A Multiwavelength Study of the Gamma-ray Binaries 1FGL J1018.6-5856 and LMC P3

Image Courtesy: https://svs.gsfc.nasa.gov/10507
Microquasars—accreting XRBs with relativistic radio jets
- Gamma-ray emission powered by inverse Compton scattering of UV photons
- Emission peaks at X-ray energies

Image Courtesy: Mirabel et al. (2012)
Gamma-Ray Binary Population

![Image of gamma-ray binary population]

**Table 3**

<table>
<thead>
<tr>
<th></th>
<th>LS 5039</th>
<th>1FGL J1018.6-5856</th>
<th>LS I+61 303°</th>
<th>HESS J0632+057</th>
<th>PSR B1259-63</th>
<th>LMC P3</th>
<th>PSR J2032+4127a</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{orb}}$</td>
<td>~3.91 d</td>
<td>~16.54 d</td>
<td>~26.5 d</td>
<td>~315 d</td>
<td>~1236.7 d</td>
<td>~10.3 d</td>
<td>40–50 yr</td>
</tr>
<tr>
<td>$e$</td>
<td>~0.24</td>
<td>...</td>
<td>~0.54</td>
<td>~0.83</td>
<td>~0.87</td>
<td>&lt;0.7</td>
<td>0.94</td>
</tr>
<tr>
<td>Spectral Type</td>
<td>O6.5 V(f)</td>
<td>O6 V(f)</td>
<td>B0 Ve</td>
<td>B0 Vpe</td>
<td>O9.5 Ve</td>
<td>O5 III(f)</td>
<td>B0 Ve</td>
</tr>
<tr>
<td>$M/M_\odot$</td>
<td>23</td>
<td>26</td>
<td>12</td>
<td>16</td>
<td>31</td>
<td>25–42</td>
<td>14.5–17.5</td>
</tr>
</tbody>
</table>

**Note.**—^aPSR J2032+4127 is a candidate HMGB that is expected to be gamma-ray bright in 2017 October–November near periastron.
Pulsar Wind Systems: Link to HMXBs?

- Driven by particle acceleration (Fermi Mechanism)
- Evolve into HMXBs?

Image Courtesy: Mirabel et al. (2012)
Why are HMGBs important?

- MeV-GeV emission dominates the spectral energy distribution
- Emission seen between radio and TeV energy bandpasses
- Rare: only seven HMGBs have been found
- Gamma-ray binaries—early stage in HMXB evolution?
- Extreme Particle Accelerators
A Multi-Wavelength Study of the Gamma-Ray Binary 1FGL J1018.6-5856


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1FGL J1018.6-5856, the first gamma-ray binary discovered by the Fermi Large Area Telescope (LAT), consists of an O6 V(f) star and suspected rapidly spinning neutron star. While 1FGL J1018.6-5856 has been postulated to be powered by the interaction between a relativistic pulsar wind and the stellar wind of the companion, a microquasar scenario where the compact object is a black hole cannot be ruled out. We present the first extensive multi-wavelength analysis of 1FGL J1018.6-5856 with the Australia Telescope Compact Array (ATCA), Fermi LAT and the Swift X-ray Telescope to better study the emission properties over the 16.53±0.006 day orbital modulation. The radio amplitude modulation is found to decline with increasing frequency, which is a possible indication of free-free absorption. This is further supported by the absence of clear modulation in the highest-frequency, 33.0 and 35.0 GHz bands, which were not previously reported. The best-fit spectral model of the Swift XRT data consists of a single powerlaw with photon index 1.3—1.7 modified by an absorber that fully covers the source. This is possible evidence that 1FGL J1018.6-5856 is a non-accreting system.

Folded Gamma-Ray Light Curve

Fermi LAT light curve in the 0.1-300 GeV band (top) based on a likelihood analysis folded on the 16.5 day orbital period. The hardness ratio (bottom) is produced taking the results from the likelihood analyses of the soft and hard energy bands, 0.1-1 GeV and 1-300 GeV, respectively.

Folded X-Ray Light Curve

Swift XRT X-ray light curves folded on the orbital period. The light blue data is prior to MJD 55984[1,2], The black data points after MJD 55984[2,3,4]. The modulation a sharp maximum at phase 0 and a broad maximum phase ~0.4. This is consistent with previous observations[1,2,3].

Phase-Resolved Radio Spectra

Orbital phase-resolved ATCA radio spectra covering frequencies in the 2.1-35.0 GHz band. The red lines indicate the best fit for a power-law model, which is a possible indication of free-free absorption.

Folded Radio Light Curves

ATCA radio light curves folded on the orbital period. A broad maximum is found at phase 0.4. The amplitude modulation decreases with increasing frequency. Light curves at 33.0 and 35.0 GHz do not show clear modulation on the orbital period[6].
Radial Velocity Semi-Amplitude

- SOAR Radial Velocity Semi-Amplitude
- Mass function consistent with Neutron Star
- Black hole only allowable: $i<16$ degrees

Image Courtesy of Strader et al. (2015)
Folded Fermi LAT Light curve and Hardness Ratio

- Phase 0 defined by the ascending node of the compact object
- Narrow spike at orbital phase ~0.75 (INFC)

$P_{\text{orb}} \sim 16.5$ days

Soft and hard energy bands are 0.1-1 GeV and 1-300 GeV
Folded Swift X-ray Lightcurves of 1FGL J1018.6-5856

- Quasi-sinusoidal X-ray modulation with narrow spike at phase 0.75 (INFC) and broad peak at phase ~0.0 (periastron?)
Folded Radio Lightcurves of 1FGL J1018.6-5856

- No narrow spike at phase 0.75 (inferior conjunction)
- Broad Peak found at orbital phase ~0.0
- Radio amplitude modulation decreases with increasing frequency

Image Modified from Coley et al. (2014b)
Orbital Phase-Resolved ATCA Radio Spectra

- Covers frequencies in the 2.1-35.0 GHz band
- Modeled with a power law; possible indication of free-free absorption
ATCA Spectral Parameters

- Power-law frequency index of the ATCA radio data folded on the orbital period (left)
- Spectral index of the ATCA radio spectra vs. flux density (right)
Preliminary Free-Free Absorption Model

- Power law modified by free-free absorption
- Orbital Inclination: 33-37 degrees
- Eccentricity cannot be constrained
Radio fluxes in the 5.5-19.0 GHz bands correlated with 0.3-10 keV X-ray flux
A LUMINOUS GAMMA-RAY binary IN THE LARGE MAGELLANIC CLOUD


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ABSTRACT

Gamma-ray binaries consist of a neutron star or a black hole interacting with a normal star to produce gamma-ray emission that dominates the radiative output of the system. Only a handful of such systems have been previously discovered, all within our Galaxy. Here, we report the discovery of a luminous gamma-ray binary in the Large Magellanic Cloud, found with the Fermi Large Area Telescope (LAT), from a search for periodic modulation in all sources in the third Fermi LAT catalog. This is the first such system to be found outside the Milky Way. The system has an orbital period of 10.3 days, and is associated with a massive O5III star located in the supernova remnant DEM L241, previously identified as the candidate high-mass X-ray binary (HMXB) CXOU J053600.0−673507. X-ray and radio emission are also modulated on the 10.3 day period, but are in antiphase with the gamma-ray modulation. Optical radial velocity measurements suggest that the system contains a neutron star. The source is significantly more luminous than similar sources in the Milky Way, at radio, optical, X-ray, and gamma-ray wavelengths. The detection of this extra-galactic system, but no new Galactic systems, raises the possibility that the predicted number of gamma-ray binaries in our Galaxy has been overestimated, and that HMXBs may be born containing relatively slowly rotating neutron stars.

Key words: gamma rays: stars – stars: individual (CXOU J053600.0−673507) – stars: neutron

1. INTRODUCTION

Although hundreds of interacting binary systems are known X-ray emitters (Liu et al. 2006, 2007), very few systems produce detectable gamma-ray emission. Here we classify gamma-ray binaries as those systems where most of the electromagnetic output of the system is at gamma-ray energies.

the duration of the gamma-ray binary phase, and the gamma-ray luminosity. From their binary population synthesis study, Meurs & van den Heuvel (1989) predicted about 30 binaries containing neutron stars during their pulsar phase, which could thus be gamma-ray binaries. Following the launch of the Fermi Gamma-ray Space Telescope mission in 2008, its Large Area

...
■ First Extragalactic Gamma-ray binary
■ Embedded in SNR DEM L241 in the Large Magellanic Cloud
■ Optical companion spectral type is O5 III (f)

Image Courtesy: Seward et al. (2012)
Radial Velocity Semi-Amplitude

- SOAR Radial Velocity Semi-Amplitude
- Mass function consistent with Neutron Star
- Black hole only allowable: $i<15$ degrees

Image Courtesy of Corbet et al. (2016)
Multiwavelength Light Curves of LMC P3

- ATCA (top), Swift XRT (middle) and Fermi (bottom) light curves
- No apparent cycle-to-cycle variability in X-ray bandpass
- Order of magnitude more luminous in X-ray and radio

$P_{\text{orb}} \approx 10.3$ days

Image Modified from Corbet et al. (2016)
Swift Cumulative Spectrum

- Power law fit with spectral index $\sim 1.3$
- No constraints on NH
- Hampered by low S/N; low effective area

Image Courtesy of Corbet et al. (2016)
Approved AO-16 XMM and NuSTAR Cycle 3 Observations

- Investigate phase dependence of $N_H$, $\Gamma$, and X-ray flux
- Search for possible neutron star rotation period with EPIC-pn
- Measure $\Gamma$ and X-ray flux out to 40 keV (NuSTAR)

Image Courtesy: http://sci.esa.int/xmm-newton/18015-xmm-newton-spacecraft/
XMM-Newton Simulated Spectrum

- Three Observations: X-ray Max, X-ray Min, Inferior Conjunction
- Estimated Uncertainties on $\Gamma$ and flux better than 5% and 8%
- Three Measurements of $N_H$
Conclusions

- 1FGL J1018.6-5856: Refined orbital period, reduced uncertainty by ~3
- 1FGL J1018.6-5856: Radio and X-ray modulation hints at free-free absorption
- LMC P3: 4× more luminous in GeV; 10× more luminous in X-ray and radio
- LMC P3: Luminosity likely driven by increased power injection
- LMC P3: O5 III (f) star hotter and more luminous than the O6 V (f) star in 1FGL J1018.6-5856
Collaborators

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