Transport:

2 shuttles on Friday:

Early – Dana (3 max): 6:30am
Megan Longo
Sarah Story (11:00am)
Parisa Roustazadeh

Late – Jamie (6 max): 12:00pm
Giulia Migliori
Daniel Castro (4:20pm)
Noe Suarez
Jon Harris
David Staszak
Nissim Fraija
Receipts available

Andrea Albert
Daniel Castro
Jamie Cohen
Amanda Dotson
Nissim Fraija
David Green
Peter Jenke
Mehgan Longo
Giulia Migliori
Katey Mulrey
Tommy Nelson
Rebecca Reesman
Parisa Roustazadeh
Gunes Senturk
Dana Saxon
David Staszak
Sarah Story
Josh D. Wood
Josh Wood

Still tracking them down...

Eduardo de la Fuente
Joe Eggen
Jon Harris
Jedidah Isler
Jeremy Maune
Noe Suarez
Gamma-ray Binary Systems

Jamie Holder
Bartol Research Institute/ University of Delaware

2011 Fermi School Lewes, Delaware
Overview

- Why are they interesting?
- Some history
- What drives them?
- Observational status
- Interpretation
- What next?
Gamma-Ray Binaries

- LS I + 61°303
- Cyg X-3
- Cyg X-1
- LS 5039
- PSR B1259-63
- 1FGL J1018.6-5856
- HESS J0632-057
Why are these few so interesting?

- Binaries are the *only* variable galactic TeV sources
- They are natural particle accelerators operating under varying, but *regularly repeating*, environmental conditions
- Provide a constraining laboratory for models of particle acceleration, and gamma-ray production, emission and absorption processes.
- May provide the keys to an understanding of astrophysical jets
- Each system is unique - and the population, as well as the data quality, is increasing
- *Caveat*: The systems are complex, with many competing processes, and the orbital parameters, nature of the binary components and the conditions in the circumstellar environment are not well known.
Two Gamma-ray binaries I won’t discuss!

Eta Carinae
Colliding wind binary
Two Gamma-ray binaries I won’t discuss!

- V407 Cyg; Nova in a symbiotic binary (white dwarf + red giant)
A history of High Energy binary results

- **Cygnus X-3** caused a lot of excitement in the 70's/early 80's
- Numerous gamma-ray and cosmic ray air shower detectors claimed evidence for a modulated signal up to $>10^{15}\text{eV}$
- Even led to the prediction of a new particle ("the Cygnet")
- A cautionary tale... these results (and many subsequent ground-based gamma-ray binary detections in the 80's, up until the advent of Whipple/HEGRA/CAT) are now widely discounted.

“Those who cannot remember the past are condemned to repeat it...”
A history of High Energy binary results

- Among 13 gamma-ray sources, COS-B detected 2CG 135+01; the error box contained a periodic radio and X-ray source (LS I +61° 303).

- Various EGRET sources were associated with binaries
  - 3EG J1824-1514 (LS 5039), Paredes et al., Science, 2000

- But weak or no variability, no periodicity, and limited positional accuracy
• 2004 – 2006: a few TeV sources strongly detected >100 GeV
  • PSR B1259-63 (H.E.S.S.)
  • LS 5039 (H.E.S.S.)
  • LS I +61° 303 (MAGIC)

• With good positions and clear, orbitally modulated variability, the associations are definitive.

• Fermi-LAT provided the next leap
  • Good sensitivity
  • Source localization
  • Near continuous monitoring
  • Firm ID of LS I +61° 303, LS 5039

• and... finally.... in 2009 both AGILE and LAT detect gamma-rays from Cygnus X-3
What drives them?

Accretion powered

- Companion star
- Ultraviolet and optical emission
- Accretion disk
- Relativistic jets
- Compact object of center
- Microblazar

Wind-driven

- Pulsar
- Be star
- Disk outflow
- Cometary radio emission
- γ-rays

Mirabel (Science 309, 714, 2006)
The black holes: Cygnus X-1

- **Cygnus X-1**
  - $21 \pm 8 \, M_\odot$ compact object,
  - $40 \pm 10 \, M_\odot$ O9.7Iab companion.
- 5.6 day circular orbit
- Accretion powered
- MAGIC observed 40 hours: no steady emission above ~100GeV
- See one episode at ~4σ, close to an X-ray flare
- AGILE also saw a ~4σ flare in 2009 above 100 MeV at a different orbital phase and spectral state.
- No Fermi-LAT detection (yet)
The microquasars: Cygnus X-3

- Cygnus X-3
  - 10-20 $M_\odot$ compact object,
  - Wolf-Rayet companion.
- 4.8 hour orbit
- Accretion powered
- AGILE detect 4 episodes of GeV emission during soft X-ray states
- New Fermi-LAT results presented yesterday (Stephane Corbel)
- Orbital modulation gives firm identification
Cygnus X-3

- 10-20 $M_\odot$ compact object,
- Wolf-Rayet companion.
- 4.8 hour orbit
- Accretion powered
- AGILE and Fermi-LAT detect it episodically
- Orbital modulation gives firm identification
- Emission peaks in the soft gamma-rays (upper end of a hard X-ray tail)
The Pulsar wind Binary: PSR B1259-63

- 48 ms pulsar orbiting a B2e companion with inclined disk
- 3.4 year, high eccentric orbit
- ~0.7 A.U separation at periastron (10 AU at apastron)
- Detected by HESS during 2004 periastron
Pulsar wind binary or accreting black hole?
It’s not always so clear (e.g. LS I +61° 303)

Radio observations show rotating tail
X-ray observations show no spectral features (e.g. no accretion disk bump)
Supports pulsar wind model

Dhawan et al.
Proceedings of the VI Microquasar Workshop

Relative wind strengths are such that you cannot produce simple elongated shape seen in VLBI images.
Gamma-ray lightcurve is more easily explained by variable accretion
Prefer microquasar model

Romero et al. astro-ph/0706.1320

• Be star wind
• pulsar wind

• $\phi = 0.23$
• $N_1 = 392138$
• $N_2 = 42671$
The “not sures”: LS 5039

- Compact object orbiting an O6.5V companion (23M⊙)
- 3.9 day, inclined orbit, e=0.35
- HESS measure clear periodicity >200GeV
- emission peaks at inferior conjunction
- spectrum varies
LS 5039

- Detected by Fermi-LAT (BSL)
- Orbital modulation now measured
- Flux variability anti-correlated with HESS
- Spectral variability, and ~2 GeV cut-off observed
LS I +61° 303

- Compact object (Black hole or Neutron star) orbiting an B0Ve companion (12M☉)
- 26.5 day, inclined orbit, e=0.54
- extended radio structures; microquasar? Probably not....
- Detected by MAGIC, then VERITAS
- Strong TeV emission initially only detected near apastron (ϕ=0.5-0.8)

LS I +61° 303

- Detected by Fermi-LAT (BSL)
- Orbital modulation well measured
- Emission peaks near periastron
- Cut-off at 6 GeV observed between LAT and VERITAS

LS I $+61^\circ$ 303

- Competing processes
  - Assume Inverse Compton production -> high energy electrons boost stellar photons to gamma-ray energies
  - At superior conjunction, Inverse Compton production peaks over all energies
  - At superior conjunction, photons > 30 GeV are most heavily absorbed
- Doesn’t fit the lightcurves very well
  - Moderate Doppler boosting helps
  - Why is there a 6 GeV cut-off?
    - Different mechanism for GeV and TeV?
    - GeV emission spectrum appears magnetospheric - but then why is the GeV emission modulated at all? Where are the pulses?
Contemporaneous observations complicate things further

- No apastron detection by VERITAS since the launch of Fermi, despite good exposure.
- Fermi light curve shows variability not associated with the orbit - and the orbital modulation has faded
- Is it “weather”? Are there longer-term cycles? More data needed!!
- LSI +61 303 is interesting, but difficult...

![Graph showing LS I Flux by Week with MJD and Orbital Phase with 5% Crab levels for 2008-2009 and 2009-2010](image)
LSI +61 303 is interesting, but difficult...
A few things to think about (not exhaustive)...

<table>
<thead>
<tr>
<th>What is the power source?</th>
<th>Accretion-powered jet</th>
<th>Pulsar wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the particle acceleration mechanism?</td>
<td>Jet shocks</td>
<td>Magnetic reconnection</td>
</tr>
<tr>
<td>What are the dominant particles?</td>
<td>Hadronic</td>
<td>Leptonic</td>
</tr>
<tr>
<td>How are the $\gamma$-rays produced?</td>
<td>Pion decay</td>
<td>Inverse Compton</td>
</tr>
<tr>
<td>Where are the $\gamma$-rays produced?</td>
<td>Near the jet</td>
<td>Wind collision region</td>
</tr>
<tr>
<td></td>
<td>Circumstellar environment</td>
<td>Pulsar magnetosphere</td>
</tr>
<tr>
<td>What modulates the flux?</td>
<td>Geometry</td>
<td>Photon fields</td>
</tr>
<tr>
<td>Other effects?</td>
<td>Wind clumping</td>
<td>Pair cascades</td>
</tr>
</tbody>
</table>

Many of these are not mutually exclusive...
• Difficult, but detailed predictions can be made, and are beginning to be strongly tested
  • (e.g. Sierpowska-Bartosik & Torres, LS 5039)
**HESS J0632+057**

- Unidentified TeV HESS source in the Galactic plane ($\Gamma=2.53$, Flux~3% Crab)
- A rare unresolved source (<2')
- VERITAS detections and limits reveal gamma-ray variability
- MWL follow-up shows a hard spectrum X-ray source ($\Gamma=1.2 - 1.9$) & faint radio source coincident with a B0pe star (MWC148). Not a Fermi source.
- Swift measures long term variability
HESS J0632+057

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- Swift measures long term variability
• Swift Observations have continued over the past 3 years

Bongiorno et al. arXiv:1104.4519
• Swift Observations have continued over the past 3 years
• Clear evidence recently found for a 320 day period
• VERITAS observations were pre-planned to cover X-ray high state
• Gamma-ray flaring detected (~4% Crab)
A New Gamma-ray Binary: 1FGL J1018.6-5856

Probability of peak at 16.6 days arising by chance is $< 10^{-7}$.

Slides shamelessly stolen from Robin Corbet’s Fermi Symposium presentation
- Different colors (top panel) show X-ray data from different 16.6 day cycles.
- Flare-like behavior near phase 0, coinciding with gamma-ray maximum.
- X-ray modulation also has a quasi-sinusoidal component with peak at phase $\sim 0.4$
TeV Emission from the Vicinity of IFGL J1018.6-5856

- H.E.S.S. (de Ona Wilhelmi et al., 2010) reported a TeV source in this region.
- The positions are consistent, but it's not certain the HESS source is associated with IFGL J1018.6-5856.
- TeV emission is seen (at least sometimes) from LS 5039 and LS I +61 303,
- Is this the TeV counterpart of IFGL J1018.6??
How else might gamma-rays be produced?

1A0535+262

- HMXB, Be-star and X-ray pulsar (PSpin=104s)
- Orbital period 110 d, eccentric orbit (e= 0.47)
- Distance 2.4±0.4 kpc
- Hard X-ray spectra; non-thermal particle populations
- Giant outbursts every ~5 years since 1975
- VHE emission?: Cheng & Ruderman mechanism; VHE maximum expected about 10-20 days after X-ray flare (Orellana & Romero 2004)

But: no detailed modeling for VHE emission, no flux prediction, SED, etc.
1A0535+262

- Dec 2009: ToO triggered on flaring Be/X-ray binaries
- 23 hours of data with VERITAS, all high elevations: mean ~70°
- Good coverage of flare phase (rising/falling edge), apastron and periastron approach
- Flare occurred at best time for VERITAS
• Results still in prep. (Gernot Maier, Angelo Varlotta)
• 5-8 hours of VERITAS observations in each bin
• No VHE emission detected
• 99% flux upper limits above 300 GeV: 0.5-2% Crab Nebula flux
• Lots of data at other wavelengths available
• Definitive results with this generation of IACTs
Summary

• Gamma-ray binaries constitute a small, but uniquely valuable, population of high energy sources.

• The field is extremely active: some key observational questions which may be resolved shortly
  
  • What is the cause of the Fermi-LAT GeV cutoffs?
  • What other binaries does the LAT see?
  • What did HESS & Fermi see from PSR B1259-63 in 2010/2011?
  • Does Cygnus X-3 produce TeV emission? When?
  • What is HESS J0632+057?

• Ongoing multiwavelength campaigns on most of these objects.