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Modulated High-Energy Gamma-Ray Emission from the Microquasar Cygnus X-3

The Fermi LAT Collaboration*

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Microquasars are accreting black holes or neutron stars in binary systems with associated relativistic jets. Despite their frequent outburst activity, they have never been unambiguously detected emitting high-energy gamma rays. The Fermi Large Area Telescope (LAT) has detected a variable high-energy source coinciding with the position of the x-ray binary and microquasar Cygnus X-3. Its identification with Cygnus X-3 is secured by the detection of its orbital period in gamma rays, as well as the correlation of the LAT flux with radio emission from the relativistic jets of Cygnus X-3. The gamma-ray emission probably originates from within the binary system, opening new areas in which to study the formation of relativistic jets.

Cygnus X-3 (Cyg X-3) motivated to a large extent the development of high-energy gamma-ray astronomy. Detections of Cyg X-3 were reported in the 1970s and early 1980s at energies of tens of MeV, TeV, PeV and possibly EeV, generating considerable excitement as these identified the system as a prime source of cosmic rays (*1–3*). However, the detections remained doubtful in part because observations in the late 1980s and in the 1990s by a more sensitive generation of ground-based telescopes failed to confirm the TeV and PeV detection of Cyg X-3 (*4, 5*), and also because both COS-B (6) and CGRO-EGRET (*7*) could not find emission from the source in the GeV range.

Here, we report the detection of a variable high-energy gamma-ray (100 MeV - 100 GeV) source that we identify with Cyg X-3 based on its location, the detection of a modulation of the gamma-ray flux at the orbital period of the binary system, and the gamma-ray variability correlated with the radio emission originating from the relativistic jets of Cyg X-3.

Cyg X-3 is a high-mass x-ray binary system (*2*) with a short orbital period of 4.8 hours (*8*) located in the Galactic plane at a distance of ~7 kpc from Earth (*9*). The nature of the compact object—neutron star or black hole—is still subject to debate; however, the companion is known to be the Wolf-Rayet star V1521 Cyg (*10*). After its discovery in 1966 (*11*), Cyg X-3 was intensively observed over a wide range of wavelengths. It frequently becomes the brightest radio source among the binary systems with major flares, because of its relativistic jets (*12–14*), which qualify the source as a microquasar. The variable emission observed in microquasars from the radio up to a few hundreds of keV is induced by the interplay between the stellar companion, the accretion flow, the optically thin electron corona, and the relativistic jets (*15–17*).

We present the results of the Fermi Large Area Telescope (LAT) observations of the Cygnus region between 2008 August 4 and 2009 September 2 [see supporting online material (SOM) for details] (Fig. 1). The pulsar PSR J2032+4127 is located very close (~30 arcminutes) to Cyg X-3 and contributes significantly to the LAT photons at the location of Cyg X-3. However, because it exhibits relatively narrow pulses (*18*), it enabled us to select the LAT data using the off-pulse phase intervals of PSR J2032+4127, a procedure that preserves 80% of LAT live time. We then performed an unbinned maximum likelihood spectral and spatial fitting analysis of a 15° radius region centered on the position of Cyg X-3. Adding a source consistent with the location of Cyg X-3 in the fitting procedure improves the fit significantly. The overall significance of the LAT source at this position amounts to more than 29 standard deviations (29σ). The position of the LAT source is RA (J2000) = 308.05° and Dec (J2000) = 40.96° with a statistical uncertainty (95% confidence level) of 0.04°, which is consistent with the location of Cyg X-3.

We also constructed the LAT light curve on 4-day (Fig. 2) and 2-day time scales, in order to highlight the gamma-ray variability of the LAT source, which is mostly dominated by two main active periods: 2008 October 11 to December 20 (MJD 54750 to 54820) and 2009 June 8 to August 2 (MJD 54990 to 55045). These phases of activity may be consistent with one or several flares, with possibly the brightest flare observed at the end of each period. The peak flux can be as high as ~ 2×10^{-6} ph cm^{-2} s^{-1} above 100 MeV.

We have fitted the spectrum of Cyg X-3 in the two active periods with a simple power law using the dataset created from the off-pulse phase intervals of PSR J2032+4127. We obtained a spectral index Γ of 2.70 ± 0.05 (stat) ± 0.20 (syst). The systematic error was estimated by using different sets of models for the diffuse emission. In view of the soft spectrum and the bright complex diffuse emission in this region, this spectral parameter may have a larger systematic uncertainty.

However, for this preliminary spectral index, the average photon flux of the LAT source in the active periods is [1.19 ± 0.06 (stat) ± 0.37 (syst)] × 10^{-6} ph cm^{-2} s^{-1} above 100 MeV, corresponding to an energy flux of (4.0 ± 0.3 (stat) ± 1.3 (syst)) × 10^{-10} erg cm^{-2} s^{-1}. This corresponds to a gamma-ray luminosity L_γ of ~ 3 ×10^{36} $(d/7kpc)^2$ erg s^{-1}, which is similar to what was was originally reported by SAS-2 (*19*) in the early 1970's for Cyg X-3 in a similar energy range. AGILE also reported gamma-ray flares in the vicinity of Cyg X-3 at similar epoch (*20*).

To securely identify the LAT source with Cyg X-3, we performed a timing analysis to search for the 4.8-hour orbital period (*8*) of Cyg X-3. For that purpose, we created a light curve for the LAT source using aperture photometry and 1000 s time bins. We extracted photons within a 1 degree radius circular region centered on Cyg X-3 in the energy range from 100 MeV to 100 GeV. We calculated the power spectra for both the entire light curve and also for only the active periods identified above (see Fig. 2). Because 1000 s is shorter than the sky survey rocking period of Fermi, the exposure of Cyg X-3 varies considerably from time bin to time bin. We therefore weighted the contribution of data points to the power spectrum by their relative exposures. While no orbital modulation is apparent when using the entire data set, two peaks, corresponding to the orbital period of Cyg X-3 and its second harmonic (in addition to low frequency noise), stand out when the analysis is restricted to the two periods of enhanced emission (Fig. 3A). The nominal probability of a false detection for a period of arbitrary frequency is 3.6 × 10^{-5} taking into account the number of trials. To investigate whether the modulation seen at the orbital period of Cyg X-3 could be an artifact, we also extracted light curves and calculated power spectra for all sources in the Fermi Bright Source List. In no case did we see significant modulation at the orbital period of Cyg X-3. A maximum likelihood analysis of light curve photons (SOM) shows that the probability to find a modulation as strong as the LAT signal with the known period of Cyg X-3 is ~ 2.4 × 10^{-9}. This confirms that the LAT source displays the orbital period of Cyg X-3 and therefore secures its identification with Cyg X-3.

The orbital period of Cyg X-3 has been reported to show secular change (*21*). To obtain the predicted parameters of Cyg X-3 at the time of our LAT observations, we therefore used the parabolic ephemeris of Cyg X-3 (*21)* and derived a period of 0.199692441(35) day and epoch of minimum x-ray flux of MJD 54856.693 (*10)*. This is consistent with the period obtained - P = 0.199655 (46) day - from the maximum likelihood analysis of the LAT light curve. We compare the LAT light curve from the active time ranges folded on the orbital period to the folded 1.5 to 12 keV x-ray light curve of Cyg X-3 from the Rossi X-ray Timing Explore All-Sky Monitor (RXTE/ASM) (Fig. 3B). The folded x-ray and gamma-ray light curves have the same asymmetric shape with a slow rise followed by a faster decay. However, a striking contrast is that the phase of LAT maximum flux is close to the phase of minimum x-ray count rate. Indeed, the LAT minimum trails the x-ray minimum by 0.3-0.4 in phase. Further observations will be needed to interpret the small (~0.1) shift in LAT maximum that occurs from the first to the second active period (SOM, fig. S1).

The soft x-ray (1.5-12 keV) from RXTE/ASM and hard x-ray (15-50 keV) from Swift/BAT light curves indicate that all LAT gamma-ray active periods from Cyg X-3 correspond to the soft x-ray state of the source (SOM, fig. S2). Cyg X-3 is known to flare in radio in the soft state, e.g., (*22*), with associated relativistic plasma ejection events (*12–14*). We have therefore compiled the radio data from our regular monitoring with the AMI telescope and the OVRO 40m telescope at 15 GHz. Inspection of the LAT and radio light curves of Cyg X-3 (Fig. 2) indicates that the LAT active periods occur close to radio flares. To quantify the relation between the gamma-ray and radio emission, we have calculated the discrete cross-correlation function normalized only by the sample variance (SOM, fig. S3). We find a positive correlation between the two wave bands. The overall correlation is dominated by the strong radio and gamma-ray flare around MJD 54810. The peak in the cross-correlation is significant at more than ~ 3σ (the exact value depending on the assumed noise properties of LAT data of Cyg X-3). The lag of the radio light curve to the gamma rays is not well constrained; a bootstrapping technique shows that it is 5 ±7 days .

The detection of Cyg X-3 by the LAT during periods of relativistic ejection events is important for linking and understanding the different components of an accreting binary system (wind of the Wolf Rayet star, compact object, accretion disk, corona and relativistic jets). A variable hard tail above 30 keV with a power law index $\Gamma \approx 2$ is present in some instances (e.g., the ultrasoft state) of the soft x-ray state associated with the onset of radio flaring episodes (*22*). The tail has been reported to extend up to several hundred keV, e.g., (*23*). The Fermi flux is compatible with the extrapolation of this tail to 100 MeV but has a steeper spectrum, suggesting we are seeing the high-energy end of a spectral component peaking in soft gamma-rays.

The hard x-ray tail is typically modeled as being due to the Compton up-scattering of photons from a soft photon source by high-energy electron in a corona (possibly the base of the jets), although the physical processes responsible for the electron's acceleration are not yet known (*22*, *23*). It is likely that the gamma-ray emission is due to the same process, however, this is only possible if the emission region is not too close to the accretion disk, or it would be absorbed by pair production on the soft x-ray photons (*24*). On the other hand, the gamma-ray modulation suggests (*25*) that the emission region size and location are bounded by the orbital separation ($a \approx 2.5 \times 10^{11}$ cm).

With the emitting region located away from the accretion disk but within the system, the companion star provides the dominant radiation field at the location of the electrons. Electrons with energies of a few GeV can then inverse Compton scatter the UV photons ($T_* \approx 10^5$K) to gamma rays. The stellar radiation field is not isotropic for the electrons, so the upscattered emission also will be anisotropic, causing a modulation of the gamma-ray emission. Assuming the location of the electrons is in phase with the compact object (as expected for jets perpendicular to the orbital plane), maximum gamma-ray emission occurs when the electrons are seen behind the Wolf-Rayet star, *i.e.*, at superior conjunction when the energetic electrons directed toward Earth suffer head-on collision with the stellar UV photons (*26*). This corresponds to minimum x-ray emission if the x-ray modulation is due to Compton scattering in the companion's wind as is usually presumed (*27*). Infrared studies also support this phasing of the orbit (*28*). The phase shift of the gamma-ray minimum (SOM, fig. S1) from $\phi = 0$ might be associated with misalignment of the axis of the jets.

The inverse Compton energy loss time scale $t_{\mathrm{ic}} \approx 1 E_{\mathrm{GeV}}^{-1}\mathrm{s}$ is short compared to the escape time scale $t_{\mathrm{esc}} = a/c \approx 8$s meaning this radiative process is quite efficient. The maximum observed gamma-ray luminosity L_γ is $5 \times 10^{36} d_{7\mathrm{kpc}}^2 \mathrm{erg\ s}^{-1}$ above 100 MeV (for a spectral index of $\Gamma = 2.7$) which is $\lesssim$ 10% of the x-ray luminosity, suggesting only a minor fraction of the accretion power is released via particle acceleration. This contrasts with the few other binaries (*29*) that are confirmed as high-energy gamma-ray emitters. In these, the dominance of gamma rays in the non-stellar radiative output, the weakness of the x-ray emission ($<10^{34}$ erg s^{-1}), and the lack of accretion signatures suggests a compact pulsar wind (*30*).

Interpreted as the propagation time of relativistic ejecta, the 5 day delay (still uncertain however) between the onset of gamma-ray and radio flaring implies that the radio emission occurs $\approx 1.3 \times 10^{16}$ cm (i.e., ≈ 900 a.u. ≈ 125 mas) away from the system. Indeed, radio emission during flares is known to occur farther out in the jet on scales of hundreds of astronomical units (distance from the core of few tens of milli-arcsecond), with measured projected expansion velocities around 10 mas/day 0.5c-0.6c, e.g., (*14*).

Unique characteristics of Cyg X-3 compared to all other microquasars are the very tight orbit and very strong Wolf-Rayet wind. With a wind mass loss ~ $10^{-5}\ M_\odot$ year^{-1} and a wind velocity ~ 1000 km s^{-1} (*10*), the densities (hereafter n_{13} in units of 10^{13} cm^{-3}) reach 10^{13} cm^{-3} at the location of the compact object, orders-of-magnitude more than in all other systems. Thus, while we have discussed a leptonic origin for the GeV photons, if cosmic ray protons are also accelerated in the source, they could have significant interaction with the nuclei in the stellar wind, producing charged and neutral pions that would decay into gamma rays and neutrinos. The time scale for proton-proton interaction is $t_{\mathrm{pp}} \approx 100 n_{13}^{-1}\mathrm{s} > t_{\mathrm{esc}}$. Assuming a 10% transfer efficiency of the proton energy into secondary particles, the required proton luminosity is ~ 10 ($t_{\mathrm{pp}}/t_{\mathrm{esc}}$)$L_\gamma$. Thus, the non-thermal energy would be larger than or (if the protons are confined) comparable to the x-ray luminosity. If this scenario is correct, something that the observation of neutrinos from this source would confirm, then the dense environment of Cyg X-3 could provide a unique opportunity to study the high-energy proton content in microquasars and their contribution to cosmic ray protons.

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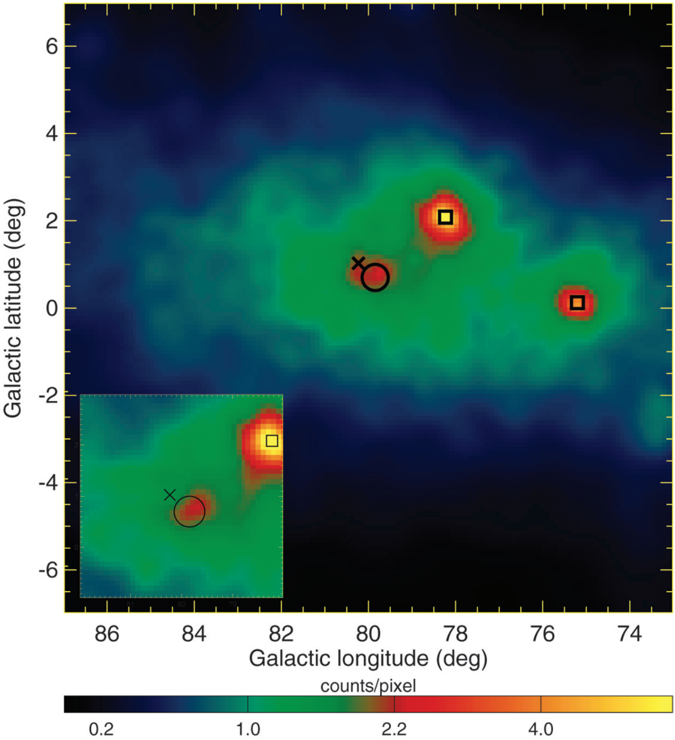
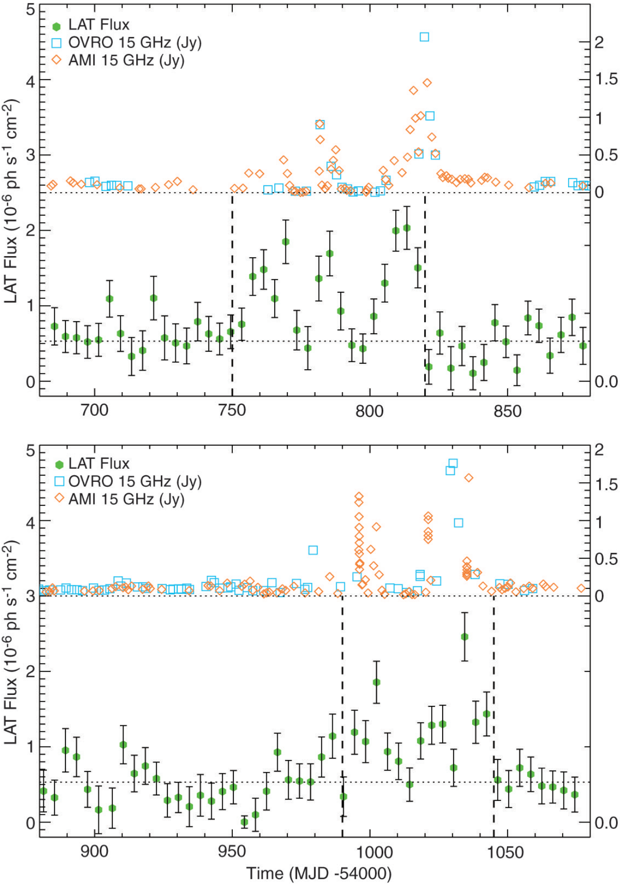
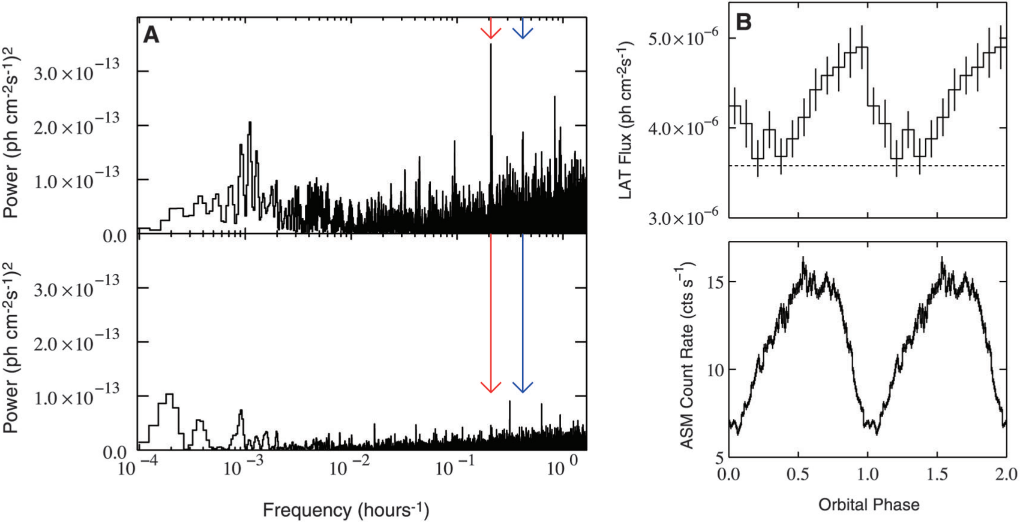
Fig. 1. 200 MeV - 100 GeV Fermi/LAT gamma-ray counts map of a 14° × 14° region centered on the position of Cyg X-3 and corresponding to the active periods discussed in the text. The map (no background subtraction) was adaptively smoothed by imposing a minimum signal-to-noise ratio of 15. It shows the region around Cyg X-3 encompassing emission from three bright gamma-ray pulsars (PSR J2021+4026, PSR J2021+3651 and PSR J2032+4127), as well as the strong Galactic diffuse emission of the Cygnus region. The locations of PSR J2021+4026 and PSR J2021+3651 are indicated by black squares, and PSR J2032+4127 is indicated by a cross. The position of Cyg X-3 is shown by the circle. Inset: Similar image for the central portion (4° × 4°) corresponding to the off-pulse dataset from PSR J2032+4127 (which is not detected in the off-pulse data). A total of ~3400 counts are detected from the LAT gamma-ray source at the position of Cyg X-3.

Fig. 2. Gamma-ray light curve with a likelihood analysis window of 4 days of the LAT source at the location of Cyg X-3. The LAT fluxes (left axis) are expressed in units of 10^{-6} ph cm^{-2} s^{-1} above 100 MeV. A power-law shape with spectral index of 2.7 is assumed for Cyg X-3 in the analysis. The parameters of the components for the model of the diffuse emission were held fixed to the values obtained in the global fit, with the exception of the normalization of the Galactic diffuse component that was left free. The vertical dashed lines illustrate the active periods discussed in the text. The horizontal dotted line indicates the average gamma-ray flux at the location of Cyg X-3 outside the active periods. In addition, at the top of each panel, we show the Cyg X-3 15 GHz radio flux (from the AMI and the OVRO 40 m radio telescopes) as a function of time (axis on the right). An offset of 0.124 Jy has been removed from the OVRO data to account for the effect of extended nearby sources that are resolved out by the AMI interferometer. A horizontal dotted line at 0 Jy is also plotted for reference. Several radio flares are detected during the LAT active periods.

Fig. 3. Power spectra and folded light curves of the LAT source at the location of Cyg X-3. (**A**) Bottom: power spectrum of the entire LAT light curve. Top: power spectrum of the identified active periods of the LAT source. The red and blue arrows indicate the frequencies that correspond to the orbital period and the second harmonic of the orbital period respectively. (**B**) Top: Light curve of Cyg X-3 during times identified as the active intervals (same as top-left) of the LAT source folded on the orbital period of the system. The data points were again weighted by their exposures. The dashed line shows the emission level (including diffuse emission) obtained by measuring the flux in the 1° aperture outside the active periods of Cyg X-3. In our definition, the compact object is directly behind the star at phase = 0 (superior conjunction). Bottom: RXTE ASM light curve of Cyg X-3 folded on the orbital period. The light curve is built using the data over the entire lifetime of RXTE.


6
4
2
0
-2
-4
-6
Galactic latitude (deg)
86
84
82
80
78
76
74
Galactic longitude (deg)
counts/pixel
0.2
1.0
2.2
4.0


LAT Flux
OVRO 15 GHz (Jy)
AMI 15 GHz (Jy)
LAT Flux (10^{-6} ph s^{-1} cm^{-2})
0
1
2
3
4
5
0.0
0
0.5
1
1.5
2
700
750
800
850
LAT Flux
OVRO 15 GHz (Jy)
AMI 15 GHz (Jy)
LAT Flux (10^{-6} ph s^{-1} cm^{-2})
0
1
2
3
4
5
0.0
0
0.5
1
1.5
2
900
950
1000
1050
Time (MJD -54000)


A
B
Power (ph cm-2s-1)2
3.0×10−13
2.0×10−13
1.0×10−13
0.0
Frequency (hours-1)
10−4
10−3
10−2
10−1
100
LAT Flux (ph cm-2s-1)
5.0×10−6
4.0×10−6
3.0×10−6
ASM Count Rate (cts s−1)
15
10
5
0.0
0.5
1.0
1.5
2.0
Orbital Phase