



## Observation of the binary system LS I +61 303 in Very-High Energy Gamma-Rays with VERITAS

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**Abstract:** The high mass X-ray binary LS I +61 303 has been observed over several months in 2006 and 2007 with the VERITAS array of imaging air-Cherenkov telescopes. A signal of high energy gamma rays with energies above 350 GeV is detected in several orbital cycles of the binary system. The detected flux of gamma rays is strongly variable with the orbital period of 26.5 days, while the maximum flux (corresponding to about 10% of the flux of the Crab Nebula) is always found at approximately apastron, suggesting a strong dependence of particle acceleration and/or propagation on the relative position of the two objects in the system.

### Introduction

The high-mass X-ray binary system LS I +61 303 is one of only three X-ray binaries detected in high-energy gamma rays [1, 2, 3]. It consists of a massive Be-type star surrounded by a dense circumstellar disk and a compact object (neutron star or black hole). Optical observations show that the compact object orbits the star every 26.5 days [4] on a close orbit, characterized by a semi-major axis of a few stellar radii only. The periastron takes place at phase 0.23, apastron is at phase 0.73, inferior and superior conjunctions are at phases 0.26 and 0.16 (phase zero defined from radio observations [5]). LS I +61 303 shows highly variable emission depending on the orbital phase across all wavelengths from radio [4] to TeV gamma-rays [3].

The unknown nature of the compact object and the uncertainty in the geometry of the system allows the existence of at least two possible models for the origin of the high-energy emission from LS I +61 303. The first class of models explains the emission of  $\gamma$ -rays through the production of non-thermal particles in an accretion powered relativistic jet ("microquasar model") [6, 7]. In the second class of models, particles are accelerated in the shock created by the collision of a relativistic pulsar wind with the wind of the companion star [8]. In both cases, the  $\gamma$ -ray emission is interpreted

as inverse Compton (IC) scattering of stellar radiation by high-energy electrons. Alternative models of  $\gamma$ -ray production include IC  $e^\pm$  pair cascades in the field of massive stars [9] or  $\pi^0$  production and decay in hadronic interactions [10].

This paper reports on the results from observations of LS I +61 303 with VERITAS; a study of the correlation between these data and contemporaneous X-ray measurements can be found in a complementary contribution [11].

### Observations with VERITAS

VERITAS is an array of four imaging Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona [12]. The construction of VERITAS is now complete, but was in progress during the observations of LS I +61 303 described here. Observations were made with two telescopes during the period from September to November 2006 (Telescopes 1 and 2), and with three telescopes during January and February 2007 (Telescopes 1, 2, and 3). The sensitivity for  $\gamma$ -rays with energies above 230 GeV of the two-telescope array in the configuration of Autumn 2006 ( $5\sigma$  in 3.3 h for a source with 10% of the flux of the Crab Nebula observed at  $70^\circ$  elevation) was somewhat lower than that of the three-telescope array operating in early 2007 ( $5\sigma$  in 1.2 h for a similar source).

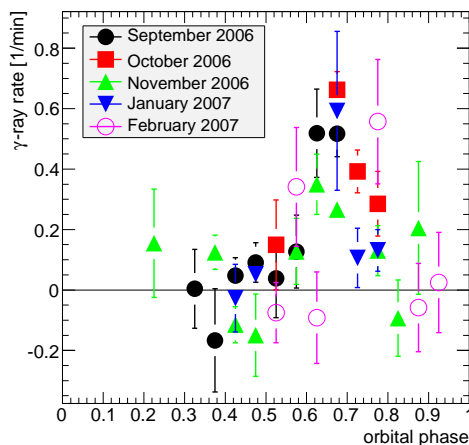


Figure 1: Rate of excess events versus orbital phase for five different orbits. Rates are not corrected for different elevations.

A detailed description of the telescopes, data acquisition, and calibration techniques of VERITAS can be found elsewhere [12, 13, 14].

The LS I +61 303 observations consist of 44 hours of data (32 h of 2 telescope and 12 hours of 3 telescope data, after run quality selection), taken at a mean elevation of around  $60^\circ$ . All observations were taken in wobble mode with offsets of the pointing direction from the position of LS I +61 303 in the sky of  $0.3^\circ$  for the 2006 data and  $0.5^\circ$  for the 2007 data. Observations were made only when the moon was below the horizon. As a result of this, and the fact that the length of an orbital cycle of LS I +61 303 is very close to the moon cycle, no observations are available in this data set at orbital phases between 0.95 and 0.2.

The data have been analysed using independent analysis packages, several cosmic-ray rejection methods, and different procedures to calculate the background rate at the position of the potential source (see [15] for details on the analyses). All of these analyses yield consistent results.

### Detection of LS I +61 303

LS I +61 303 has been detected by VERITAS with a total significance of  $8.8\sigma$ . The emission of photons from LS I +61 303 is, as previous observations at these energies indicate [3] and studies at

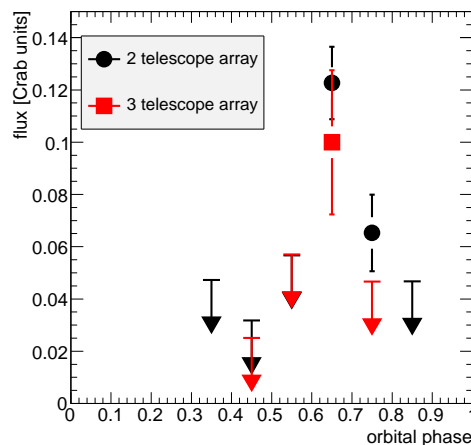


Figure 2: Fluxes and upper flux limits in units of the flux of the Crab Nebula versus orbital phase from observations of LS I +61 303. A significance of  $3\sigma$  is required for all flux calculations; upper flux limits are 99% confidence limits.

other wavelengths show (e.g.[18] and references therein), strongly variable with orbital phase. Figure 1 shows the measured  $\gamma$ -ray rate vs orbital phase for different orbital cycles. The rates are not corrected for any observational effects like elevation, array configuration, or dead times (3-7%), in order to illustrate how apparent the variability is.  $\gamma$ -ray emission is only measurable when the two objects of the binary system are furthest away from each other (radio phases 0.5 to 0.8). Table 1 summarizes the observations during these high state orbital phases. The source has been detected at a significance level of about  $4\sigma$  or above during all except one orbital cycle (February 2007). The lack of a detection in this cycle is consistent with measurements in other cycles due to the small exposure during this month. Additionally, the data in this month were not taken at orbital phases close to 0.7, at which the highest rates are measured during other cycles. Combining the data from all five observed orbits shows that the flux of high energy  $\gamma$ -rays varies between lower than 3% of the Crab Nebula flux (using a confidence limit of 99% and assuming a Crab-Nebula-like spectral energy dis-

Month	Config-uration	Wobble offset	Obs.time [h]	On events	Bck. events	Norm.	Signi-ficance	Flux [Crab units]
September 2006	2-tel	0.3°	7.2	396	859	0.33	5.2 $\sigma$	0.064±0.01
October 2006	2-tel	0.3°	7.0	420	794	0.33	7.4 $\sigma$	0.092±0.01
November 2006	2-tel	0.3°	5.0	228	498	0.33	3.9 $\sigma$	0.050±0.01
January 2007	3-tel	0.5°	3.6	178	507	0.30	3.8 $\sigma$	0.049±0.01
February 2007	3-tel	0.5°	2.3	120	394	0.30	1.9 $\sigma$	<0.065

Table 1: Summary of observations of LS I +61 303 during the high state orbital phases from 0.5 to 0.8. Upper limits on the integral  $\gamma$ -ray flux are given for significances below  $3\sigma$  for events above an energy of 350 GeV assuming a differential spectral index of the source spectrum of  $\Gamma = -2.5$ . The confidence level is 99%.

tribution) to above 10% in the high state phase<sup>1</sup> (see Figure 2). The combination of data from different orbital cycles assumes implicitly that the maximum emission takes place at the same phase during every orbit and that the fluxes do not vary from one cycle to the next. While the available data appear to indicate that this is the case (Figure 1), the statistics are sufficiently poor that the existence of significantly varying lightcurves cannot be excluded and are even predicted in some emission models (e.g.[19]). In addition, the folding of the data with the length of the radio orbit assumes similar periodicity for the radio and the  $\gamma$ -ray data. Using Lomb-Scargle statistics [20], the probability for a period of 26.4960 days [4] in the  $\gamma$ -ray data is 99.94%.

In order to study the position and extension of the  $\gamma$ -ray emission around LS I +61 303, a sky map of the significance of the signal around the binary system was constructed (see Figure 4). The extension of the excess is compatible with the point spread function of the two telescope system and therefore consistent with a point source (Figure 3). The maximum in the sky map, determined by a fit of a two dimensional Gaussian distribution to the image, is compatible with the position of the optical counterpart.

## Conclusions

The detection of high-energy emission from LS I +61 303 by VERITAS shows strong variability which is clearly linked to the orbital motion of the binary system. The majority of the  $\gamma$ -ray flux is emitted at apastron over a time scale of only a few days. This suggests that the  $\gamma$ -ray production

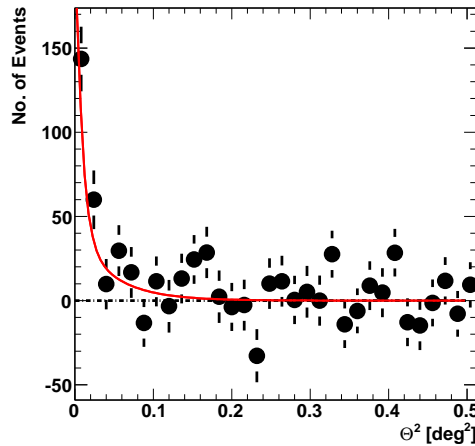


Figure 3: The distribution of  $\Theta^2$  for excess events (points) from LS I +61 303 during orbital phases 0.6-0.7 and from Monte Carlo simulations assuming a point-like source.

region is close to or inside the binary system and that the tight orbit, combined with the dense stellar wind of the Be-star, produces a continuously changing environment for particle acceleration and absorption. Future observations with the complete four-telescope VERITAS array will allow us to test the stability of the lightcurve over several orbits and to measure the emission spectrum as a function

1. The relatively low flux makes it impossible to sample the data in shorter intervals than the width of the high state. The absolute level of the flux in each bin therefore depends strongly on the definition of the phase intervals. Varying starting points and lengths of the phase intervals can alter flux values by up to 50%.

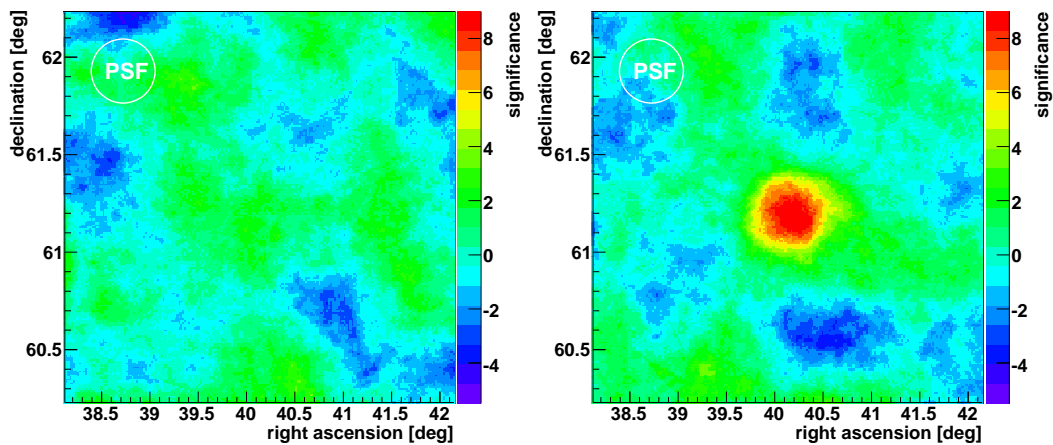


Figure 4: Significance map of the region around LS I +61 303 for data taken with two telescopes only. Left: Observations during orbital phases 0.8 to 0.5 (about 13 hours of data). Right: Observations during orbital phases 0.5 to 0.8 (about 18 hours of data). The white circle shows the  $1\sigma$  point spread function for the two-telescope array of VERITAS.

of orbital phase. These measurements, along with further contemporaneous multiwavelength observations, will provide constraining tests of the available models.

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