Binaries at very-high energies - Recent results from VERITAS

- Status of VERITAS
- Observation of binaries
- Cygnus X-3, V 407 Cygni, LS I +61 303, HESS J0632+057

Gernot Maier for the VERITAS Collaboration

Tuesday, April 23, 13
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 
  <30h
- several upgrades: T1 move, 
  mirror alignment, L2 trigger, 
  PMTs
VERITAS upgrade and new observation modes

> replacement of all PMTs in the VERITAS cameras
  - improved quantum efficiency by 35% (Hamamatsu R10560-100-20)
  - energy threshold in analysis lowered to 85 GeV (was 135 GeV)

> new observation modes for increased temporal coverage
  - ~850 hours of normal operations
  - ~200 hours of moonlight operations (at nominal + reduced HV)
  - ~250 hours of bright moonlight observations with UV filters in front of the cameras
VERITAS upgrade and new observation modes

- replacement of all PMTs in the VERITAS cameras
  - improved quantum efficiency by 35% (Hamamatsu R10560-100-20)
  - energy threshold in analysis lowered to 85 GeV (was 135 GeV)
- new observation modes for increased temporal coverage
  - ~850 hours of normal operations
  - ~200 hours of moonlight operations (at nominal + reduced HV)
  - ~250 hours of bright moonlight observations with UV filters in front of the cameras
Obtaining observing time on VERITAS

> guest proposals are very welcome: next round of proposals in Summer 2013
  - access through a member of the VERITAS collaboration - joint proposals

> Joint Fermi/VERITAS Guest investigator program
  - up to 120 hours (15% of total observing time) reserved for proposals through Fermi GI program (not more then 25% of any RA band)
  - first time for cycle 6 (Jan 2013), if successful, the program will continue in 2014
<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>D (kpc)</th>
<th>Orbital Period [d]</th>
<th>TeV/GeV Detection</th>
<th>Type of Observation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HESS J0632+057</td>
<td>B0pe + ??</td>
<td>1.5</td>
<td>321</td>
<td>✘/✔</td>
<td>regular (10-30 h/season)</td>
<td>2009, 2013</td>
</tr>
<tr>
<td>Cygnus X-1</td>
<td>O9.7 Iab+black hole</td>
<td>2.2</td>
<td>5.6</td>
<td>✔/✔</td>
<td>ToO (X-rays/LAT)</td>
<td>-</td>
</tr>
<tr>
<td>Cygnus X-3</td>
<td>Wolf Rayet + BH?</td>
<td>7</td>
<td>0.2</td>
<td>✓/✘</td>
<td>ToO (X-rays/LAT)</td>
<td>-</td>
</tr>
<tr>
<td>Be X-ray Binary snapshot program</td>
<td>Be-XRB</td>
<td>-</td>
<td></td>
<td></td>
<td>filler program</td>
<td>-</td>
</tr>
<tr>
<td>BAT flaring hard X-ray objects</td>
<td>SGRs+XRBs</td>
<td>-</td>
<td></td>
<td></td>
<td>ToO</td>
<td>-</td>
</tr>
<tr>
<td>Millisecond pulsar binaries</td>
<td>MSPB</td>
<td>-</td>
<td></td>
<td></td>
<td>regular (10-15 h/season)</td>
<td>-</td>
</tr>
<tr>
<td>Magnetars</td>
<td>SGRs+AXPs</td>
<td>-</td>
<td></td>
<td></td>
<td>ToO (GRB pipeline)</td>
<td>Proc of ICRC 2009</td>
</tr>
<tr>
<td>Crab Nebula/Pulsar</td>
<td>PWN/Pulsar</td>
<td>2</td>
<td></td>
<td>✔/✔</td>
<td>regular + ToO</td>
<td>Science 334, 69 (2011)</td>
</tr>
</tbody>
</table>
Binary monitoring example: Cygnus X-3

Fermi LAT (200 MeV - 300 GeV)

VERITAS Observations
March 24/27th 2012: 2h

F(E>100 GeV) < 1.8x10^{-12} cm^{-2}s^{-1}

(99%, γ=-2.5)

trigger event in hard X-rays

Fermi GBM (8 keV-1 MeV)

Swift BAT (10-150 keV)

much more data on Cyg X-3: near TeV 2032+4130
Observation of the Nova in V 407 Cygni

- Nova in symbiotic binary
  - Mira-type red giant and a white dwarf
  - expanding shell from thermo-nuclear explosion on white dwarf shocks wind of the red giant

- LAT detection at >100 MeV of March 2010 nova
  - two models: IC of accelerated electrons on RG electrons or $\pi^0$ decay from interactions of accelerated protons

- VERITAS observations 9 days after onset of nova
  - 5h of observations at 50-66° zenith angle
  - UL (95%, E=1.2 TeV): $F < 2.3 \times 10^{-12}$ erg cm$^{-2}$s$^{-1}$

Observation of the Nova in V 407 Cygni

> Nova in symbiotic binary
  - Mira-type red giant and a white dwarf
  - expanding shell from thermo-nuclear explosion on white dwarf shocks wind of the red giant

> LAT detection at >100 MeV of March 2010 nova
  - two models: IC of accelerated electrons on RG electrons or $\pi^0$ decay from interactions of accelerated protons

> VERITAS observations 9 days after onset of nova
  - 5h of observations at 50-66° zenith angle
  - UL (95%, E=1.2 TeV): $F < 2.3 \times 10^{-12}$ erg cm$^{-2}$s$^{-1}$

Simple parameterization of proton spectrum:

$$N_p = N_{p,0}(E_p + m_p c^2)^{-s_p} e^{-E_p/E_{cp}}$$

**LS I +61 303: 150 h of VERITAS observations**

- Be star + compact object at 2 kpc
- 26.5 day orbit; unknown inclination
- 4.5 y modulation in radio
- Pulsar wind binary or microquasar (radio inconclusive?)
  - Massi et al 2012: microblazar
LS I +61 303: 150 h of VERITAS observations

- Be star + compact object at 2 kpc
- 26.5 day orbit; unknown inclination
- 4.5 y modulation in radio
- pulsar wind binary or microquasar (radio inconclusive?)
  - Massi et al 2012: microblazar

high X-ray activity throughout orbit
(large variations, strongest at apastron/periastron)
extended radio emission peaks at periastron and apastron
Fermi LAT: MeV-GeV emission throughout orbit
(2008-2009: strongest emission at phases ~0.4 - after periastron)
LS I +61 303: 150 h of VERITAS observations

> Be star + compact object at 2 kpc
> 26.5 day orbit; unknown inclination
> 4.5 y modulation in radio
> pulsar wind binary or microquasar (radio-Inferior Conj.

- Matter accretion: unknown inclination
- Mass: 0.7 AU
- Period: 2 kpc
- Duration: 4.5 y

Throughout orbit, phases ~0.4 - 0.6

Gernot Maier | Binary observations with VERITAS | April 2013
goals for 2011/2012 observations:

- part of long-term observing plan
- correlation studies with X-rays and MeV/GeV gamma rays

contemporaneous observations with VERITAS (>350 GeV), Fermi LAT (300 MeV-20 GeV) and Swift XRT (2-10 keV)

- 11.9σ detection (25 h of VERITAS data)
- nightly detection in phases 0.5-0.8 (5-15% of the Crab Nebula flux)

also: strong detection in 2012/2013 (not presented here)
**LS I +61 303: contemporaneous observations**

**Orbital Phase** $\Phi$

**VERITAS**
- Hourly fluxes

**Fermi LAT**
- Flux ($0.3-300$ GeV)

**Swift XRT**
- Flux ($2-10$ KeV)

**Time (MJD)**
- 55910 to 55945
LS I +61 303: contemporaneous observations

orbital phase $\Phi$

- **VERITAS**
  - nightly fluxes
  - evidence for nightly variability $\sim 3.5\sigma$

- **Fermi LAT**

- **Swift XRT**

Gernot Maier | Binary observations with VERITAS | April 2013
LS I +61 303: correlation study

Correlation coefficient for VERITAS - Swift XRT: 0.36 (strictly simultaneous)
LS I +61 303: correlation study

Correlation coefficient for VERITAS - Swift XRT: 0.36 (strictly simultaneous)

Correlation coefficient for VERITAS - Fermi LAT: 0.11 (daily fluxes for Fermi LAT)
LS I +61 303: spectral energy distribution

Two components?
Pulsar at GeV and
Pulsar wind/stellar wind at TeV?

Fermi LAT
(12/01/11-02/01/12)

VERITAS
(12/16/11-01/21/12)

4 GeV cutoff
HESS J0632+057

MWC 148: B0pe star; d=1.5 kpc

- 2004: discovery (H.E.S.S.) (+discussion that this might be a binary system)
- 2009: evidence for variability (VERITAS)
- 2010: detection (VERITAS)
- 2011/2012: detection (H.E.S.S./MAGIC/VERITAS)

- (still) no Fermi LAT detection

- until 2011: unidentified point source without obvious counterpart
HESS J0632+057 - long-term X-ray observations

\[ \text{Flux (0.3-10 keV) \times 10^{12} \text{ erg cm}^{-2} \text{ s}^{-1}} \]

Jan 2009 - Feb 2012

Z-transformed discrete correlation function:
period of \( 315^{+6}_{-4} \) days

Swift XRT observations typically 5 ks per week for more than 3 years!
HESS J0632+057 - folded light curve (315 days orbit)

Note: large uncertainty in orbital solution (+321 d period)

Casares et al. 2012
HESS J062+057: 8 years of observations

Flux (E>1 TeV) $[x10^{-12} \text{ cm}^{-2} \text{s}^{-1}]$

Flux (0.3-10 keV) $[x10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}]$

orbital period $P=315^{+6}_{-4} \text{ d}$

Total VERITAS data set: 144h
total detection significance: 15.5σ

Note: large uncertainty in orbital solution (+321d period)

Gernot Maier | Binary observations with VERITAS | April 2013
HESS J062+057: 8 years of observations

Total VERITAS data set: 144h
total detection significance: 15.5σ

orbital period \( P = 315^{+6}_{-4} \) d

X-ray/VHE time lag at maximum: \(-3.3^{+8.1}_{-10.8}\) days

Note: large uncertainty in orbital solution (+321d period)

Casares et al 2012

Note: large uncertainty in orbital solution (+321d period)

Intermediate point

X-ray/VHE time lag at maximum: \(-3.3^{+8.1}_{-10.8}\) days
HESS J062+057: 9 years of observations

orbital period $P = 315^{+6}_{-4}$ d

Total VERITAS data set: 162h
18.8 + 15 h in 2012/2013

Flux (E>1 TeV) [$10^{-12}$ cm$^{-2}$ s$^{-1}$]

Flux (0.3-10 keV) [$10^{-12}$ erg cm$^{-2}$ s$^{-1}$]

Note: large uncertainty in orbital solution (+321d period)

Casares et al 2012

VERITAS / H.E.S.S. / MAGIC

preliminary

Gernot Maier | Binary observations with VERITAS | April 2013
HESS J062+057: Energy spectra

Remarkably stable from orbit to orbit

Energy spectra phases 0.2-0.4

Flux ($E > 1$ TeV) [cm$^{-2}$s$^{-1}$]

Energy spectra

phase 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Flux (0.3-10 keV) [$10^{-12}$ erg cm$^{-2}$s$^{-1}$]

Remarkably stable from orbit to orbit

VERITAS phase 0.2-0.4 (2010-2012)
H.E.S.S. (Aharonian et al. 2007)
MAGIC (Aleksic et al. 2012)

MJD 5296-55956
Conclusions

- large set (>300 h) of VERITAS binary observations
- LS I +61 303 more puzzling than ever
  - orbit-to-orbit and possibly day-to-day variability
  - no GeV/TeV correlation, SED connection?
- HESS J0632+057 first binary detected through VHE gamma-ray observations
  - 9 years of observations
  - very regular emission pattern
- >300 binaries in the galaxies, Why these 2?
  - Be star, radio emission, geometry, ..?