TeV Observations of Galactic Binary Systems with VERITAS

Jamie Holder for the VERITAS Collaboration
Department of Physics and Astronomy and the Bartol Research Institute
Unversity of Delaware
DE 19716, USA

1 Introduction

High Energy (HE; 30 MeV - 30 GeV) and Very High Energy (VHE; 30 GeV - 30 TeV) gamma-ray emission has been detected from a number of galactic binary systems in recent years. The association of the gamma-ray source with the binary system is definitive in those cases where orbital modulation of the gamma-ray flux is observed. Binary systems which emit gamma-rays constitute a source class with rather indistinct boundaries, with few members, displaying wide variation in the properties of the binary components and the observed emission characteristics. Nevertheless, as natural particle accelerators operating under varying, but regularly repeating, environmental conditions, they provide a uniquely constraining environment for models of particle acceleration and gamma-ray production and emission processes.

The observational status can be summarized as follows. Clear HE and VHE detections exist for the known high-mass X-ray binary systems LS I +61°303 [1, 2, 3] and LS 5039 [4, 5], while Cyg X-3 and PSR B1259-63 have been detected only at HE [6, 7] and VHE [8] respectively. Evidence at the 4.1σ level for VHE emission from the stellar mass black hole candidate Cyg X-1 has been reported by Albert et al. [9] during a single short flaring episode, and transient HE emission has been reported by AGILE [10], but is not confirmed by contemporaneous Fermi-LAT observations, which place limits appreciably below the reported AGILE flux [11]. HE detections of a gamma-ray source co-located with Eta Carina [12, 13] can be interpreted as particle acceleration in the colliding wind region between the two massive stars which make up the system, although the absence of a clear orbital modulation signature lends support to alternative explanations unrelated to the binary nature of the system (e.g. [14]). The recent Fermi-LAT detection of transient HE emission associated with a nova outburst of the symbiotic star system V407 Cyg [15] adds a new and unexpected member to the class of gamma-ray binaries. Finally, the unidentified HESS source HESS J0632+057 has been proposed as a VHE binary candidate [31], although the binary identification in this case remains far from certain.

VERITAS [16] is an array of four, 12 m diameter imaging atmospheric Cherenkov telescopes used for gamma-ray astronomy in the VHE regime. The array has been fully operational since 2007 and, following the relocation of the prototype telescope to a more favorable location in summer 2009, has sufficient sensitivity to detect a source with 1% of the flux of the Crab Nebula in $\sim$ 30 hours. Deep observations of numerous binary systems have been made with VERITAS over the past few years. In these proceedings we report on some recent measurements of LS I +61°303, HESS J0632+057 and 1A 0535+262.

2 LS I +61°303

LS I +61°303 is a high-mass X-ray binary system consisting of a compact object, either black hole or neutron star, orbiting a B0Ve companion with a mass of $\sim$12.5 $M_{\odot}$ and a circumstellar disk. The orbital period is 26.5 days, and the orbit is eccentric ($e = 0.537$), with the separation between the binary components varying from $\sim$ 0.1 A.U. at periastron, to $\sim$ 0.7 A.U. at apastron.

The detection of extended structures in radio observations identified LS I +61°303 as a potential microquasar, with high energy emission produced in jets driven by accretion onto the compact object, presumably a black hole [17]. More recent observations indicate that the radio structures are not persistent, and can be more easily explained by the interaction between a pulsar wind and the wind of the stellar companion [18, 19], although alternative interpretations are still possible [20, 21].

High energy emission, spatially coincident with LS I +61°303, although with large positional errors, was detected by COS-B [22] and EGRET [23]. The detection of a variable VHE source at the location of LS I +61°303 with MAGIC [1], later confirmed by VERITAS [2], completed the identification of this source as a gamma-ray binary. The VHE emission reported by both experiments for observations made prior to 2008 is spread over approximately one quarter of the orbit, with a peak around apastron (orbital phase $\phi = 0.775$). Fermi-LAT observations provided the definitive HE detection and have revealed a number of interesting features [3]. The HE emission reported in the detection paper is modulated at the orbital period, with an emission peak slightly after periastron ($\phi = 0.225$). The overall spectrum shows a sharp exponential cutoff at 6 GeV, and so does not connect smoothly with the published VHE spectra.

The existence of orbital modulation in the gamma-ray flux is often explained by the varying efficiency of the inverse Compton process around the orbit, although we note that many alternative explanations exist (see e.g. [24] for a review). In this scenario, inverse Compton gamma-ray production along our line of sight is most efficient at superior conjuction ($\phi = 0.081$), where stellar photons interact head-on with energetic leptons produced either directly in the pulsar wind or in the pulsar wind/ stellar wind shock interaction region. The density of stellar photons also plays a role in the efficiency of gamma-ray production, with the highest density occurring at periastron. The VHE flux is further modulated by photon-photon absorption around the orbit, which peaks near superior conjuction and may dominate over the modulation effects due to production efficiency at energies above $\sim$ 30 GeV. Orbital modulation of the HE and VHE flux, with large differences between the lightcurves observed in each energy band, is therefore not unexpected. Other effects, for example Doppler boosting of the emission [25] or cascading of high energy photons to lower energies may also play a role and provide a better fit of the models to the observations.

Two observational features are not yet well explained, and to some extent have been misinterpreted in most of the modelling work thus far. The first is the existence of the 6 GeV cut-off in the Fermi-LAT spectrum. This feature is too low in energy to be explained by pair absorption, and so might possibly point towards a different origin for the HE and VHE emission; for example, the HE emission might be largely magnetospheric, since similar cut-offs are observed in many Fermi-LAT pulsar spectra [3]. In this case, however, it is difficult to explain the observed orbital modulation of the HE flux. A key point to note is that the published HE/VHE spectra are comprised only of non-contemporaneous observations. All of the VHE observations were made before the launch of Fermi, and contain only data taken during apastron high states. **There is no direct evidence that the VHE emission continues beyond the Fermi-LAT cutoff, for observations made at the same time**.

Figure 1 summarizes VERITAS observations since the launch of Fermi. In 2008-9, apastron coverage was limited due to bright moon conditions. VERITAS observations therefore focussed on attempting to obtain reasonably deep coverage over a wide phase range, during two orbital cycles. Only marginal evidence (3.4 σ) for a gamma-ray signal in the complete 37 hour dataset was obtained [26], and upper limits in each phase bin are presented in the figure. In 2009-2010, apastron was visible during full dark time, and so observations were targeted towards deep exposures at this phase. 18 hours of data were collected over three orbital cycles, resulting in no significant gamma-ray excess (0.8 σ). The upper limits, particularly around apastron phases in 2009-2010, are significantly below the previously reported fluxes; in the case of VERITAS this is due, in part, to the fact that the observations were made with a much more sensitive instrument, since the early detections were made during the array construction phase. These results lead to the second observational feature we wish to highlight; **there is no strong evidence for VHE gamma-ray emission from LS I +61°303 since the launch of Fermi-LAT**. A corollary to this observation is that there is no direct evidence that the HE and VHE lightcurves are in anti-phase with each other, as is often assumed. It should also be stressed that the recent VERITAS observations do not prove that VHE emission has been completely absent since the launch of Fermi; as shown in Figure 1, the sampling is extremely limited, and even during those periods where observations were made, each observation consisted of typically 1-2 hour exposures, separated by at least a day. Variability from the source has been observed at X-ray wavelengths on timescales from hours to as short as a few seconds [28]. The VHE emission may be similarly variable, or there may be significant orbit-to-orbit variability; either case could simply explain the VERITAS observations.

A further interesting observational feature was presented at this conference [27]. In March 2009 the average HE flux observed by Fermi-LAT increased by $\sim 40\%$. Additionally, a periodic analysis of LAT data since the flux increase shows no strong evidence for orbital modulation of the flux. Clearly, the gamma-ray emission of LS I +61°303 cannot be simply characterized. The solution to this lies in future broadband, contemporaneous, coordinated observing campaigns, as are frequently arranged for the gamma-ray blazars.

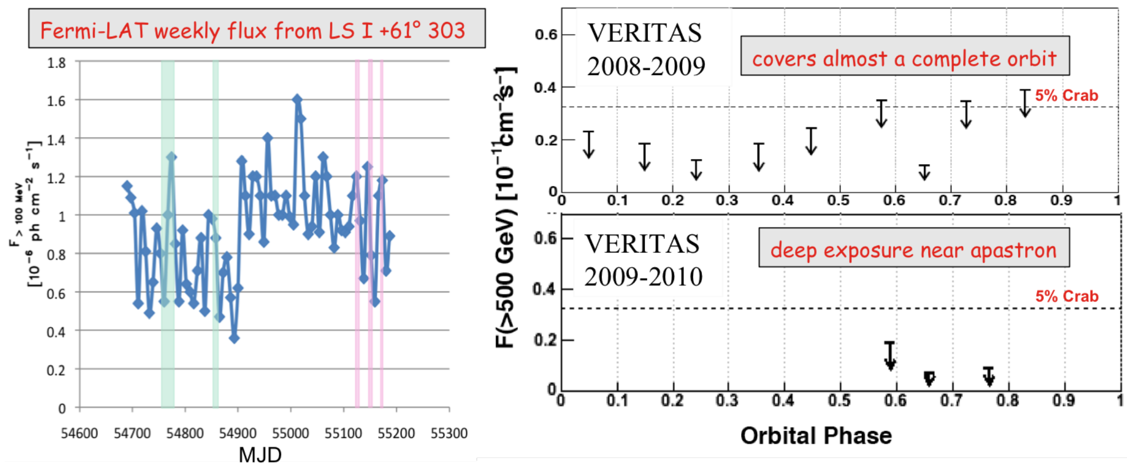

Figure 1: VERITAS observations of LS I +61°303 since the launch of Fermi-LAT. On the left is shown the LAT weekly lightcurve (courtesy of R. Dubois), with the VERITAS observation periods indicated by shaded bands. Observations during each shaded band consisted of a series of up to two hour exposures, separated by at least one day. Orbital phase-binned upper limits for the two observing seasons are shown on the right.

3 HESS J0632+057

HESS J0632+057 is an unidentified VHE source, serendipitously detected using the H.E.S.S. imaging atmospheric Cherenkov array during observations of the region of the Monoceres supernova remnant and the Rosette Nebula [29]. The source is unusual among unidentified VHE sources in that it is unresolved, with an upper limit to the extension of 2'. Observations at other wavelengths have revealed a faint, variable radio source [30], and a variable, hard spectrum X-ray source [31, 32], with positions compatible with that of HESS J0632+057, and also with the location of MWC 148, a B0pe star. These features have led to the suggestion that HESS J0632+057 may be a gamma-ray binary system, previously unidentified at other wavelengths [31].

Further weight was added to this argument by VERITAS observations of the source made in 2006, 2008 and 2009 totalling 30 hours, which failed to detect any evidence for gamma-ray emission, thus establishing the source as variable in the VHE band (at the 4σ confidence level) [33]. Figure 2 shows the result of new observations with VERITAS from the 2009/2010 observing season, which verify this result. An 8 hour exposure in October 2009 did not detect the source, while a 20 hour exposure in February/March 2010 led to a clear detection (7.5 σ), with a position in agreement with both HESS J0632+057 and MWC 148, and a flux of $\sim 50\%$ of the original H.E.S.S. detection. Extended multiwavelength campaigns are again necessary to establish the nature of this object. The detection of an orbital periodicity in the emission at any wavelength would provide definitive evidence for the presence of a binary system.

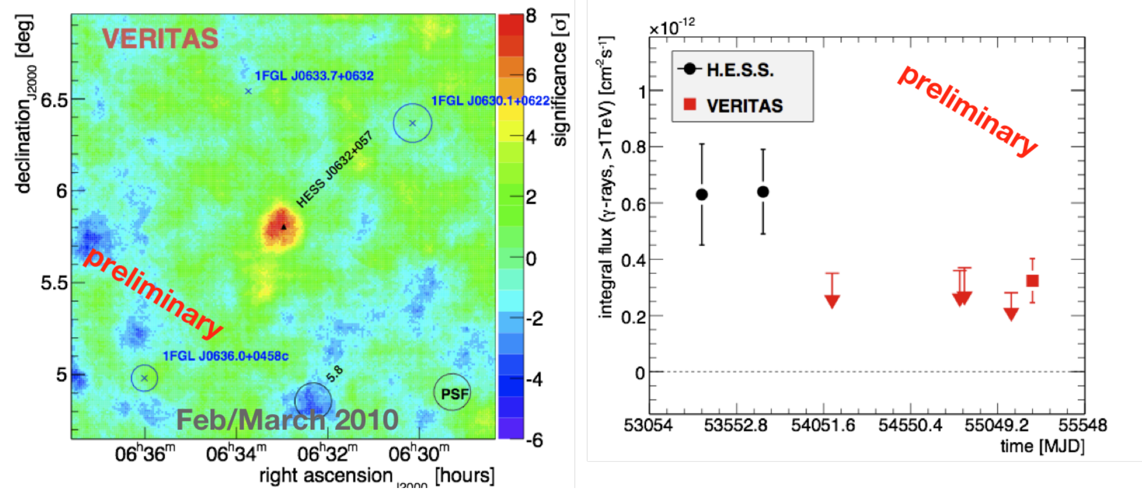

Figure 2: VERITAS observations of HESS J0632+057. On the left is shown the VERITAS significance map for a 20 hour exposure in February/March 2010. The right-hand plot shows the complete H.E.S.S./VERITAS VHE lightcurve.

4 1A 0535+262

1A 0535+262 is a high mass X-ray binary system at a distance of 2.4 ± 0.4 kpc, consisting of a Be star (spectral type O9.7IIIe) and a magnetized X-ray pulsar with a spin period of 104 s [34]. The binary period is 110 days, and the orbital eccentricity, $e = 0.47$ [35]. The source shows luminous "Type II" X-ray outbursts, with much higher peak fluxes than the "Type I" bursts associated with periastron passage. Type II bursts have occurred approximately every 5 years since the first X-ray detection in 1975 and typically last for $\sim$ 1 month. The hard X-ray spectrum observed during these outbursts points to the existence of non-thermal particle populations. Orellana & Romero [36] have discussed the possibility of VHE emission from systems such as this through a scenario in which relativistic protons, accelerated through the Cheng-Ruderman mechanism [37], impact the surface of a transient accretion disk and produce gamma-rays via neutral pion decay.

In December 2009 the detection of a giant X-ray outburst from 1A 0535+262 [38, 39] triggered observations with VERITAS. The source was regularly monitored from December 6th 2009 (MJD 55171) until February 20th 2010 (MJD 55247), yielding a total exposure of 28 hours covering almost one complete 110 day orbital cycle. The X-ray flare itself lasted for $\sim$ 40 days and reached a peak flux of $\sim$ 5 Crab in the Swift-BAT $15 - 50$ keV range, making this the brightest outburst ever observed from this source. Figure 3 details the VERITAS coverage with respect to the binary orbit and the X-ray flare. No evidence for gamma-ray emission was detected, either in the complete dataset or when the data were divided into four subsets covering the rising and falling edges of the flare, and two post-flare periods at apastron and approaching periastron. The outburst occurred at an ideal time for VERITAS observations, with the instrument operating at its highest sensitivity to-date, during a period of dark, clear skies and without strong competition from other source

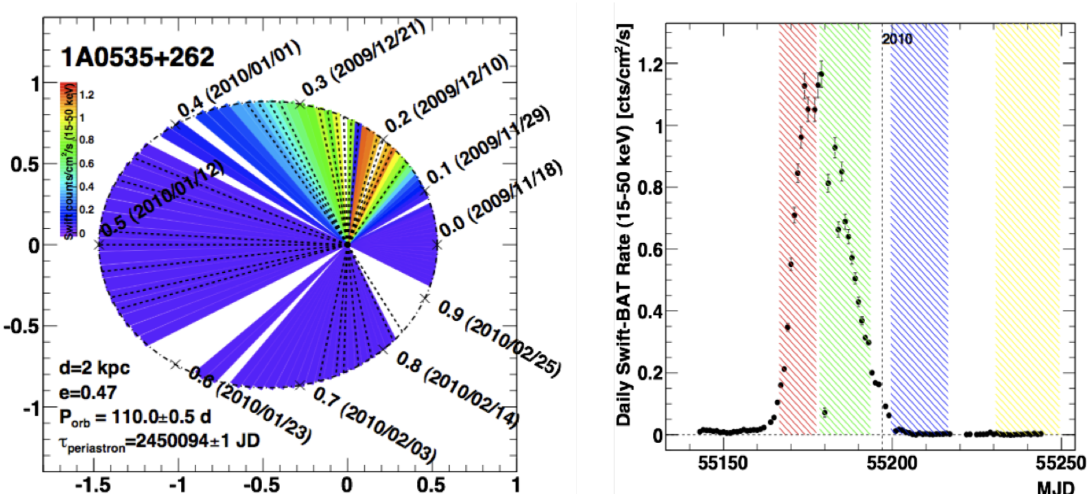

Figure 3: VERITAS observations of 1A 0535+262. On the left is shown the orbit of the binary system. The colour scale of the shaded regions indicates the Swift-BAT $15-50$ keV count rate; the dashed lines indicate the dates of VERITAS observations. The right-hand plot shows the Swift-BAT count rate ligt curve. The four shaded regions indicate the division of VERITAS data into rising (red) and falling (green) flare edges, apastron (blue), and approaching periastron (yellow).

candidates. Since such outbursts occur only once every five years, and since 1A 0535+262 is the most well studied of the Be/X-ray binaries showing Type II outbursts, these data likely provide the definitive results on this source class for this generation of imaging atmospheric Cherenkov telescopes.

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References

[1] J. Albert, et al., Science, 312, 1771, 2006.

[2] V.A. Acciari, et al., ApJ, 679, 1427, 2008.

[3] A.A. Abdo, et al., ApJ, 701, L23, 2009.

[4] F.A. Aharonian, et al., A&A, 460, 743, 2006.

[5] A.A. Abdo, et al., ApJ, 706, L56, 2009.

[6] M. Tavani, et al., Nature, 462, 620, 2009.

[7] The Fermi LAT Collaboration, Science, 326, 1512, 2009.

[8] F.A. Aharonian, et al., A&A, 442, 1, 2005.

[9] J. Albert, et al., ApJ, 665, L51, 2007.

[10] S. Sabatini, et al., ApJ, 712, L10, 2010.

[11] R. Dubois, et al., "Proc. ICREA Workshop on The High-Energy Emission from Pulsars and their Systems", Sant Cugat, Spain, April 12-16, 2010

[12] M. Tavani, et al., ApJ, 698, L142, 2009

[13] A.A. Abdo, et al., ApJSupp., 188, 405A, 2010

[14] S. Ohm, J.A. Hinton & W. Domainko, ApJL *preprint arXiv:1006.2464*

[15] C.C. Cheung, et al., Astronomer's Telegram #2487, 2010.

[16] R.A. Ong, et al., in "Proc 31st ICRC", Lodz, Poland, 2009, *preprint arXiv:0912.5355*

[17] M. Massi, et al.,A&A, 376, 217, 2001.

[18] V. Dhawan, et al., in "Proc. of the VIth Microquasar Workshop: Microquasars and Beyond", Como, 2006.

[19] J. Albert, et al., ApJ, 684, 1351, 2008.

[20] G.E. Romero, et al., A&A, 474, 15, 2007.

[21] M. Massi & L. Zimmerman, A&A, 515, 82, 2010.

[22] W. Hermsen, et al., Nature, 269, 494, 1977.

[23] M. Tavani, et al., ApJ, 497, L89, 1998.

[24] A. Sierpowska-Bartosik, & D. Torres, ApJ, 693, 1462, 2009

[25] G. Dubus, B. Cerutti & G. Henri, A&A, 516, 18, 2010.

[26] J. Holder, et al., in "Proc 31st ICRC", Lodz, 2009.

[27] R. Dubois et al., these proceedings.

[28] A. Smith, et al., ApJ, 693, 1621, 2009.

[29] F.A. Aharonian, et al., A&A, 469, L1, 2007.

[30] J.L. Skilton, et al., MNRAS, 399, 317, 2009.

[31] J.A. Hinton, et al., ApJ, 690, L101, 2009.

[32] A.D. Falcone, et al., ApJ, 708, L52, 2010.

[33] V.A. Acciari, et al., ApJ, 698, L94, 2009.

[34] A. Giangrande, et al., A&AS, 40, 289, 1980.

[35] M. Finger, R.B. Wilson & B.A. Harmon, ApJ, 459, 288, 1996.

[36] M. Orellana & G.E. Romero, Ap&SS, 297, 167, 2005.

[37] K.S. Cheng & M. Ruderman, ApJ, 373, 187, 1991

[38] C.A. Wilson-Hodge, et al., Astronomer's Telegram #2324, 2009.

[39] H.A. Krimm, et al., Astronomer's Telegram #2336, 2009.