VHE Observations of Galactic binary systems with VERITAS

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Abstract: A few Galactic objects are known to be variable sources of photons with energies above 100 GeV. These systems are mostly binaries, where variability can often be connected to the orbital period. Particle acceleration and gamma-ray production processes in binaries are generally not well understood. We present here an overview of VERITAS observations of binary systems at very-high energies (VHE) with emphasis on LS I +61 303 and 1A0535+262. The results are discussed in the context of recent observations of RXTE, Swift and Fermi LAT at X- and Gamma-ray energies.

Keywords: acceleration of particles; binaries; gamma rays: observations - individual (1A 0535+262; LS I +61 303)

1 Introduction

Several high-mass X-ray binaries have been detected in the VHE energy range in the past years. These binaries constitute the only known class of galactic objects with variable point-like VHE emission. The class currently contains three members: PSR B1959-63/LS 2883 [6], LS 5039 [7] and LS I +61 303 [9, 2]. A fourth TeV binary might be the unidentified VHE source HESS J0632+057 [8], a variable gamma-ray source located in the Monoceros region.

The variable emission from VHE binaries is likely connected to changes in physical parameters associated with the orbital movement. This makes each of these systems unique, since orientation, sizes, and eccentricity of the orbits vary widely. Orbital periods range from a few days in PSR B1959-63 to several years in LS 5039 to several years in PSR B1959-63. The changes during an orbit are not of geometrical nature only, beside distances and orientation of the objects towards each other and the observer are variations in photon and matter densities around the acceleration sites the main causes for the variable emission.

PSR 1259-63 is currently the only VHE binary with a clearly identified compact object - a 48 ms pulsar orbiting a Be star in an eccentric orbit. No pulsed emission at any wavelength has been detected from the binaries LS 5039 and LS I + 61 303, although pulsed signals might get absorbed in the dense photon field of the nearby bright companion stars (see e.g. [19]). In general, the VHE emission in these objects is explained by the acceleration of charged particles in shocks created by the collision of the wind of the stellar companion with the expanding pulsar wind or by acceleration in accretion-powered jets. The high-energy particles produce VHE photons in hadronic and/or leptonic (inverse Compton scattering of low-energy stellar photons) interactions.

We present in the following observations of two binary systems with VERITAS at energies above 100 GeV: LS I +61 303 was observed for more than 60 hours during several orbital phases between 2008 and 2010 and the Be/X-ray binary 1A0535+262 was observed during a giant X-ray outburst in December 2009 for a full orbit. For details on the X-ray analysis and results, see [4, 5].

2 VERITAS

VERITAS is an array of four imaging atmospheric-Cherenkov telescopes (IACT) located at the Fred Lawrence Whipple Observatory in southern Arizona. It combines a large effective area ($>10^5$ m²) over a wide energy range (100 GeV to 30 TeV) with good energy (15-20%) and angular ($\approx 0.1\degree$) resolution. The field of view of the VERITAS telescopes is 3.5°. The high sensitivity of VERITAS enables the detection of sources with a flux of 1% of the Crab Nebula in about 25 hours of observations. For more details on the VERITAS instrument, see e.g. [16].

3 LS I +61 303

The high-mass X-ray binary LS I +61 303 consist of a BO-Be star surrounded by a dense circumstellar disk and a compact object of unknown nature (neutron star or black hole). Optical observations show that the compact object orbits the star every 26.5 days [14, 10] on a close orbit, characterized by a semi-major axis of a few stellar radii only. Periodic variability correlated with the orbital cycle has been
observed across the electromagnetic spectrum. Long-term X-ray observations show that there is additionally variability of the orbital profiles on multiple time scales, from individual orbits up to years [23]. Beside the periodic variability, intense X-ray flares with flux increases by several factors on the time scale of seconds have been observed [21].

Fermi-LAT observations show that the gamma-ray emission at energies about 30 MeV is modulated with the orbital period (peaking after periastron, $\Phi = 0.225$) [1]. The energy spectrum shows a sharp exponential cutoff at 6 GeV. The LAT results reveal overall flux variations not connected to the orbital movement by up to 40%. In the VHE range, LS I +61 303 has been detected by ground-based gamma-ray observatories with emission peaking around apastron [9, 2]. The measured energy spectra for the apastron passage can be described by a power law, with a spectral index of 2.4 and a flux above 300 GeV corresponding typically to about 10-15% of the flux from the Crab Nebula.

Figures 1-3 show fluxes and flux-upper limits per orbital phase bin calculated from 64.5 hours of VERITAS observations between October 2008 and January 2011. The covered phases by VERITAS observation are influenced by the moon cycle which does not allow a complete coverage of a single orbital phase [1]. The strategy for the observing season 2008/2009 was to achieve the widest possible coverage during an orbital phase with a flux sensitivity in the range of 5% of the flux of the Crab Nebula. For 2009/2010, the goal was to achieve a deep exposure around apastron in co-

1. Note that observations taken under moderate moonlight conditions are included in the presented data set.
ordination with Swift XRT observations. In the observing season 2010/2011, the phases between superior conjunction and periastron were in the focus of the observations. These results are remarkable in the following ways:

- No strong evidence for emission from LS I +61 303 during the apastron phases was observed during the observations taken in 2008-2010. The 2009/2010 measurements, with a deep exposure of about 17 hours in the phase interval $\Phi=0.5-0.8$, result in upper flux limits (99% confidence level) of less than 5% of the flux of the Crab Nebula. Note that the object has been detected before at flux levels of 10-15% of the flux from the Crab Nebula during these orbital phases.

- LS I +61 303 has been detected in September-November 2010 close to the phase of superior conjunction (much closer to periastron passage), a region of the binary orbit previously undetected by VHE instruments. A total of 13.9 hours of LS I +61 303 were accumulated resulting in a post-trials significance of 5.6 standard deviation. The source flux above 300 GeV in the $\Phi=0-0.1$ phase bin was measured to about 5% of the flux of the Crab Nebula.

- The detection of the binary close to superior conjunction does not directly implicate that the processes responsible for gamma-ray emission above 300 GeV are different than those at lower gamma-ray energies. The energy spectrum as published by the Fermi LAT collaboration with a cutoff at 6 GeV is an average spectrum for many orbital periods, the data presented here are for a single phase bin at one orbital period.

The light curves from VERITAS show that beside the variability correlated with the orbital cycle, there is additional orbit-to-orbit variability with no obvious pattern. The number of upper flux limits and gaps in the light curves shown in Figures 1-3 indicate the two main difficulties for observing LS I +61 303 with current instruments despite the long exposure of more than 60 hours: firstly, the orbital period is close to the lunar periodicity (IACTs cannot observe during periods of bright moonlight) and secondly the fluxes away from the apastron regions seem to be close to the sensitivity limits of the instruments. Only continuing monitoring in the X-ray to VHE energy ranges together with well coordinated multiwavelength campaigns will allow us in the coming years to probe short and long term variability and the emission mechanisms more precisely.

4 1A0535+262

1A0535+262 is a nearby (distance of $\approx 2$ kpc) Be/X-ray binary consisting of a pulsar of period 103 s in an eccentric orbit ($e = 0.47$) with an O9.7-B0 IIIe star. The orbital period is 111 days. Giant outbursts at X-ray wavelengths are observed approximately every five years from the direction of 1A0535+262. They are thought to be associated with the formation of a transient accretion disk [22]. VHE gamma rays are thought to be produced through hadronic or leptonic scenarios. In hadronic models, protons...
are accelerated in the magnetosphere of the neutron star and impact the transient accretion disk. The pp-interactions in the accretion disk produces VHE gamma rays via the decay of neutral pions [12]. In leptonic models, electrons are accelerated in strong shocks formed by the interaction between pulsar wind and stellar wind. These relativistic electrons may produce VHE gamma rays by upscattering ambient photons. The high-energy photons are expected to interact with ambient photons to produce $e^+e^-$ pairs, leading to orbital modulation of the VHE gamma-ray flux [11]. The system is therefore opaque to gamma rays near the peak of the outburst, the highest gamma-ray flux is expected at the beginning or end of the outburst, when thermal emission from the accretion disk is at a minimum [20].

VERITAS observed 1A0535+262 shortly after the onset of the giant outburst in December 2009 for a complete orbital period. The Swift BAT measurement in Fig 4 shows that the hard X-ray flux reached a level of $>5$ times that of the Crab Nebula. The triggering condition for observation of flaring X-ray binaries with VERITAS was fulfilled on 2009 December 5, observations started on 2009 December 6, shortly after the beginning of the giant flare. They were delayed by one day due to very bright moonlight conditions. The observation covered most of the flare, included the apastron phase, and continued for almost 90 days until the following periastron phase (see Figure 5).

No evidence for VHE gamma rays has been found for the complete VERITAS data set consisting of 23 hours of high-quality observations. The flux upper limit at the 99% confidence level [15], assuming a power-law-like source spectrum with a spectral index of $\Gamma = 2.5$, is $F (\geq 0.3 \text{ TeV}) < 0.5 \times 10^{-12} \text{ ph cm}^{-2} \text{s}^{-1}$ (about 0.4% of the flux of the Crab Nebula above 0.3 TeV).

The VERITAS data were arranged in different periods, as gamma-ray production and absorption is expected to vary with orbital movement and flaring state. The four periods are: rising portion and falling portion of the giant flare, apastron and periastron. No VHE emission has been detected in any of these periods; upper limits between 0.9 and 2.0% of the flux of the Crab Nebula ($> 0.3 \text{ TeV}$) have been derived.

X-ray observations with the Swift XRT and RXTE PCA instruments show that the spectra are best fitted with a model that consists of blackbody and Comptonized emission from thermal electrons at temperatures of approximately 2 keV and 6 keV, respectively [4].

The non-detection at VHE wavelengths, the results from the spectral analysis of the X-ray observations, and the non-detection of 1A0535+262 at radio wavelengths indicates that there is no significant non-thermal electron population in this system. The VERITAS upper limit are placing additionally constrains on hadronic models, with the upper limits below the predicted flux levels by e.g. [18].

1A0535+262 represents the archetype of the class of Be binary systems which exhibit giant outbursts and the VERITAS observations were the best we could hope to get in terms of coverage and exposure. A detection or significantly better flux upper limits will probably have to wait for a next-generation ground-based gamma-ray observatory.

In summary, extensive observations of the two binaries LS I +61 303 and 1A0535+262 with VERITAS showed that VHE emission processes in binaries are not well understood. A significant improvement in coverage of the different orbital periods and in sensitivity are probably needed to constrain or refute the large variety of theoretical models.

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