Gamma-ray Binaries: 1FGL J1018.6-5856, a Hunt for New Systems, Cyg X-3

Robin Corbet
(UMBC/NASA GSFC)
on behalf of the Fermi-LAT collaboration
Resources

1FGL J1018.6-5856:


Cyg X-3:


Many Cyg X-3 slides are thanks to Anna Szostek, Guillaume Dubus, and Stephane Corbel!
What Makes a Gamma-ray Binary?

• To make a gamma-ray binary you need:
  – Power source
  – Non-thermal mechanism. e.g. Fermi acceleration at shocks + inverse Compton scattering.

• The “conventional” mechanisms are:
  – Accreting microquasar with relativistic jets
  – Pulsar interacting with the wind of an O or B type companion. (Pulsar and stellar winds collide and form shocks.)
X-ray binaries may go through a gamma-ray binary phase early in their lives.

A newly born neutron star is expected to be rapidly rotating and highly magnetized.

Relativistic pulsar wind interacts with companion's wind and produces gamma-rays until neutron star has spun down (e.g. Dubus 2006).

Meurs & van den Heuvel (1989) predicted ~30 such systems in the Galaxy in this brief phase.

Pulsar wind pressure dominates for:

\[ P_{\text{spin}} < 230 B_{12}^{1/2} M_{15}^{-1/4} \text{ms} \]
Either the mechanisms that make gamma-ray binaries occur infrequently, or else more systems (as predicted) remain to be discovered!
The Fermi LAT

Fermi was launched on June 11, 2008

The primary instrument is the LAT: 100 MeV (or lower) to 300 GeV (and higher).

The LAT has several advantages over previous detectors:

- **Instrument performance:** Improved effective area, field of view, angular resolution.
- **Observation mode:** the LAT operates in sky survey mode almost all the time. The **entire sky is observed every ~3 hours**. Can study binaries on wide range of timescales.
The Hunt for New Binaries

- Known gamma-ray binaries show modulation on their orbital periods.
- Hope to find new binaries from the detection of periodic variability.
- Even with the improved sensitivity of the LAT, count rates are still low.
  - Even a “bright” source may only give ~20 photons/day.

Need highest possible signal-to-noise light curves and make sensitive period searches.
Optimizing Light Curves

There are two basic ways to make LAT light curves:

- Maximum likelihood fitting.
- Aperture photometry.

Likelihood fitting is slow, and is difficult/impossible if not many photons are present in a time bin.

Aperture photometry is non-optimal. Ignores source photons outside the aperture, includes background inside the aperture.

Problem compounded by strong LAT PSF energy dependence.

Instead, use a “weighted photon/infinite aperture” technique. Sum the probabilities that each photon came from source of interest.

Can give a significant increase of Signal/Noise
To search for periodic modulation, use power spectra.

We want ability to search for short orbital periods, like Cyg X-3's 4.8 hour period.

Short time bins are needed (e.g. < 1ks). Shorter than the LAT sky survey period of ~3 hours.

This gives big variations in exposure.

Use “exposure weighting” of each data point's contribution to the power spectrum.
The 1FGL Search

Made weighted-photon light curves for all 1,451 1FGL (1st Fermi catalog) sources:

3 degree radius aperture.

600 s time bins (barycenter corrected).

100 MeV to 200 GeV.

752 days long (2.06 years) for initial search.

Calculated exposure-weighted power spectra for all sources: 0.05 to 752 days.

Easily detected LS I +61 303 and LS 5039, but not Cyg X-3. (To detect Cyg X-3 must only use data from active states.)

And a candidate for a new binary...
A 16.6 Day Period in 1FGL J1018.6-5856

Probability of peak at 16.6 days arising by chance is $< 10^{-7}$. Second (and possibly higher) harmonics of this period are also seen. Modulation at 16.6 days is *not* seen in any other Fermi source.
Flux/Spectral variability on 16.6 day period

- Gamma-ray spectrum is also modulated on the 16.6 day period. (Harder when bright.)

- Qualitatively similar to LS 5039 (3.9 day period), but not LS I +61 303.

- Except... LS 5039 is softer when bright.
A prominent X-ray source is present at the edge of the LAT error circles. Optical source seen at X-ray position.
Large X-ray variability (Swift XRT)

- 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 $\sim 0.4$. 
Optical Spectrum

- H, He I/II lines indicate early spectral type.
- He II 4686 Å absorption ⇒ main sequence.
- He II/I ratio ⇒ O6
- NIII emission ⇒ O6V((f)).
- Spectral type is almost identical to LS 5039.

Interstellar absorption lines ⇒ E(B-V) ~1.25.
V ~12.6 (ASAS Catalogue)
Distance ~5 kpc (± 2kpc)
Variable Radio Counterpart

The radio flux appears to be modulated on the orbital period. But, no increase at phase 0. Radio flux may be following sine wave component of X-ray flux.
TeV Counterpart to 1FGL J1018.6?


Positionally coincident with SNR G284.3–1.8 and 1FGL J1018.6– 5856 (diffuse extension towards PSR J1016–5857).

TeV emission is seen (at least sometimes) from LS 5039 and LS I +61 303,

Is this the TeV counterpart of 1FGL J1018.6??

Temporal variability in the TeV source would confirm association.
• 1FGL J1018.6-5856 is a new gamma-ray binary with X-ray, optical, and radio counterparts.

• We don’t definitely know what is driving the gamma-ray emission.
  – J1018.6 may contain a rapidly rotating pulsar interacting with the wind of an O star.
  – But other explanations might be possible. e.g. magnetar model proposed for LS I + 61 303 (Torres+ 2012).
Continued Observations of 1FGL J1018.6-5856

Several multi-wavelength programs will provide more information on 1FGL J1018.6-5856

X-rays: Swift monitoring (Donato/Cheung)


X-rays: Suzaku phase constrained (Tanaka et al.)

- Emission mechanisms.

Radio: ATCA (Edwards et al.)

- Orbital modulation of radio flux. Long term variability.

Optical: Radial velocity measurements (Romani et al.)

- Determine system geometry, constraints on nature of compact object (neutron star vs. black hole).

Optical: photometry (McSwain et al.)

- System geometry and constraints on compact object.
Continued Search for More Binaries

- So far, we've only found binary periods in bright sources.

- LAT binary search sensitivity is continually improving as more data accumulates. (Noise $\alpha$ I/Time)

- “Pass 7” LAT data enhanced the soft response.

- 2FGL catalog increased number of sources, and more accurately parameterized known sources. (Important for weighting.)

- Continue to perform periodicity searches on all cataloged sources, hoping to find more binaries!

Evolutionary models predict we should see more binaries in the “iceberg” of sources...

Many of these sources are still unidentified!
The Gamma-ray Flares of Cyg X-3

normal star (IR, optical)

relativistic outflow (radio, IR)

probe link with gamma-rays

accretion disk (optical, X, LE γ)

black hole or neutron star

Figure courtesy of G. Dubus.
Cygnus X-3

Bright X-ray binary with Wolf-Rayet primary.

Short orbital period: 4.8 hours.

Black hole candidate.

Radio outbursts common and relativistic jets are produced:

⇒ Cyg X-3 is a “microquasar”.

Highly unusual source - perhaps unique in the Galaxy?

The only accretion-powered gamma-ray binary known.

Some prefer to describe Cyg X-3 as a “gamma-ray emitting X-ray binary” because $L_X > L_γ$. 


Cyg X-3: a microquasar in γ-rays

**AGILE & Fermi/LAT detections**


**Swift/BAT 15-50 keV**
Cyg X-3: a microquasar in γ-rays

AGILE & Fermi/LAT detections


Fermi
Abdo et al. 2009
Cyg X-3: a microquasar in $\gamma$-rays

**AGILE & Fermi/LAT detections**


---

**Fermi**

Abdo et al. 2009
Major radio flare, March 21, 2011

Corbel+ 2012

Accretion

non-thermal / thermal

Ejection
Gamma-ray activity in period 1 (2011)

X-ray
15-50 keV

gamma-ray
>100 MeV

radio
11 & 15 GHz
Gamma-ray activity in period 1 (2011)

- **X-ray**
  - 15-50 keV

- **Gamma-ray**
  - >100 MeV

- **Radio**
  - 11 & 15 GHz

7-12 Jan 2012, 219th AAS, Texas, Anna Szostek
Gamma-ray activity in period 1 (2011)

7-12 Jan 2012, 219th AAS, Texas, Anna Szostek

Cygnus X-3

X-ray
15-50 keV
0.02 cts/cm²/s

gamma-ray
>100 MeV

radio
11 & 15 GHz
Gamma-ray activity in period 1 (2011)

X-ray
15-50 keV
0.02 cts/cm²/s

gamma-ray
>100 MeV

0.3 Jy
radio
11 & 15 GHz
Relation between flare onset and gamma-ray trigger in period 2 (2011)

Simultaneous rise in radio + non-thermal X-ray + gamma-ray

gamma-ray >100 MeV

radio 11 & 15 GHz

X-ray hardness ratio & RXTE spectra (arrows)
Relation between flare onset and gamma-ray trigger in period 2 (2011)

Gamma-rays turn off before flare peak

gamma-ray >100 MeV

radio

11 & 15 GHz

X-ray hardness ratio & RXTE spectra (arrows)

Simultaneous rise
radio + non-thermal X-ray + gamma-ray
Relation between flare onset and gamma-ray trigger in period 2 (2011)

Simultaneous rise
radio + non-thermal X-ray + gamma-ray

Gamma-rays turn off before flare peak

Onset of the flare here?

Flare peak

gamma-ray >100 MeV

radio 11 & 15 GHz

X-ray hardness ratio & RXTE spectra (arrows)
Relation between flare onset and gamma-ray trigger in period 2 (2011)

Is gamma-ray trigger at onset of the flare?

Gamma-rays turn off before flare peak

Flare peak

Onset of the flare here?

Simultaneous rise
radio + non-thermal X-ray + gamma-ray

Gamma-rays turn off
before flare peak

gamma-ray >100 MeV

radio
11 & 15 GHz

X-ray
hardness ratio & RXTE spectra (arrows)
Relation between flare onset and gamma-ray trigger in period 2 (2011)

Is gamma-ray trigger at onset of the flare?

Gamma-rays turn off before flare peak

gamma-ray >100 MeV

Onset of the flare here?

Non-thermal component in spectrum

Simultaneous rise
radio + non-thermal X-ray + gamma-ray
Orbital Modulation in Cyg X-3

• During the first two outbursts from Cyg X-3 (2008, 2009) modulation of LAT flux on the orbital period was clearly detected.

• Modulation also detected in 2011 outburst. But investigation hampered by short duration.

• Analysis being undertaken using Pass 7 with improved soft response...
Possible scenario

(7-12 Jan 2012, 219th AAS, Texas, Anna Szostek et al.)

- Shock forms at various distances along the jet (Lindfors et al. 2007; Miller-Jones et al. 2009)

- Transition IN/OUT of the ultrasoft X-ray state signal a decrease/increase in jet efficiency with non-thermal region moving CLOSER/FURTHER from the compact object

- Gamma-ray emission is most efficient at “sweet-spot” bounded by strong pair production on thermal X-rays and declining seed photon density for inverse Compton scattering (Cerutti et al. 2011; Sitarek & Bednarek 2011)

- Detections prior to and after the quenched state when shock moves through this region