

Decadal VERITAS Observation of LS I +61°303 : Detection of TeV emission around the entire orbit

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The TeV binary system LS I +61°303 has a compact object in an eccentric orbit around a Be star about 2 kpc from Earth. LS I +61°303 exhibits modulated gamma-ray emission around its 26.5 days orbit, mostly detectable at TeV energies around its apastron passage, with maximum flux during the $\phi = 0.55 - 0.65$ phase range. Multiple flaring episodes with nightly flux variability at TeV energies have been observed since its detection in 2006. At one time significant TeV emission was also detected in late 2010 from the source close to its periastron passage at superior conjunction. The TeV spectrum is well fitted by a power law with small variations of spectral index of ~ 2.6 over the years. GeV, X-ray, and radio emission have been detected along the entire orbit, enabling detailed study of the modulation pattern and its super-orbital period, such comprehensive study of the LS I +61°303 orbit in the TeV regime has not been presented before. VERITAS has observed LS I +61°303 for over a decade now, accruing 200+ hours of data during different parts of its orbit. In this work, we have analyzed all available data for LS I +61°303 since September 2007 in individual phase bins of width $\Delta\phi = 0.1$ and performed a spectral analysis for two different parts of the orbit. TeV emission is now detected in 9 out of 10 phase bins, around the entire orbit for the first time in VERITAS data. Hint of spectral variation might also be present between different parts of the orbit. The implication of these results is discussed in the context of determining the nature of the unknown compact object (neutron star or microquasar) and a discussion of the absorption mechanisms in the system.

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1. Introduction

There are five high mass X-ray binary systems in our galaxy with majority of their power output at gamma ray energies (> 100 GeV). All these binary systems hosts a massive O/B type star and a compact object (CO), out of which only PSR B1259-63 is confirmed to host a pulsar. For the rest i.e. LS I +61°303, LS 5039, HESS J0632+057, and 1FGL J1018.6-5856, the nature of the CO is ambiguous, it could be either a neutron star or a blackhole, see [1] for review of these systems. Primarily, the orbital periods of gamma ray binaries modulate their flux across the electromagnetic spectrum but the exact physical mechanism producing the non thermal emissions in these systems is unclear.

LS I +61°303 was first detected by VERITAS in 2007 and has been extensively observed since then [2, 3, 4]. The flux from LS I +61°303 is strongly modulated from radio to TeV energies by the 26.5 day orbital period of the system [5]. The system also exhibits superorbital flux modulations on a longer ~ 4.6 year timescale which is attributed to the rapidly spinning Be star of $10 - 15 M_{\odot}$ in the system [6]. There are two popular competing models for the very high energy (VHE) emission from LS I +61°303 based on the nature of the CO. The first model assumes the compact object to be a microquasar where the relativistic charged particles present in jets of the stellar blackhole produce the VHE emission, similar to active galactic nuclei [5]. The second model assumes the systems hosts a neutron star; VHE emission is produced by accelerated charged particles at the shock front of the colliding winds from the neutron star and the massive Be star, similar to PSR B1259-63 [7]. While the microquasar model emulates three decades of radio observations and presents an impressive theory of astronomy of beats using periods associated with the system [8], no signature X-ray emission from an accretion disc has been observed from LS I +61°303 which would be essential to power its relativistic jets [7]. The neutron star model falls short in explaining the energy budget of the system, a much more powerful wind from the Be star would be required to overwhelm the typical pulsar wind of $\sim 10^{36}$ erg s^{-1} expected in LS I +61°303 [9]. For detailed arguments for and against both the microquasar and neutron star models refer to [7, 9].

A magnetar-like event from the direction of LS I +61°303 observed by *Swift* in 2012 sparked a debate of the first magnetar in a binary system [10]. The highly magnetized neutron star would transition from propeller to ejector and back to propeller based on the surrounding matter densities along each eccentric orbital motion. We present the results from the long term monitoring of LS I +61°303 here and discuss the ejector-propeller flip-flop model in context. A similar decade long study of another gamma ray binary HESS J0632+057 and an outline of the binary discovery program by VERITAS is presented elsewhere in this conference [11].

2. VERITAS Observations and Data Analysis

The VERITAS Observatory is an array of four Imaging Atmospheric Cherenkov Telescopes located at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona ($31^{\circ}40' N$, $110^{\circ}57' W$, 1.3km a.s.l.). The full array began operations in September 2007 (V4 configuration - Sep 2007 to July 2009) and has been upgraded twice. During the first upgrade, one of the telescopes was relocated, increasing the collection area and improving the angular resolution (V5 configuration September 2009 - July 2012). In the second upgrade, the PMTs and the telescope trigger system

were upgraded, improving the the array's response at low energies (V6 configuration - Sep 2012 to current). In the current V6 configuration, VERITAS is sensitive to very high energy (VHE) gamma rays from 85 GeV to > 30 TeV and detects a source with flux corresponding to 1% of the Crab Nebula in less than 25 h. For details of the instrument and its performance see [12].

LS I +61°303 is one of the most observed sources by VERITAS with over 240 hours of data on the source over the 10 years since its discovery at TeV energies. The orbital phase $\phi = 0$ is set on **MJD 43366.275**, the date of discovery of LS I +61°303 as a variable radio source and the 26.5 d orbit is divided into equal 10 phases. The entire data set is distributed unevenly around the orbit with maximum exposure during phase range $\phi = 0.5 - 0.8$ near the apastron passage. A summary of the VERITAS observations is shown in Table 1.

Table 1: VERITAS Decadal Dataset of LS I +61°303 Observations

Observing Season	Instrument Epoch	Quality Selected Livetime [min]	Detection Significance (σ)
2007 / 2008	V4	1518	6.2
2008 / 2009	V4	2305	3.8
2009 / 2010	V5	1207	0.7
2010 / 2011	V5	933	4.6
2011 / 2012	V5	1551	14.0
2012 / 2013	V6	490	6.5
2013 / 2014	V6	522	5.6
2014 / 2015	V6	1746	21.4
2015 / 2016	V6	1137	16.0
2016 / 2017	V6	703	12.4
All	V4, V5, V6	12112	29.2

Standard analysis for a point source is performed using advanced Boosted Decision Tree technique (BDT) [13]. The source is significantly detected at energies > 300 GeV in 7 out of 10 observing seasons. Spectral analysis is performed by dividing the orbit in two parts, the first part close to the apastron passage covering 3 phases bin $\phi = 0.5 \rightarrow 0.8$ and the second for rest of the orbit covering phases $\phi = 0.5 \rightarrow 0.8$. The later 7 phases are further divided into two parts based on the location of the compact object (CO) behind the Be star and its disc ($\phi = 0.8 \rightarrow 0.2$) or in front of them ($\phi = 0.2 \rightarrow 0.5$). Spectral analysis is also performed for both these phase intervals.

3. Results

LS I +61°303 is detected at $> 5\sigma$ significance level in 9 out of 10 phase bins around the orbit. A summary of the results from each of the phase bin of width $\Delta\phi = 0.1$ is summarized in Table 2 and a shown in Fig 2. In the single phase bin ($\phi = 0.4 - 0.5$) the significance is 3.8σ , slightly below the defined significance level for claiming discovery. Integral flux estimate of the quiescent TeV emission from LS I +61°303 (> 300 GeV) in phases $\phi = 0.8 \rightarrow 0.4$ is $\sim 3\%$ of the steady Crab Nebula flux. Spectral index of -2.6 is assumed to calculate the integral flux in each bin.

Table 2: LS I +61°303 Phase Binned Results

Phase bin (ϕ)	Pre-trial Significance (σ)	Integral Flux above 300 GeV [$\times 10^{-12} \text{ cm}^2 \text{ s}^{-1}$]	% of Crab	Exposure [min]
0.0 \rightarrow 0.1	5.6	2.90 ± 0.61	2.8	992
0.1 \rightarrow 0.2	5.4	4.03 ± 0.80	3.8	663
0.2 \rightarrow 0.3	5.1	2.77 ± 0.60	2.6	1186
0.3 \rightarrow 0.4	6.1	3.35 ± 0.61	3.2	1178
0.4 \rightarrow 0.5	3.8	< 4.59	< 4.3	547
0.5 \rightarrow 0.6	15.9	6.57 ± 0.54	6.2	1289
0.6 \rightarrow 0.7	18.8	7.40 ± 0.44	7	2517
0.7 \rightarrow 0.8	8.0	3.69 ± 0.46	3.5	1630
0.8 \rightarrow 0.9	5.2	3.53 ± 0.62	3.3	731
0.9 \rightarrow 0.0	5.0	3.81 ± 0.85	3.6	543

The spectrum LS I +61°303 is well fitted with a power-law of the form

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

A combined spectral analysis on the 3 phases near apastron ($\phi = 0.5 \rightarrow 0.8$) yields a spectral index $\Gamma = -2.63 \pm 0.06_{stat}$ with reduced $\chi^2 = 1.1$, consistent with previously measured spectral indices calculated for historical TeV outbursts. For the rest of the orbit ($\phi = 0.8 \rightarrow 0.5$) a spectral index $\Gamma = -2.81 \pm 0.16_{stat}$ is calculated with reduced $\chi^2 = 0.3$. A spectral study of the 2 subdivisions of the phase $\phi = 0.5 \rightarrow 0.8$ interval yields a spectral index $\Gamma = -2.86 \pm 0.21_{stat}$ when the CO is behind the disc of the Be star ($\phi = 0.8 \rightarrow 0.2$) compared to $\Gamma = -2.62 \pm 0.22_{stat}$ when it is in front of the disc and Be star ($\phi = 0.2 \rightarrow 0.5$). The errors on the spectral index are due to limited photon statistics and systematics.

4. Discussion

The nature of the CO of LS I +61°303 has been an active topic of debate since neither the microquasar model nor the pulsar wind binary model are able to fully explain all existing observations. The baseline TeV emission and VHE outbursts near apastron could be explained by the neutron star flip flop model [10]. This model assumes that LS I +61°303 hosts a young neutron star which flip flops between its ejector and propeller phases as the CO revolves around the Be star. Near periastron, the intense ram pressure of the decreted matter from the Be shrinks the Alfvén radius of the neutron star. In this propeller state the neutron star's magnetosphere extends beyond the co-rotation radius of the surrounding matter. The centrifugal force prevents the surrounding co-rotating matter from accreting onto the magnetic poles. The accumulated plasmon mass spirals around like a vortex with concomitant high voltages and shocks between the layers creating the quiescent TeV emission that is observed [15]. As the neutron star travels further from the dense stellar surroundings it transitions to from propeller phase to ejector phase, expelling the plasmon

and producing TeV outbursts. The ejector-propeller flip-flop model fits the well with the flux variability in the various parts of the orbit as seen in Figure 1, a lower flux during propeller state of the neutron star (i.e. $\phi = 0.8 \rightarrow 0.5$) and flaring TeV flux near apastron passage where the neutron star in its ejector expelling the accumulated matter from the previous state (i.e. $\phi = 0.5 \rightarrow 0.8$). The orbit-to-orbit variability that is seen in the peak flux close to apastron passage [4] could be dependent on the mass of the accumulated matter during the propeller state of the neutron star. The microquasar model [8] as well as the pulsar wind shock model [7] although both present reasonable explanations for the observed TeV outbursts near apastron, would need need adjustment to explain the newly discovered baseline TeV emission and flux variations for the rest of the orbit.

The spectral energy distribution of VHE emission from LS I +61°303 close to its apastron in phases $\phi = 0.5 \rightarrow 0.8$ has been stable over the years at ~ 2.6 . A similar spectral trend is seen for the phase range $\phi = 0.2 \rightarrow 0.5$. In the phase range $\phi = 0.8 \rightarrow 0.2$ hint of a softer index $\Gamma \simeq -2.86$ may be present but cannot be confirmed due to statistical uncertainty. Upper limits are calculated for the highest energy bins in the spectral energy distribution due to limited photon statistics and a cutoff above ~ 3 TeV cannot be excluded. An evolving spectral behavior in different parts of the orbit could be a possibility for LS I +61°303 similar to LS 5039, where a cutoff at 6 TeV near its inferior conjunction passage is seen [16].

The correlation seen between X-ray and TeV emission from LS I +61°303 favors a single zone model for the binary where charged particles produce synchrotron X-rays and VHE gamma rays by

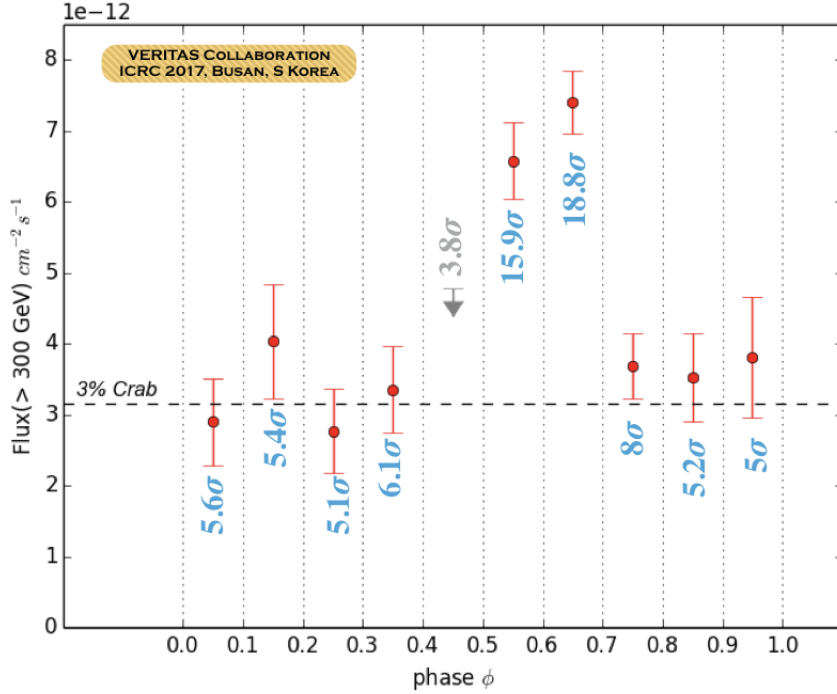


Figure 1: Phase Binned flux of LS I +61°303 for decadal data.

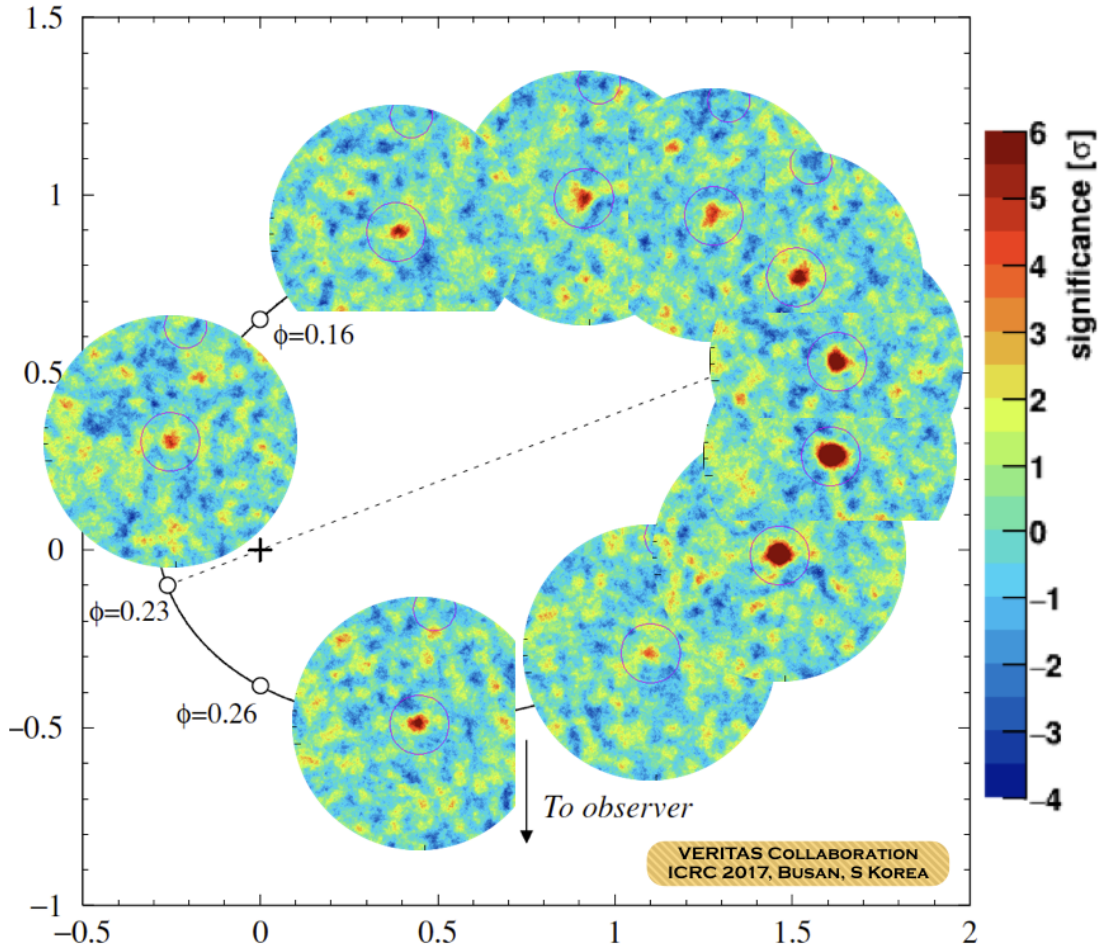


Figure 2: VERITAS skymaps of LS I +61°303 arranged by orbital phase ϕ . Image locations are approximate and illustrative only, the orbit is unresolved at TeV energies. The time progression is counter-clockwise. The orbital parameters used are from [14]

synchrotron self-Compton processes [3]. A detailed multiyear correlation study at X-ray, GeV and TeV energies will be presented in a forthcoming publication. Yet the theory of astronomical beats and the observed anti-correlation between X-ray luminosity and X-ray spectral index points towards a microquasar in the system. It is clear that LS I +61°303 is a much more complex source and further observations are required. Multiwavelength observations specifically focussed on the rest of the orbit away from apastron could resolve the debate on the nature of the CO. Correlated emission patterns around different part of the orbits would be key to identifying the various particle populations at work. Fast variability studies at TeV energies on timescales of ~ 1000 s by CTA will yield deeper insights on the size of the VHE emitting regions.

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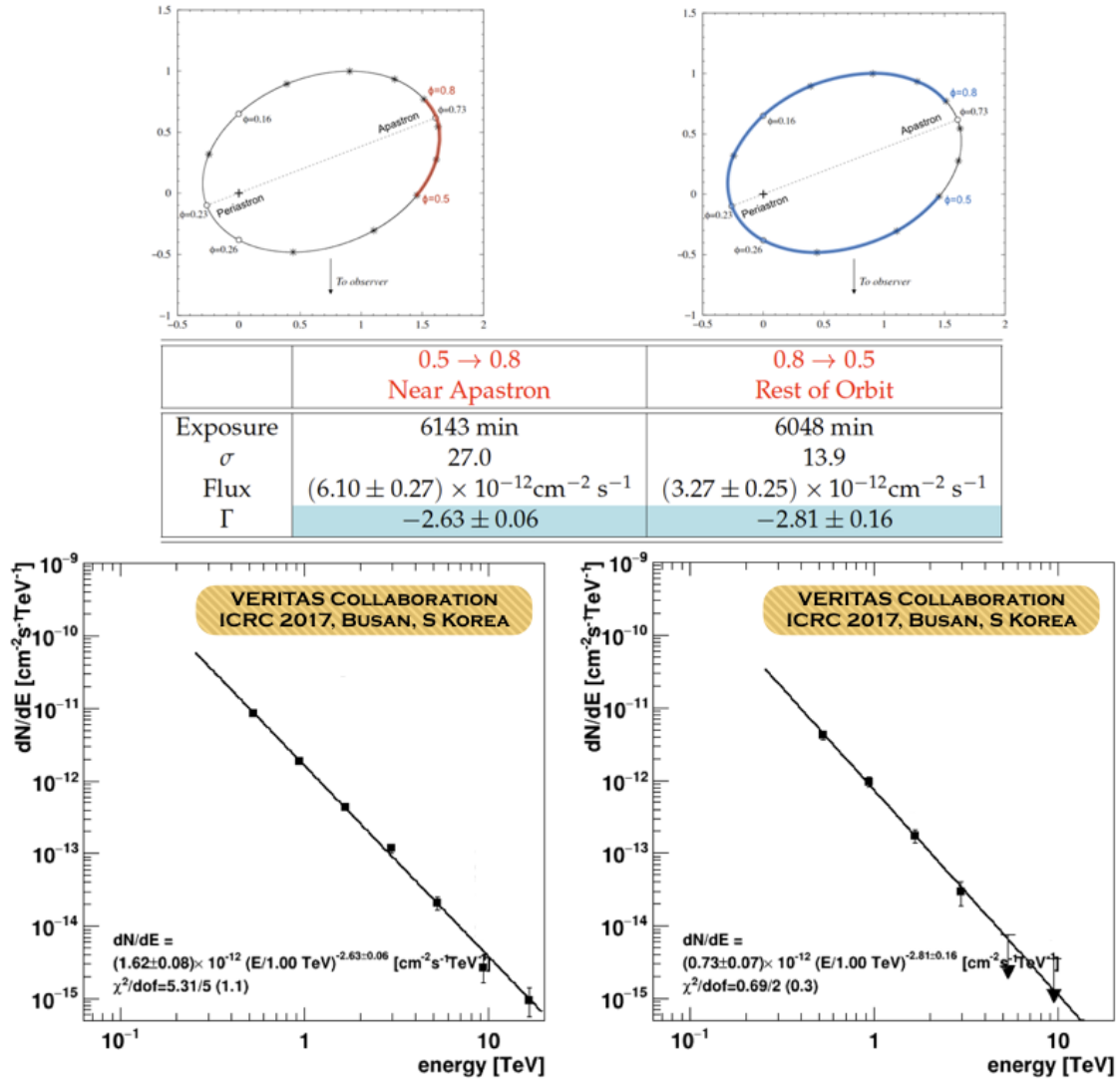


Figure 3: Spectral energy distribution (SED) for LS I +61°303 for two parts of the orbit (parts of the orbit shown on top panels). SED on the *left* is near apastron passage covering $\phi = 0.5 \rightarrow 0.8$ and SED on the *right* is for the rest of the orbit for $\phi = 0.8 \rightarrow 0.5$. The orbital parameters shown on top panel are used from [14]

Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.

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