small subset of data from September 2017 to January 2021 is shown in Figure 2. The details of the analysis and orbital phase light curve of entire data has been shown in [16]. It can been seen that the peak emission occur during its apastron passage in orbital phase of 0.55-0.65. Moreover, LS I +61° 303 is detected above 5σ in most of the bins, except phase bins (0.1-0.2), (0.2-0.3), and (0.9-1.0), where the significance is about 4σ [17].

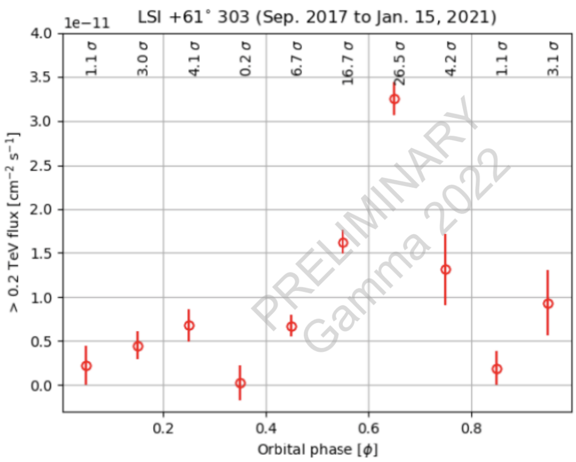

Figure 2: Orbital phase binned light curved of LS I +61° 303

In this work, we study the correlation of >0.3 TeV flux from VERITAS data with 0.3-10 keV flux from *Swift*-XRT data. For this study, two datasets were formed based on simultaneity of the VHE and X-ray data. The first one with both the observations simultaneous within 0.5 h and the second one with the observations simultaneous within 24 h. The correlation coefficients were found to be 0.69±0.11 and 0.53±0.07, for the first and second dataset, respectively.

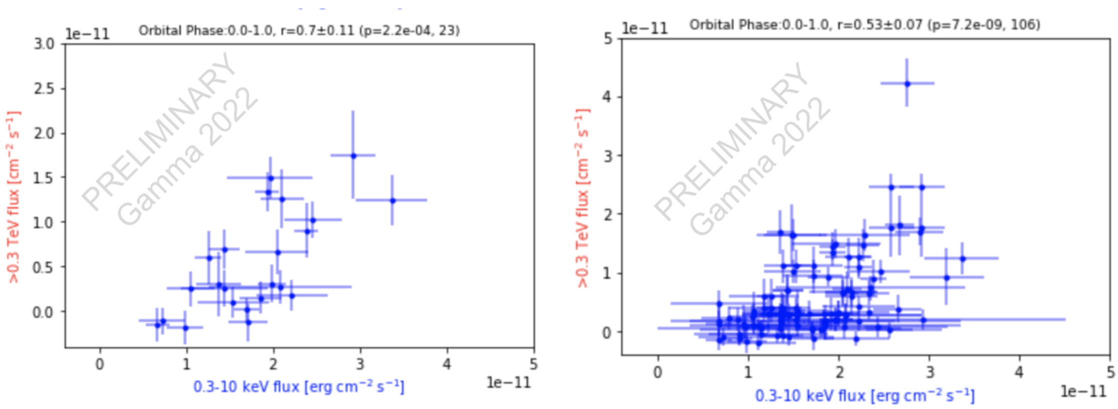

Figure 3: LS I +61° 303

For HESS J0632+057, the data from three major atmospheric Cherenkov telescopes: H.E.S.S. [18], MAGIC [19], and VERITAS [13] were used to study the very high energy (VHE) γ-ray emission from this source, resulting in a total of 450 h over 15 years, between 2004 and 2019. The orbital phase light curve of this dense dataset is shown in Figure 4 (Left). The VHE γ-ray fluxes were found to be modulated with the orbital period of 316.7 ± 4.4(stat) ± 2.5(sys), consistent with the value obtained at X-ray energies [15]. For studying the correlation between VHE and X-ray emission, the γ-ray observations were grouped over several nights to get significant detection. While X-ray observations are nightly averaged and those taken during the grouped γ-ray observations, were considered in the correlation analysis. The correlation coefficient was found to be 0.82.

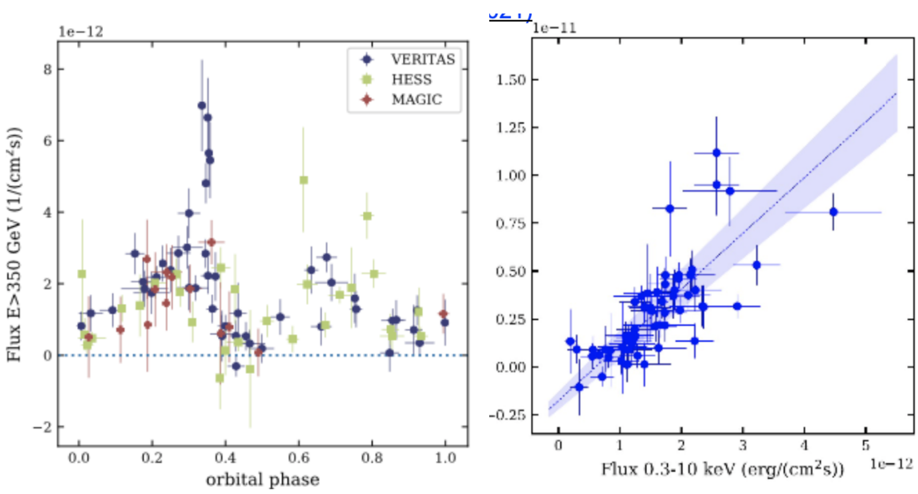

Figure 4: HESS J0632+057

4. Summary

For LS I +61° 303, the VHE and X-ray emissions were found to be moderately correlated. This may suggests the same or partially overlapping emission regions in the source. The strong correlations for these two emission for HESS J0632+057, could suggest their common origin and existence of single particle population. Also, the dense observational coverage over several orbits of HESS J0632+057 has reveled the short-timescale and orbit-to-orbit variability for this γ-ray binary.

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