VERITAS Observations of LS I +61°303 in the Fermi Era

Jamie Holder* for the VERITAS Collaboration†

*Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, USA.
†see R.A. Ong et al. (these proceedings) or http://veritas.sao.arizona.edu/conferences/authors?icrc2009

***Abstract*. The high-mass X-ray binary system LS I +61°303 is well known as a rare example of a variable Galactic GeV and TeV gamma-ray emitter. Despite years of study, many aspects of the system remain unclear; the nature of the compact object, the particle acceleration mechanisms and the gamma-ray emission and absorption processes can all be modelled in a variety of different scenarios. Here we report on a deep exposure of LS I +61°303made with the VERITAS array during the 2008-2009 observing season. These are the first TeV observations made with contemporaneous coverage at lower energies by the LAT onboard Fermi, and as such provide a new set of constraints for system models.**

***Keywords*: LS I +61°303, VERITAS, Gamma-ray observations.**

I. INTRODUCTION

LS I +61° 303 is a high-mass X-ray binary system at an estimated distance of ~ 2 kpc, composed of a compact object and a B0 Ve star of 12.5 $M_\odot$ with a circumstellar disc. The observed radio through optical emission is modulated with a period ($P = 26.4960 \pm 0.0028$ days), which is believed to be associated with the orbital period of the binary system [1], [2]. New spectroscopic optical measurements by Aragona et al. [3] provide a reassessment of the orbital elements, with periastron now believed to take place at phase $\phi = 0.275$ and the orbital eccentricity $e = 0.537 \pm 0.034$.

X-ray modulation at the orbital period has been measured with the Rossi X-Ray Timing Explorer (RXTE) All-Sky Monitor [4], [5], although regular observations taken every 2 days over a period covering 6 orbital cycles in 2007-2008 with the RXTE Proportional Counter Array (PCA) show no evidence for phase-dependent flux modulation [6]. These same measurements, as well as later measurements by Ray & Hartman [7] reveal bright X-ray flaring episodes lasting longer than 10 minutes, with substructure on the timescale of a few seconds, and possible quasi-periodic oscillations. A much shorter timescale flare, lasting 0.23 seconds, has also been detected with the Swift Burst Alert Telescope (BAT) [8]. In both cases, the X-ray variability may be related to other sources in the same field-of-view (e.g. [9]).

A gamma-ray source coincident with LS I +61°303 was first detected by COS-B [10]; observations with the Energetic Gamma Ray Experiment Telescope (EGRET) revealed variability on both short (∼daily) and long (∼monthly) timescales [11]. Firm identification of the gamma-ray source with LS I +61°303 was achieved when ground-based TeV gamma-ray observatories provided an accurate position for the site of the variable gamma-ray emission [12], [13].

With the exception of the Crab Nebula, LS I +61°303 is now possibly the most heavily observed TeV source, with deep exposures by Whipple [14], MAGIC [12], [15], [16] and VERITAS [13], [17] accumulated over many years. TeV emission is only strongly detected around apastron (around phases $\phi = 0.5 - 0.8$), although weak evidence for low-flux emission at other phases has been reported [16], [17]. Analysis of the complete MAGIC dataset has revealed modulation of the gamma-ray flux close to the binary orbital period. The relatively low source flux combined with an orbital period closely matched to the lunar cycle means that the variability of the TeV emission with phase is often investigated using data taken over many orbital cycles, thus implicitly assuming no major orbit-to-orbit variability. Comparison with observations at other wavelengths also often assumes a consistent orbital dependence; clearly, strictly contemporaneous observations allow more rigorous conclusions to be drawn.

The launch of the Large Area Telescope (LAT) onboard the Fermi Gamma-ray Space Telescope provides the opportunity for such studies. First results from LAT observations [18] show that LS I +61°303 is detected continuously over all phases and that the lightcurve shows orbit-to-orbit variability. Unlike the behaviour at TeV energies, the emission measured by the LAT peaks at apastron. To coincide with the first LAT observations, VERITAS conducted an intensive observing campaign during one orbital cycle in October/November 2008, covering phases $\phi = 0.03 - 0.75$. Further observations were made to overlap with a Suzaku X-ray exposure in January/February 2009. The results of the VERITAS observations are presented here.

II. OBSERVATIONS

VERITAS [19], [20] is an array of four imaging atmosperic Cherenkov telescopes located at the basecamp of the Fred Lawrence Whipple Observatory near Tucson, Arizona. The array has been fully operational since mid-2007 and has sensitivity sufficient to detect a source with 1% of the steady Crab Nebula flux in < 50 hours. Observations cover the energy range from 100 GeV to beyond 30 TeV with an energy resolution of 15-20% above 300 GeV, and an angular resolution per gamma-ray photon of 0.1° at 1 TeV.

Observations of LS I +61°303 were made during clear nights with all four telescopes operating and no major hardware problems. The source was offset from the centre of the field-of-view by 0.5° to allow simultaneous background estimation (*wobble* mode [21]). In October/November 2008, 28.6 hours of data were collected over 19 nights, from $\phi = 0.03 - 0.75$; although we note that observations on the last 3 nights ($\phi = 0.67 - 0.75$) were only possible at decreasing source elevation angles (and so lower sensitivity). Observing conditions were excellent; this dataset is the most sensitive TeV exposure yet obtained within a single orbital cycle of LS I +61°303. Observations in January/February 2009 were planned to coincide with a 130 ks Suzaku exposure beginning 2009-01-25 at 16:22 UTC. 8.2 hours of observations were made on 5 nights, from $\phi = 0.64 - 0.91$. Poor weather resulted in a four-day gap in coverage, from $\phi = 0.68 - 0.83$. All of these observations are summarized in Table I.

III. Results

The data were analysed using standard VERITAS analysis tools [13] and with gamma-ray selection cuts suitable for a point-like source with a spectrum similar to that of the Crab Nebula. The background in the source region was estimated using the "ring-background" method [22]. The mean elevation at which these observations were made is 57°, resulting in an energy threshold (defined as the peak of the differential gamma-ray rate for a Crab Nebula-like spectrum) for this analysis of 440 GeV. All results have been verified using two independent analysis chains.

The complete 36.8 hour exposure results in a 3.4σ excess and a mean integral flux above 500 GeV of $(6.2\pm2.6)\times10^{-13}$ph cm^{-2}s^{-1}. Table I shows the results for each of the individual night's observations. The quoted significance values are not corrected for statistical trials (24 nights = 24 trials). We find no significant evidence for emission on any single night, pre- or post-trials. Figure 1 shows flux upper limits as a function of orbital phase for the two orbits covered here, and for both orbits combined.

IV. Discussion

The lack of strong emission from LS I +61°303 during these observations is somewhat suprising, but does not necessarily contradict previous measurements. The conclusion of previously published MAGIC and VERITAS results is that the source is, on average, detected at TeV energies in the phase range $\phi = 0.5 - 0.8$. Low statistics have not allowed us to draw firm conclusions about the light curve shape in this region, or to address the possibility of orbit-to-orbit variability. As noted above, the apastron coverage during this campaign was limited, with large data gaps. For example, the coverage between phases 0.72 and 0.82 consists of only 40 minutes at 47° elevation; the peak of the TeV emission might well have occured between these phases for these orbits and been undetectable.

Much stronger conclusions can be drawn for the October/November 2008 observations over phase ranges $\phi = 0.0 - 0.65$, with a large dataset of nightly observations at high elevation angles. The source is not detected by VERITAS during any of the phase bins in this range, while strictly contemporaneous Fermi measurements show the GeV lightcurve peaking during periastron (around $\phi = 0.275$) [18]. Clearly, the GeV and TeV flux states are not correlated.

There are now many models in the literature which describe high energy processes in LS I +61°303 (e.g. [23], [24], [25], [26], [27], [28], [29], [30]. These consider both accretion-driven and pulsar-wind scenarios and invoke both hadronic and leptonic relativistic particle populations. Their predictions are often fit to mean broadband spectral energy distributions (SEDs) gathered from observations made at different times in different wavelengths. The evidence presented here for a lack of correlation between the TeV and GeV fluxes shows that the orbital dependence of the emission in these wavebands is not the same, providing an additional constraint for the models to address. A number of processes could be important in this; the energy dependence of photon-photon absorption leads to differing opacities for GeV and TeV emission around the orbit(e.g. [30]). Synchrotron loss rates and inverse Compton efficiencies are both also expected to vary as the compact object encounters changing stellar wind densities and photon fields [31], which will modify the TeV and GeV fluxes differently.

V. Acknowledgements

This research is supported by grants from the US Department of Energy, the US National Science Foundation, and the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland, and by STFC in the UK. We acknowledge the excellent work of the technical support staff at the FLWO and the collaborating institutions in the construction and operation of the instrument.

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TABLE I: Daily results for VERITAS observations of LS I +61°303 in 2008-2009

Date	MJD	Orbital Phase	Exposure(mins)	Mean Elevation	ON	OFF	alpha	significance
20081021	54760	0.03	120	59°	45	421	0.11	-0.1
20081022	54761	0.07	100	57°	36	245	0.11	1.6
20081023	54762	0.11	100	59°	35	212	0.11	2.0
20081024	54763	0.15	20	55°	2	42	0.11	-1.3
20081025	54764	0.18	124	56°	25	269	0.11	-0.9
20081026	54765	0.22	140	57°	31	282	0.11	0.0
20081027	54766	0.25	100	58°	21	218	0.11	-0.6
20081028	54767	0.29	40	59°	18	93	0.11	2.1
20081029	54768	0.33	100	58°	29	183	0.11	1.8
20081030	54769	0.37	125	59°	24	210	0.11	0.2
20081031	54770	0.41	60	58°	17	87	0.11	2.0
20081101	54771	0.44	80	60°	21	158	0.11	0.8
20081102	54772	0.48	80	59°	28	155	0.11	2.4
20081104	54774	0.56	100	60°	32	188	0.11	2.1
20081105	54775	0.60	68	57°	17	113	0.11	-1.2
20081106	54776	0.63	180	58°	33	330	0.11	0.5
20081107	54777	0.67	80	53°	25	141	0.11	-2.1
20081108	54778	0.71	60	53°	8	92	0.11	0.6
20081109	54779	0.75	40	47°	9	61	0.11	0.8
20090125	54856	0.64	115	57°	25	219	0.11	0.2
20090126	54857	0.68	80	58°	8	123	0.11	-1.6
20090130	54861	0.83	100	56°	14	69	0.11	1.9
20090131	54862	0.87	114	55°	21	195	0.11	-0.1
20090201	54863	0.91	80	54°	23	151	0.11	1.4

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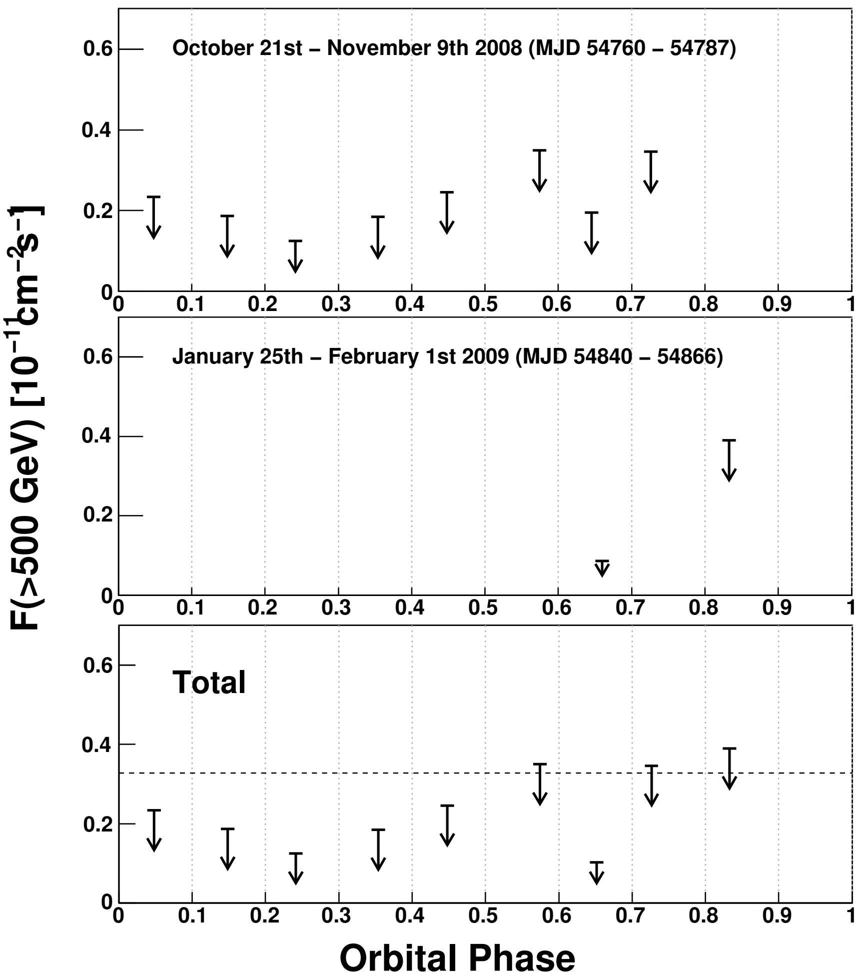

Fig. 1: Integral upper flux limits to the emission from LS I +61°303 above 500 GeV as a function of the orbital phase. Limits are at the 95% confidence level assuming a power law spectral index $\alpha = -2.5$. Arrows are placed at the mean phase of observations within each of the 10 phase bins. The dashed line indicates 5% of the integral flux from the Crab Nebula above the same threshold