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

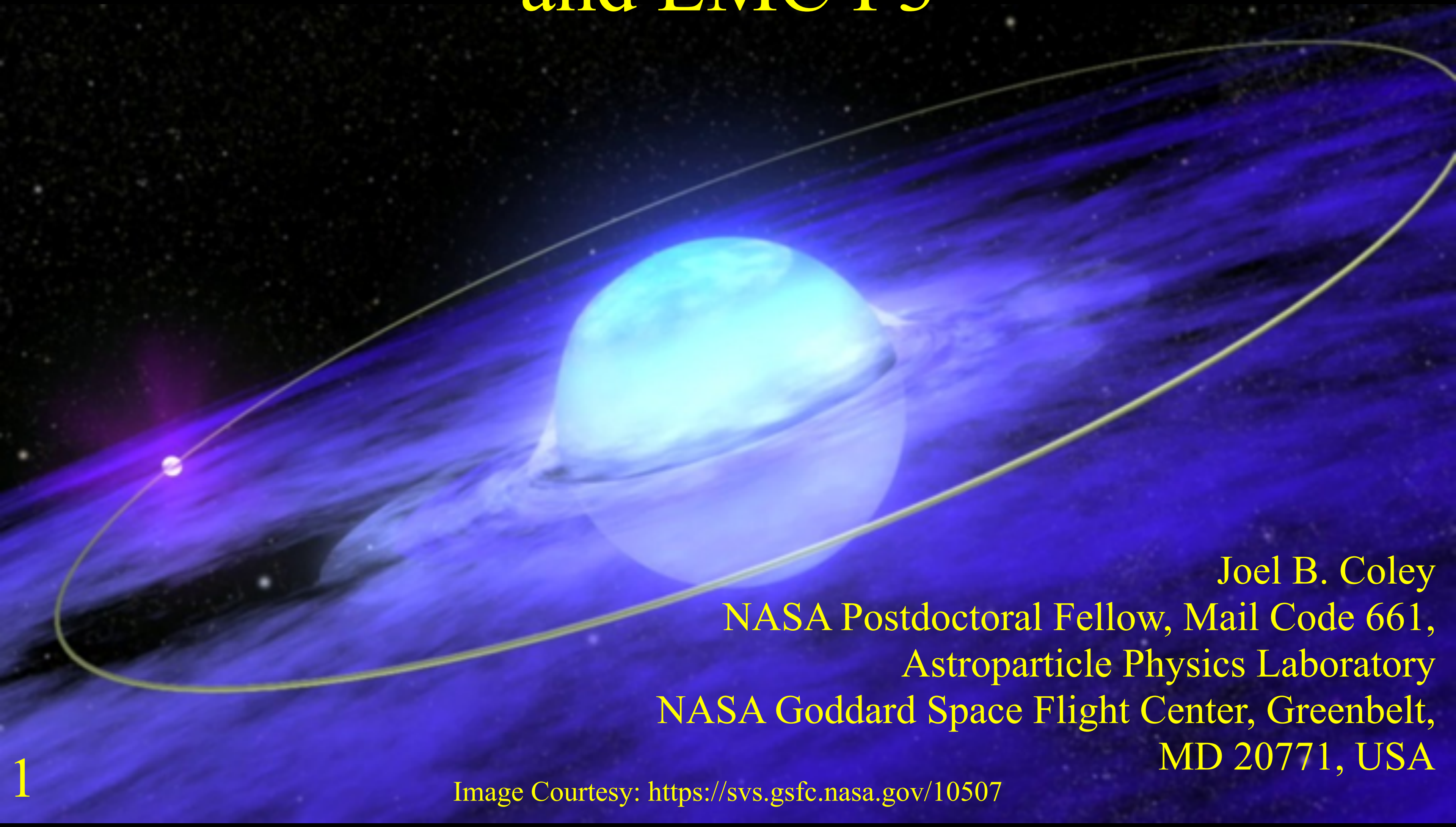

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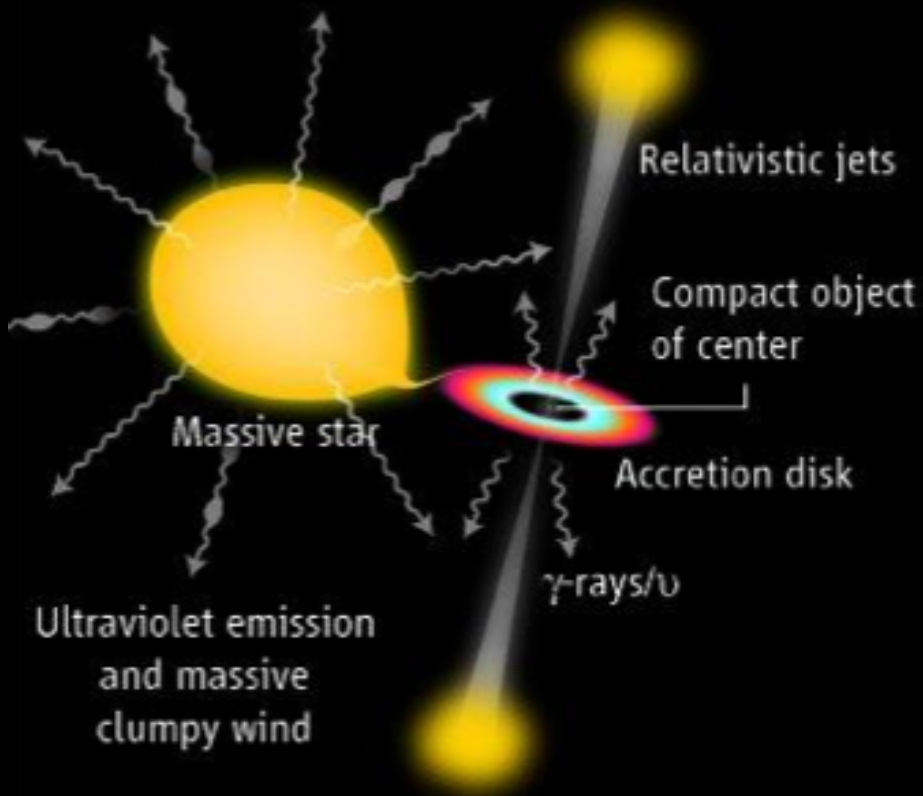
Image Courtesy: https://svs.gsfc.nasa.gov/10507

# Microquasars




- 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

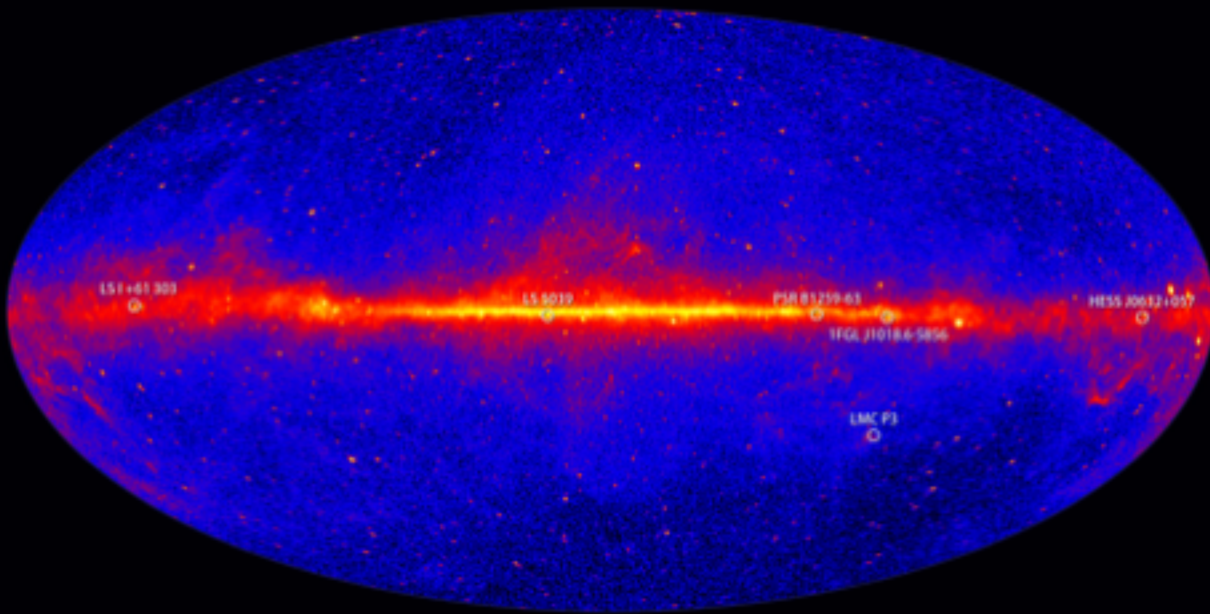


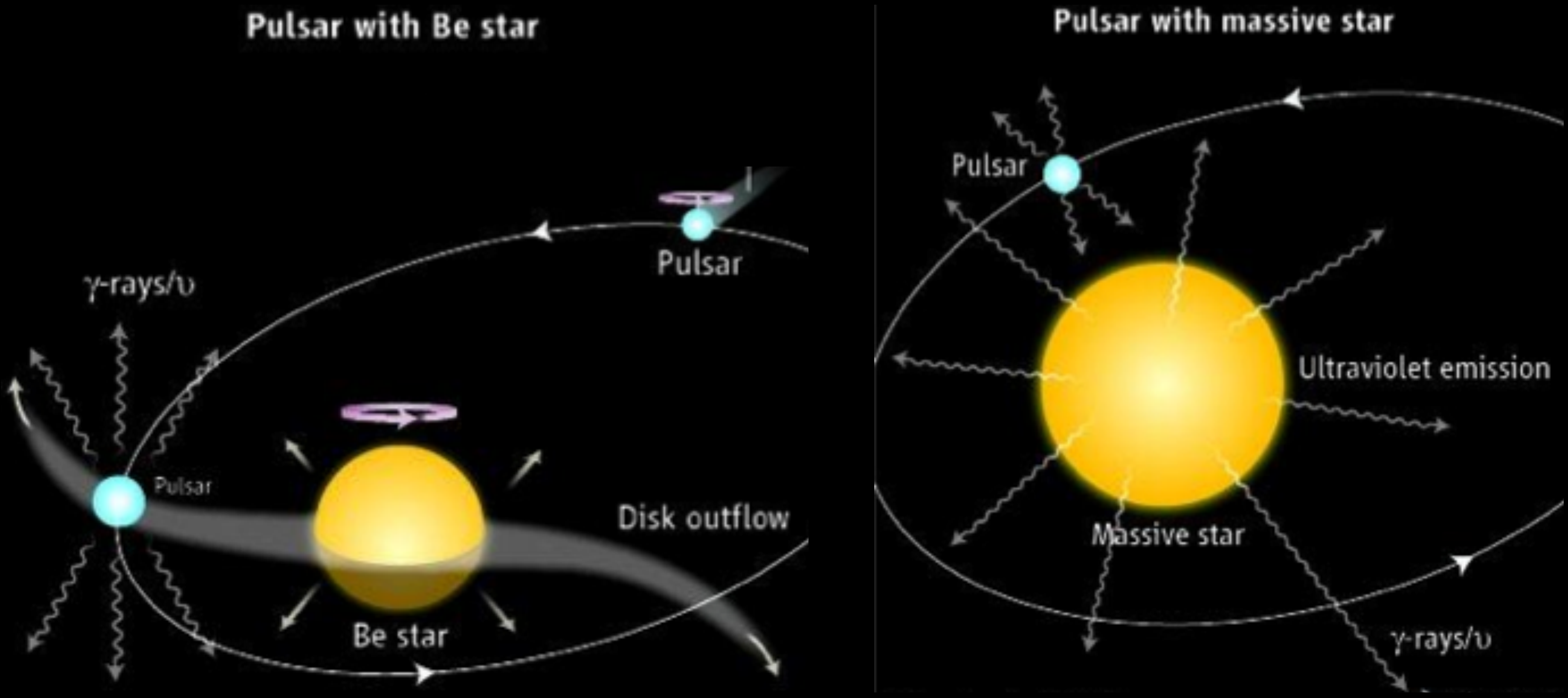

TABLE 3

GAMMA-RAY BINARIES

| | LS 5039 | 1FGL J1018.6-5856 | LS I+61 303° | HESS J0632+057 | PSR B1259-63 | LMC P3 | PSR J2032+4127[a] |
|---|---|---|---|---|---|---|---|
| $P_{orb}$ | ~3.91 d | ~16.54 d | ~26.5 d | ~315 d | ~1236.7 d | ~10.3 d | 40–50 yr |
| $e$ | ~0.24 | ··· | ~0.54 | ~0.83 | ~0.87 | <0.7 | 0.94 |
| $i$ | 13–64 | ~25–40? | 10–60 | 47–80 | 19–31 | <66 | |
| Spectral Type | O6.5 V(f) | O6 V(f) | B0 Ve | B0 Vpe | O9.5 Ve | O5 III(f) | B0 Ve |
| $M/M_\odot$ | 23 | 26 | 12 | 16 | 31 | 25–42 | 14.5–17.5 |

NOTE.—[a]PSR 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?



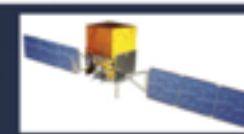

- Driven by particle acceleration (Fermi Mechanism)
- Evolve into HMXBs?



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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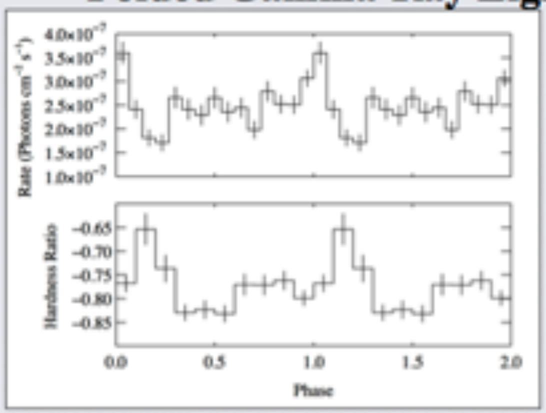
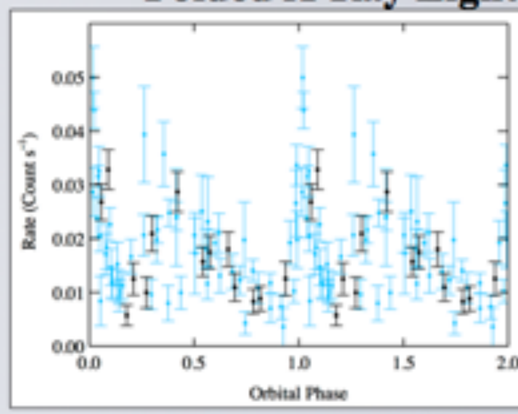
1FGL J1018.6-5856, the first gamma-ray binary discovered by the Fermi Large Area Telescope (LAT), consists of an O6 V(f) star and suspected rapidly spinning neutron star. While 1FGL J1018.6-5856 has been postulated to be powered by the interaction between a relativistic pulsar wind and the stellar wind 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 16.531±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



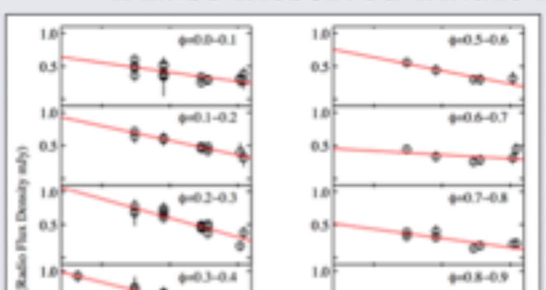

Fermi LAT light curve in the 0.1-300 GeV band (top) based on a likelihood analysis folded on the 16.5 day orbital period. The hardness ratio (bottom) is produced taking the results from the likelihood analyses of the soft and hard energy bands, 0.1-1 GeV and 1-300 GeV, respectively.

## Folded X-Ray Light Curve



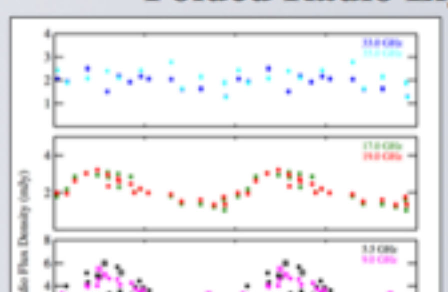

Swift XRT X-ray light curves folded on the orbital period. The light blue data is prior to MJD 55984[1,2]. The black data points after MJD 55984[2,3,4]. The modulation a sharp maximum at phase 0 and a broad maximum phase ~0.4. This is consistent with previous observations[1,2,5].

## Phase-Resolved Radio Spectra



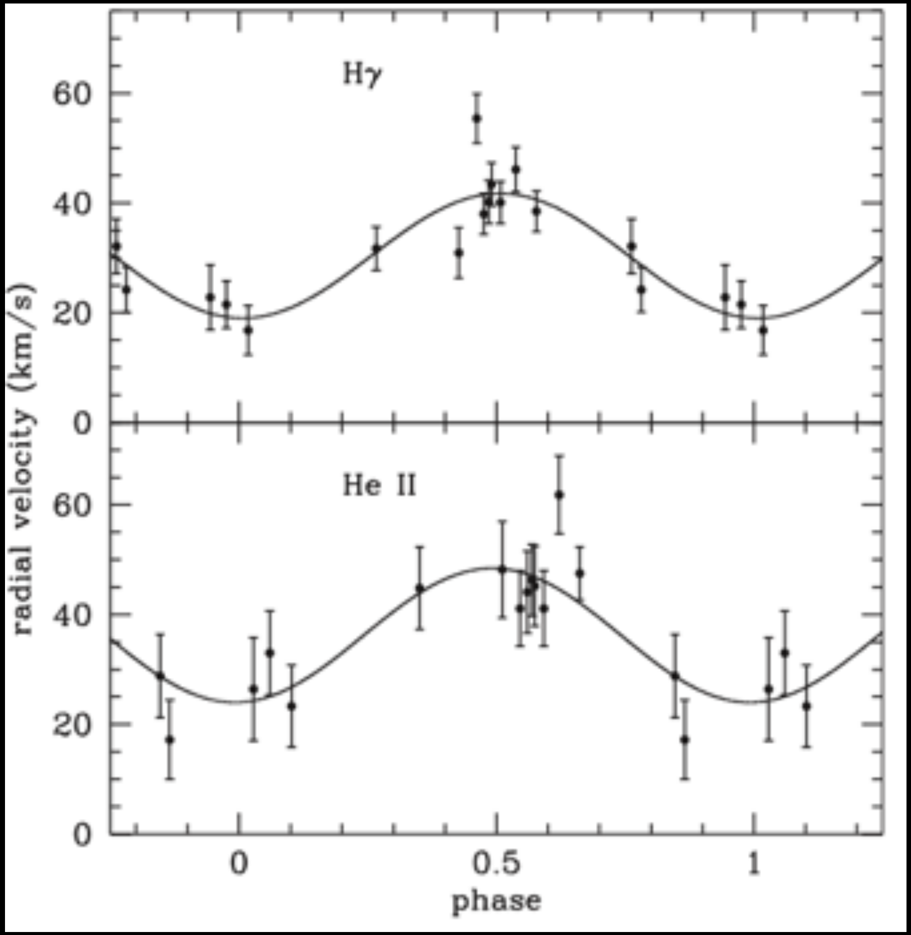
Orbital phase-resolved ATCA radio spectra covering frequencies in the 2.1-35.0 GHz band. The red lines indicate the best fit for a power-law model, which is a possible indication of free-free absorption.

## 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[4].

# Radial Velocity Semi-Amplitude

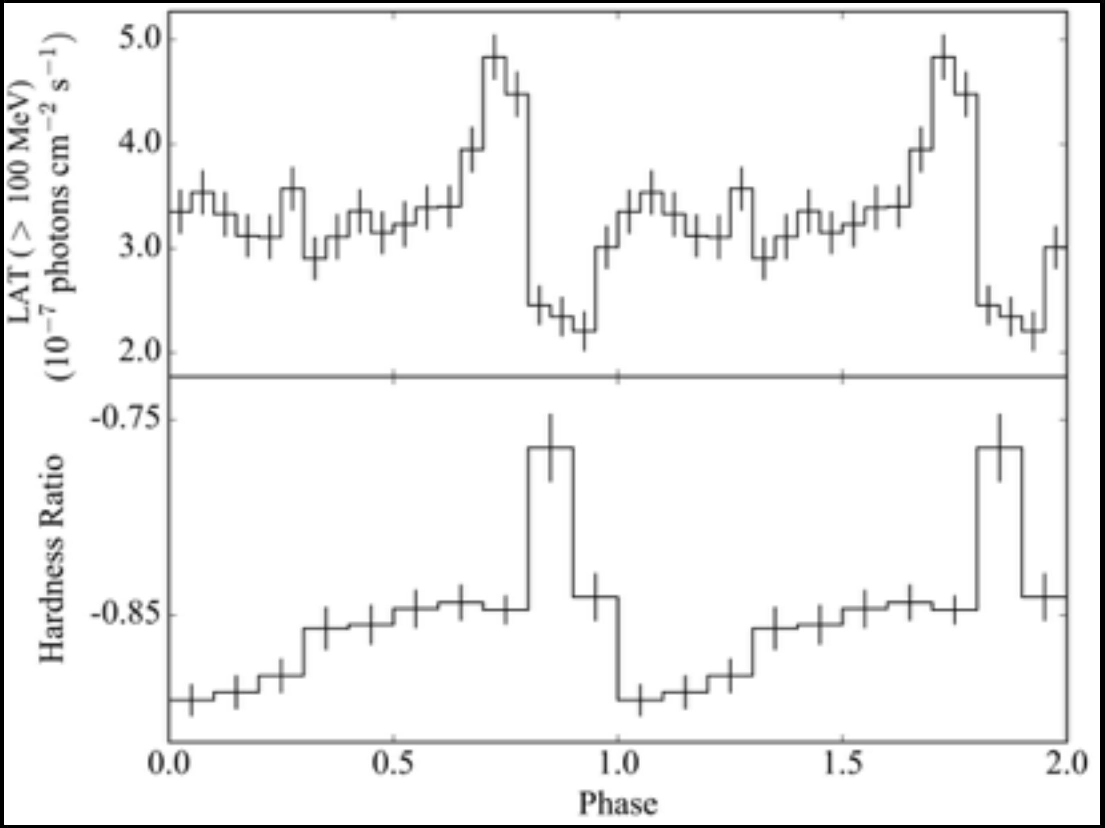



- SOAR Radial Velocity Semi-Amplitude
- Mass function consistent with Neutron Star
- Black hole only allowable: i<16 degrees

Image Courtesy of Strader et al. (2015)

# Folded Fermi LAT Light curve and Hardness Ratio

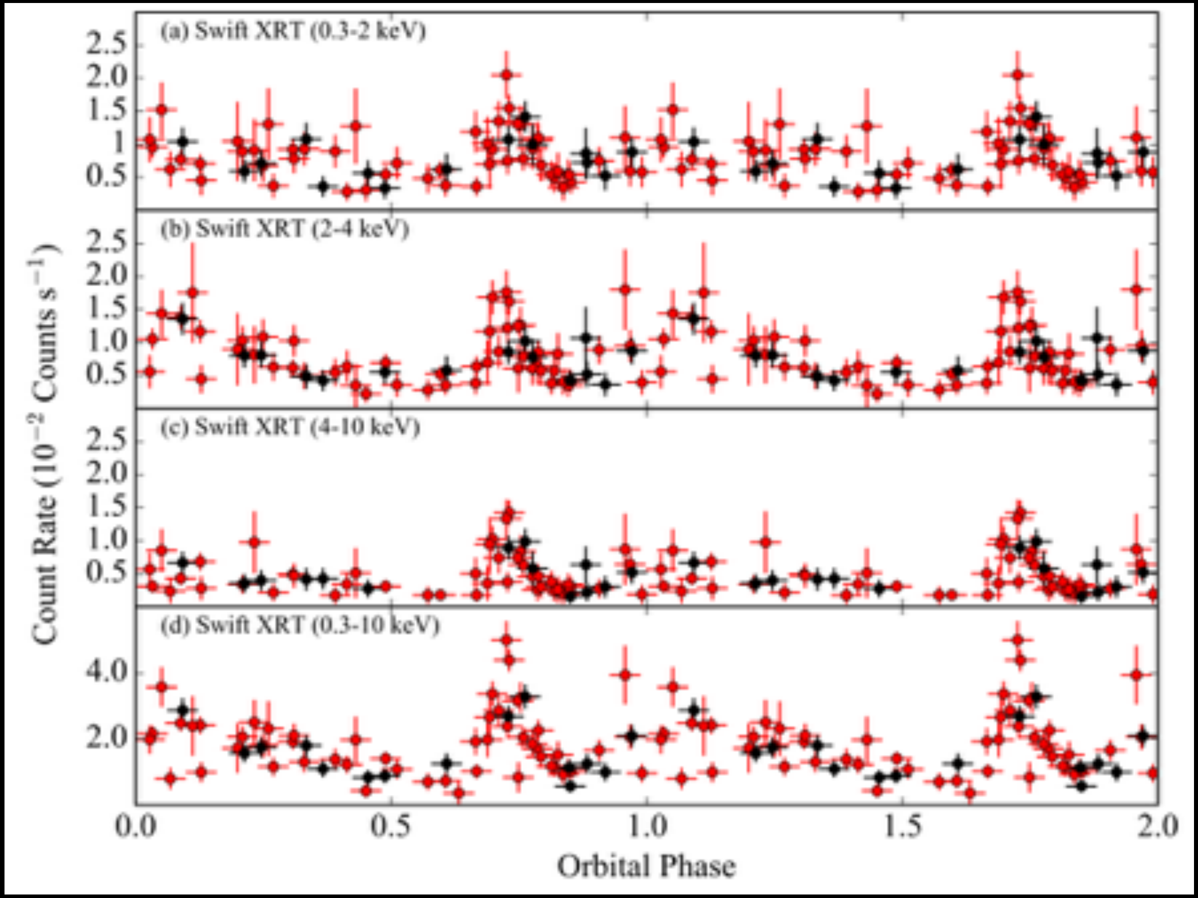
$P_{orb}$~16.5 days




Soft and hard energy bands are 0.1-1 GeV and 1-300 GeV

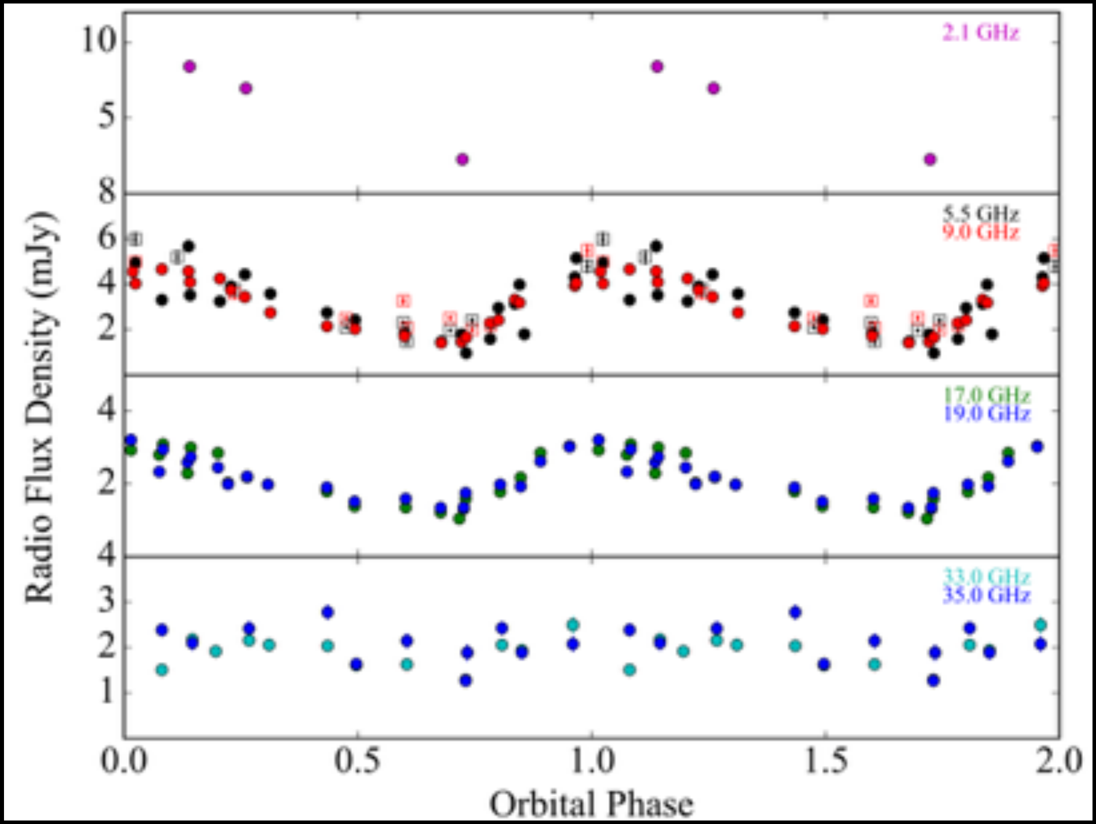
- Phase 0 defined by the ascending node of the compact object
- Narrow spike at orbital phase ~0.75 (INFC)

# 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?)

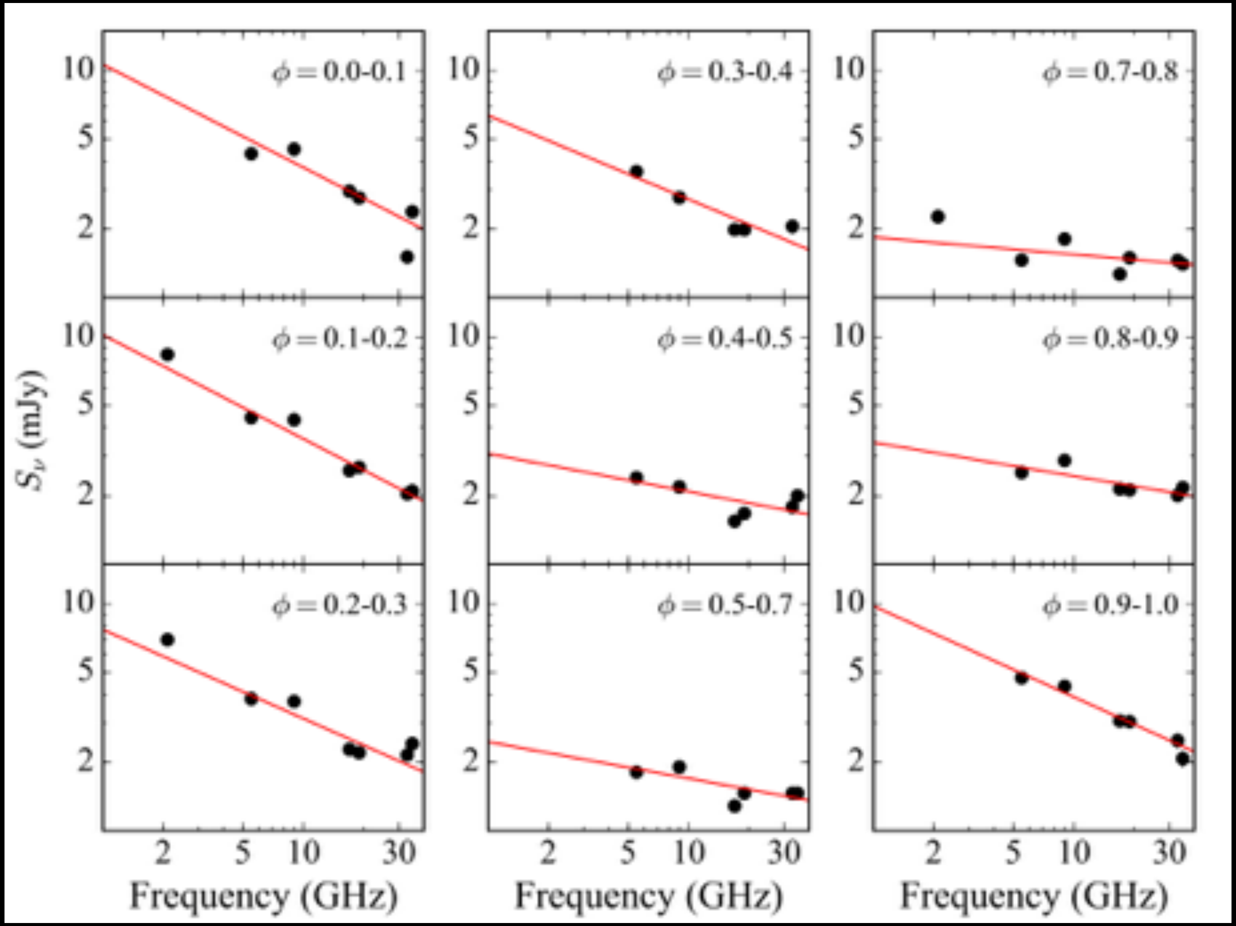
# Folded Radio Lightcurves of 1FGL J1018.6-5856




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

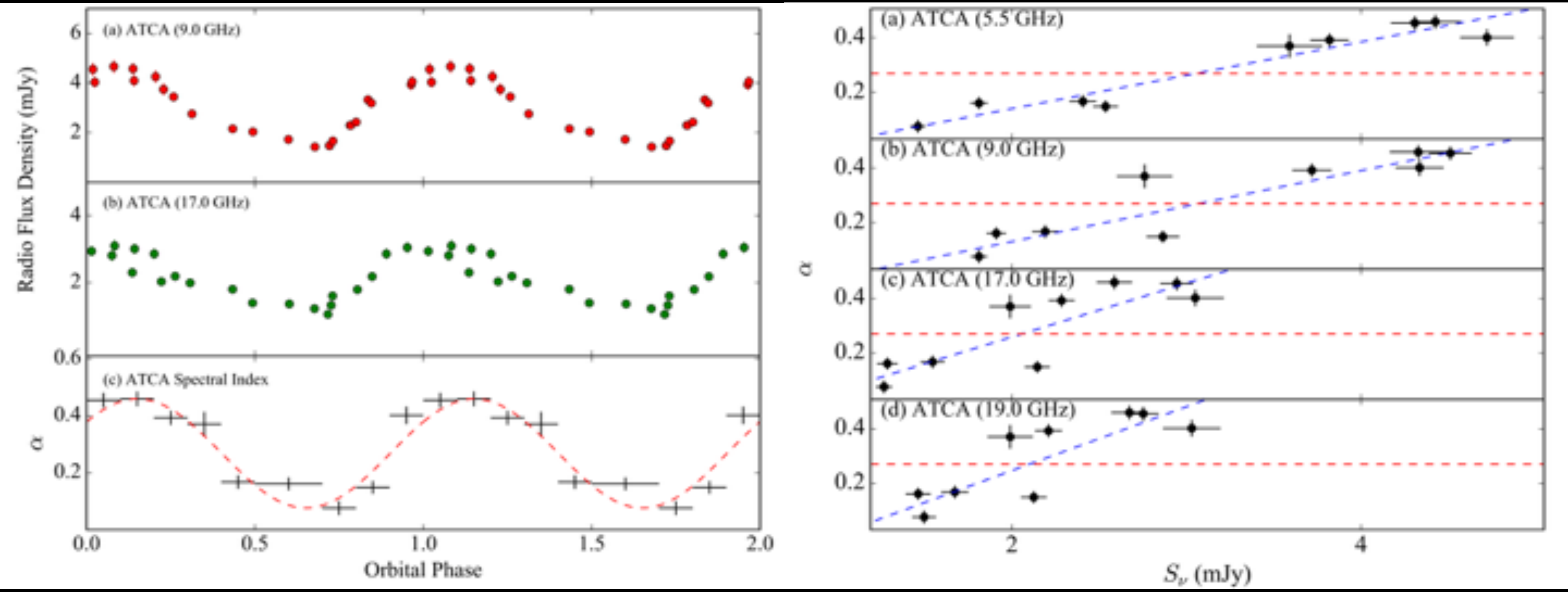
Image Modified from Coley et al. (2014b)

# Orbital Phase-Resolved ATCA Radio Spectra



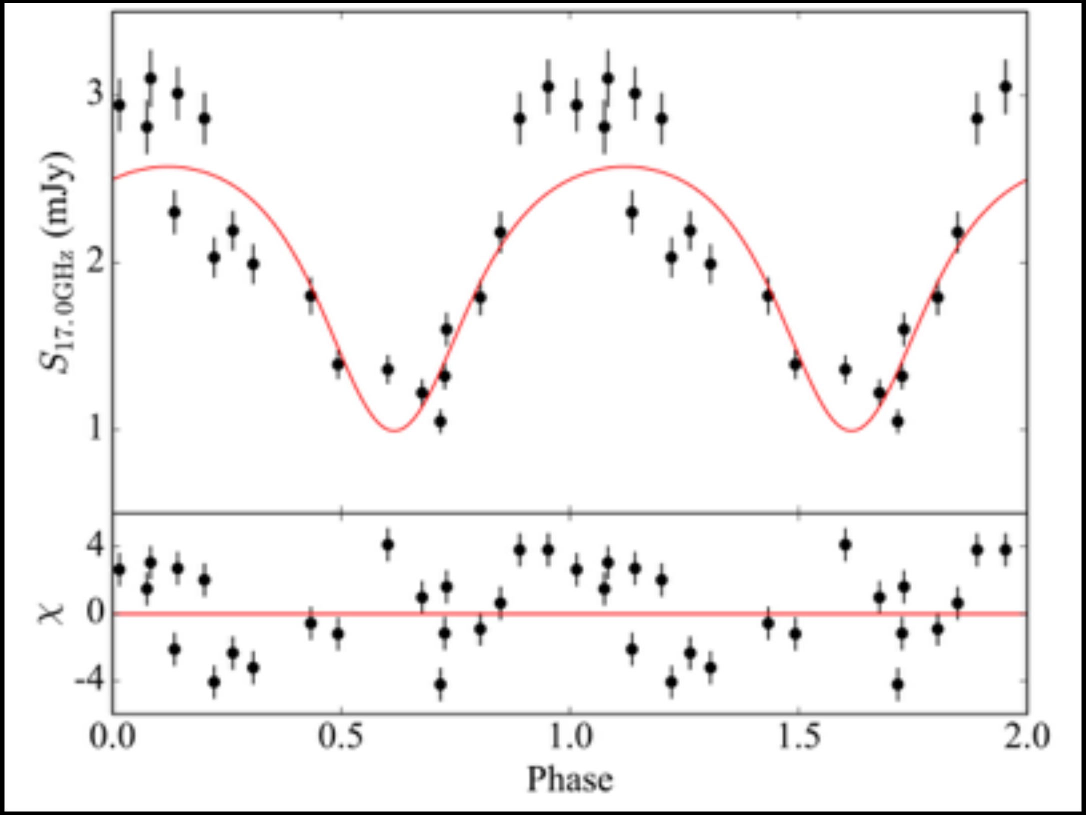

- Covers frequencies in the 2.1-35.0 GHz band
- Modeled with a power law; possible indication of free-free absorption

# ATCA Spectral Parameters



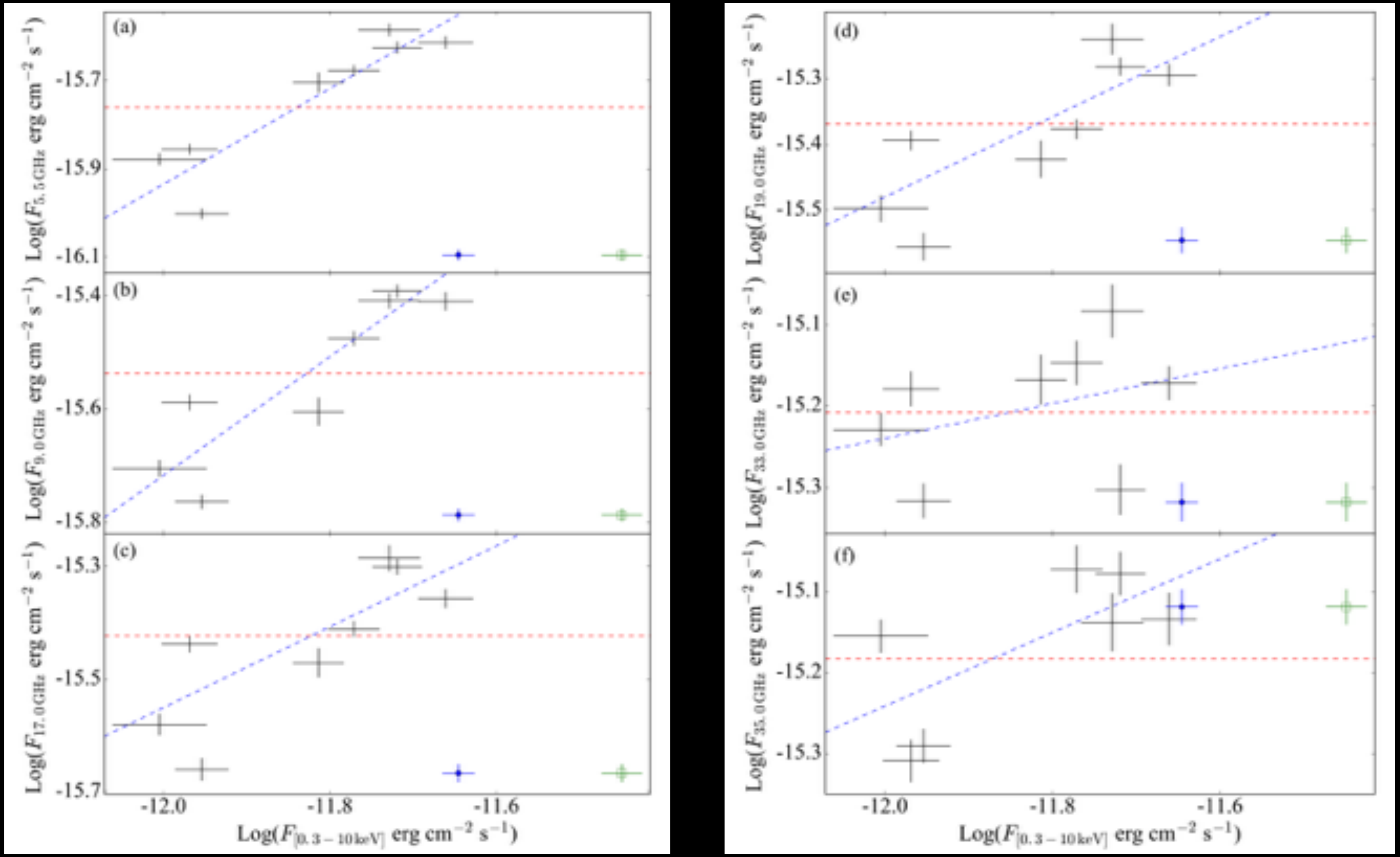

- Power-law frequency index of the ATCA radio data folded on the orbital period (left)
- Spectral index of the ATCA radio spectra vs. flux density (right)

# Preliminary Free-Free Absorption Model




- Power law modified by free-free absorption
- Orbital Inclination: 33-37 degrees
- Eccentricity cannot be constrained

# Emission Region Constraints




- Radio fluxes in the 5.5-19.0 GHz bands correlated with 0.3-10 keV X-ray flux

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# 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 anti-phase 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

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

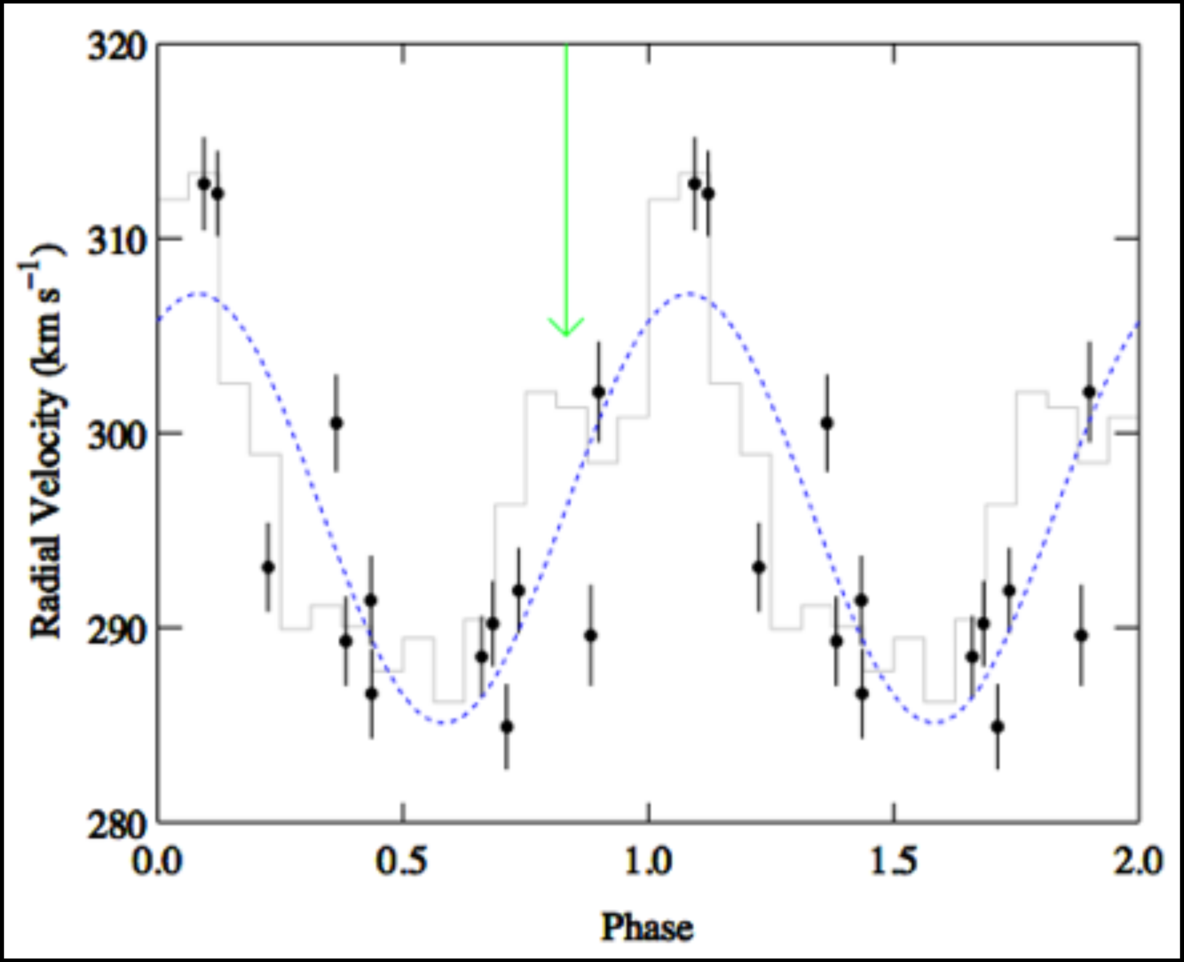
# LMC P3

- 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

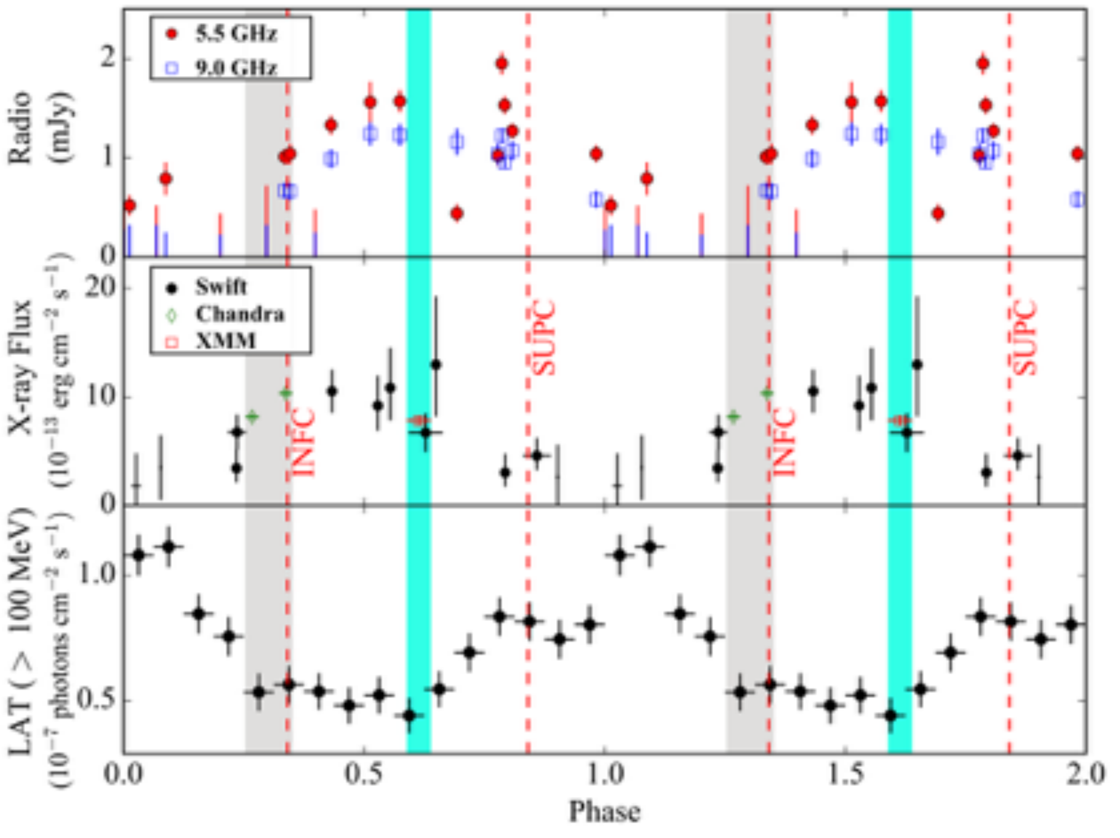



- SOAR Radial Velocity Semi-Amplitude
- Mass function consistent with Neutron Star
- Black hole only allowable: $i<15$ degrees

Image Courtesy of Corbet et al. (2016)

# Multiwavelength Light Curves of LMC P3

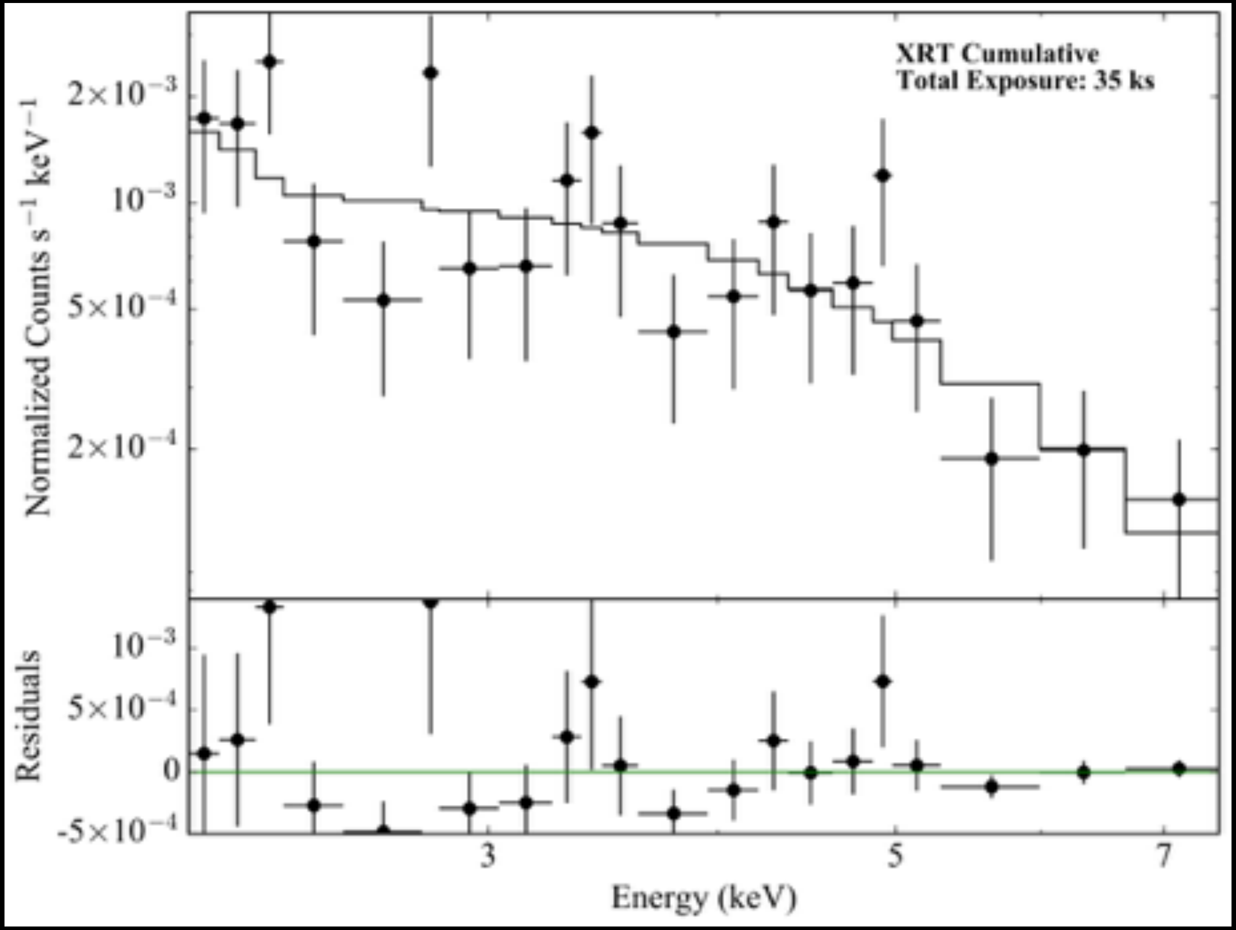
$P_{orb}$~10.3 days




- 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

Image Modified from Corbet et al. (2016)

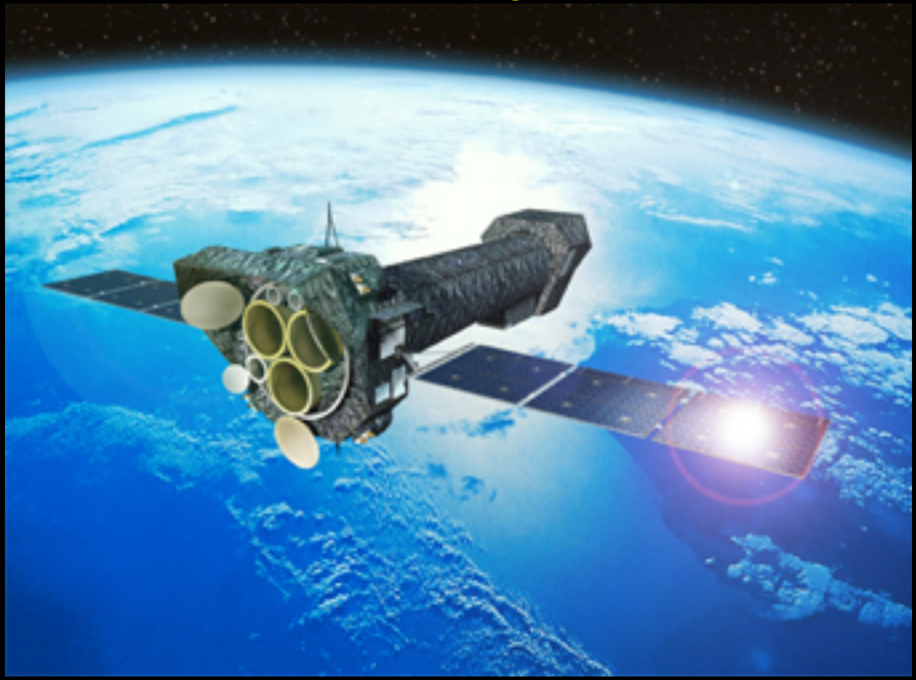
# Swift Cumulative Spectrum

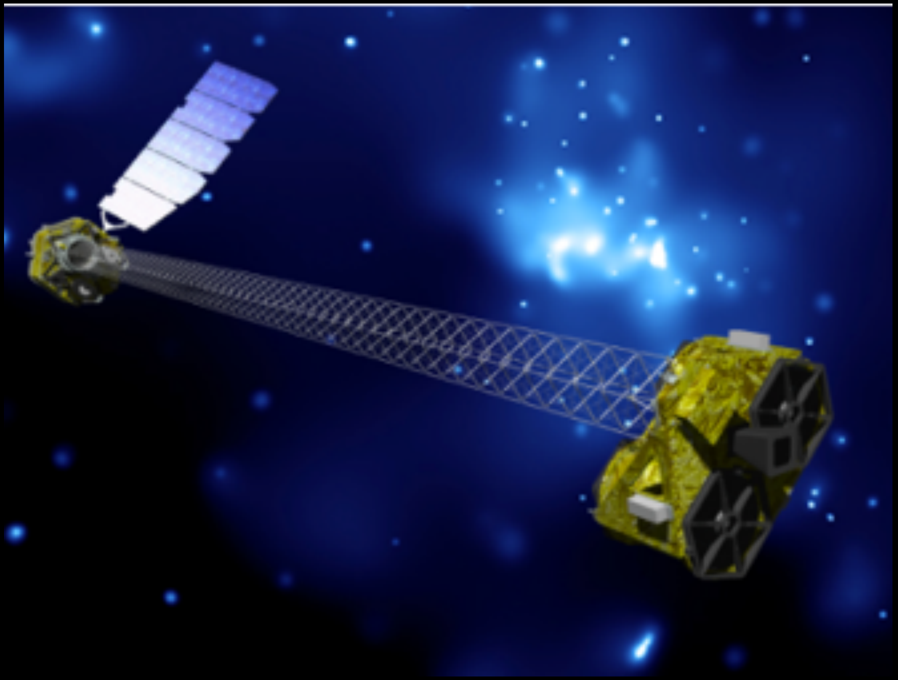



- Power law fit with spectral index ~1.3
- No constraints on NH
- Hampered by low S/N; low effective area

Image Courtesy of Corbet et al. (2016)

# Approved AO-16 XMM and NuSTAR Cycle 3 Observations



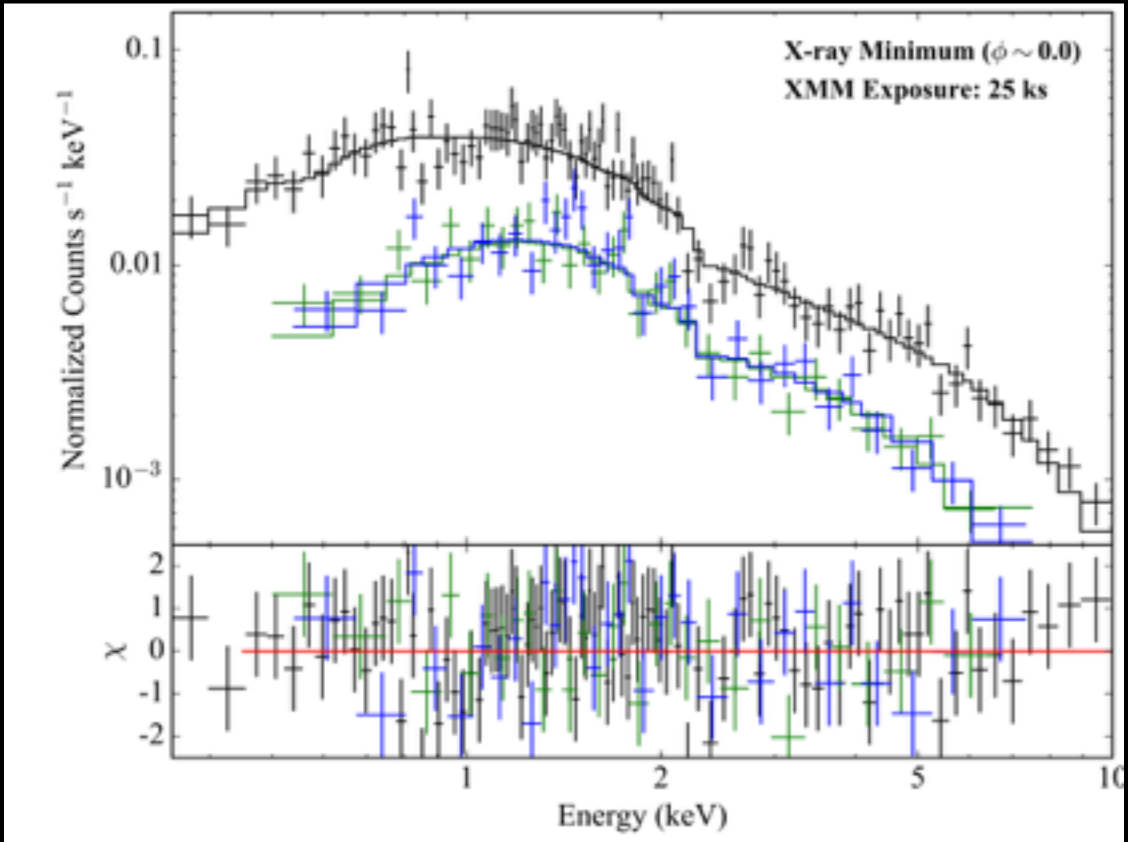


- Investigate phase dependence of $N_H$, $\Gamma$, and X-ray flux
- Search for possible neutron star rotation period with EPIC-pn
- Measure $\Gamma$ and X-ray flux out to 40 keV (NuSTAR)



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 Γ 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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