Observations of Galactic binary systems with VERITAS

The VERITAS Binary Discovery Program

11 years of observations on HESS J0632+057
Gamma-ray binaries: key questions

Why do some binary systems emit gamma-rays?
- Only 5 out of >120 known HMXBs are known to emit gamma rays above 100 GeV

Are binaries pulsar-wind or accretion powered?
- Are microquasars gamma-ray emitters?

What modulates the variability?
- More and different variability detected than originally expected (on all time scales: flares, orbit, multi-year cycle, etc.)

What is the role of stellar winds?

How many gamma-ray binaries are out there?
- HESS J0632+057 was not even known to be a binary system (and is not yet detected at MeV-GeV energies)
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array of four 12 m Imaging Atmospheric Cherenkov Telescopes located in southern Arizona

- fully operational since 2007
- energy range: 100 GeV to >30 TeV
- field of view of 3.5°
- angular resolution ~0.1°
- point source sensitivity: 5σ detection at 1% Crab in <25h
- several upgrades: T1 move, mirror alignment, L2 trigger, PMTs
What constitutes an ideal candidate for a TeV binary?

<table>
<thead>
<tr>
<th></th>
<th>type</th>
<th>D (kpc)</th>
<th>orbital period [d]</th>
<th>Radio (10^{29}\text{erg/s})</th>
<th>1-10 keV (10^{35}\text{erg/s})</th>
<th>&gt;0.1 GeV (10^{35}\text{erg/s})</th>
<th>&gt;100 GeV (10^{35}\text{erg/s})</th>
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</thead>
<tbody>
<tr>
<td>LS 5039</td>
<td>06.5V+neutron star? BH?</td>
<td>2.5</td>
<td>3.9</td>
<td>6.0</td>
<td>0.12</td>
<td>2.8</td>
<td>0.14</td>
</tr>
<tr>
<td>LS I +61 303</td>
<td>Be?+neutron star? BH?</td>
<td>2 (?)</td>
<td>26.5</td>
<td>28.7</td>
<td>0.14</td>
<td>2.3</td>
<td>0.13</td>
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<tr>
<td>PSR B1259-63</td>
<td>Be + 48ms pulsar</td>
<td>1.5</td>
<td>1237</td>
<td>6.3</td>
<td>0.23</td>
<td>2.8</td>
<td>0.09</td>
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<tr>
<td>1FGL J1018.6-5856</td>
<td>06.5V+neutron star? BH?</td>
<td>5</td>
<td>16.6</td>
<td>4.2</td>
<td>0.17</td>
<td>9.7</td>
<td>0.09</td>
</tr>
<tr>
<td>HESS J0632+057</td>
<td>B0pe + ??</td>
<td>1.5</td>
<td>315</td>
<td>0.04</td>
<td>0.01</td>
<td>&lt;0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- O or B(e) star system, LAT detection(?), non-thermal radio source, correlated multiwavelength variability, …

following Dubus (2013)
What constitutes an ideal candidate for a TeV binary?

- massive star with strong stellar wind (O or B star)
- young pulsar with wind strong enough to create a standing shock and quench the infall of the stellar matter ($\dot{E} \approx 10^{36} \text{ erg/s}$)
- short-lived phase in the evolution of pulsar wind - massive star systems (might learn something about the population)

Sketch from Szostek & Dubus (2011)

see also e.g. Dubus 2006, Mirabel 2012
The VERITAS Binary Discovery Program

> systematic search for new gamma-ray binaries in the Galaxy
  - goal is to observe each system for 10-12 hours with VERITAS

> 14 objects selected
  - a massive companion star of O or B(e)-type
  - a relatively small distance (<5 kpc),
  - preference for orbital periods < 50 days

> IGR J00370+6122
  - B star, ~15 days orbit, bright integral source (quite similar to LS I +61 303)

> XTE J0421+560
  - X-ray transient, Be star, 19 days orbit

> V662 Cas
  - wind-accretion, supergiant, high-mass X-ray binary, B-star, neutron star, 11.6 day orbital period

> LS V +44 17
  - Be X-ray binary pulsar, 150 d orbit,
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VERITAS Results:

<table>
<thead>
<tr>
<th>Binary</th>
<th>Observing Time</th>
<th>Elevation Range</th>
<th>Significance</th>
<th>Flux upper limits (99% confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGR J00370+6122</td>
<td>1009 minutes</td>
<td>52° – 61°</td>
<td>2.8</td>
<td>$3.6 \times 10^{-13}$</td>
</tr>
<tr>
<td>XTE J0421+560</td>
<td>1466 minutes</td>
<td>50° – 66°</td>
<td>-0.7</td>
<td>$5.2 \times 10^{-13}$</td>
</tr>
<tr>
<td>V662 Cas</td>
<td>694 minutes</td>
<td>52° – 56°</td>
<td>0.1</td>
<td>$1.2 \times 10^{-12}$</td>
</tr>
<tr>
<td>LS V +44 17</td>
<td>849 minutes</td>
<td>48° – 77°</td>
<td>-2.7</td>
<td>$3.1 \times 10^{-13}$</td>
</tr>
</tbody>
</table>
MWC 148: B0pe star
- distance 1.1-1.7 kpc
- $M=16M_\oplus$, $R=6.6R_\oplus$, $T=3\times10^5K$
- thick equatorial disk
- weak, variable (day-month), extended radio source
- Swift, XMM, Chandra, Suzaku: variable (day-month) hard X-ray source (absorbed power law with variable index)
- **long-term Swift observations:** $315\pm5$ d modulation
- no pulsation found in deep searches (Chandra, GBT)
- no MeV-GeV Fermi LAT detection
HESS J0632+057

Monoceros Loop

Rosetta Nebula

DSS

XMM

star: MWC 148

circle: XMM-Newton best fit

2004: serendipitous discovery (H.E.S.S.) and discussion that this might be a binary system

2009: evidence for variability (no detection with VERITAS)

2010: detection with VERITAS

2011/2012: detection (H.E.S.S./MAGIC/VERITAS)
orbital period $315^{+6}_{-5}$ days (Aliu et al 2014)

new X-ray data still consistent with this value
VERITAS observed HESS J0632+057 for 220 hours since 2006 (total detection significance: $23.1\sigma$)

part of the long-term observation plan: will continue monitoring HESS J0632+057 with 15 hours / year
HESS J0632+057 - Gamma-ray observations

Phase folded light curve (315 days orbital period)
Remarkable light curve

double outburst around apastron (when the massive star is many (>100) solar radii way)

dip at apastron

lower flux state around periastron ($d_{\text{periastron}} \sim 10$ solar radii)

Unclear role of the stellar disk - possibly interaction of pulsar wind with an extended misaligned disk of the Be star (Okazaki 2012)?
Phase folded light curve (315 days orbital period)

- Phases 0.2-0.4: 19.7σ
- Phases 0.4-0.6: 2.7σ
- Phases 0.6-0.8: 11.4σ
- Phases 0.8-0.2: 6.2σ

Casares et al (2012)
HESS J0632+057 - energy spectra vs phases

Casares et al (2012)

Gernot Maier
Binary Observations with VERITAS | ICRC 2017

<table>
<thead>
<tr>
<th>Orbital phase</th>
<th>all phases</th>
<th>0.2-0.4</th>
<th>0.4-0.6</th>
<th>0.6-0.8</th>
<th>0.8-0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation time (h)</td>
<td>220.5</td>
<td>88.5</td>
<td>45.1</td>
<td>26.9</td>
<td>60</td>
</tr>
<tr>
<td>Significance (σ)</td>
<td>23.1</td>
<td>19.7</td>
<td>2.7</td>
<td>11.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Flux Normalization Φ₀ at 1 TeV</td>
<td>4.1 ± 0.2</td>
<td>6.4 ± 0.4</td>
<td>-</td>
<td>6.2 ± 0.7</td>
<td>2.1 ± 0.4</td>
</tr>
<tr>
<td>Photon index γ</td>
<td>2.67 ± 0.05</td>
<td>2.70 ± 0.06</td>
<td>-</td>
<td>2.55 ± 0.13</td>
<td>2.67 ± 0.2</td>
</tr>
<tr>
<td>χ²/N</td>
<td>15.2/8</td>
<td>22.8/7</td>
<td>-</td>
<td>2.7/7</td>
<td>0.8/3</td>
</tr>
</tbody>
</table>
HESS J0632+057 - energy spectra vs phases

- well measured energy spectra in three different phase ranges
- no hint of changes of spectral shape with orbital phase
- similar physical conditions at the gamma-ray emission sites during the high states before and after the apastron phase?
variability pattern of the phase-folded gamma-ray light curve follows the X-ray light curve
VERITAS binary discovery program
- search for new Northern sky binaries

HESS J0632+057: first binary detected through VHE gamma-ray observations
- 11 years of observations (220 hours);
  clear detection at all phases except ‘dip’ state
- regular emission pattern following closely the X-ray light curve

missing bits required for detailed modelling: long-term optical observations (orbital solution), state, orientation, and variability of circumstellar disk, …