Gamma-ray evidence for a jet–orbit misalignment in the X-ray binary Cyg X-3

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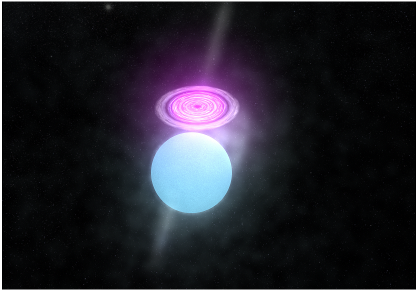

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Outline

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X-ray binaries are systems consisting of a normal star and a collapsed star (neutron star (NS) or black hole (BH)) and which are luminous in X-rays

- First discovered in X-rays
- Powered by accretion from the donor star onto the compact object (accretor)
- X-ray emission comes from the inner part of the accretion disk

X-ray binaries

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High-mass X-ray binary $(M_{\rm donor} \geq M_\odot)$

Low-mass X-ray binary $(M_{\rm donor} < M_\odot)$

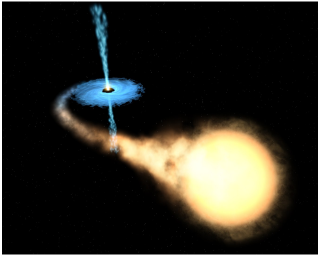
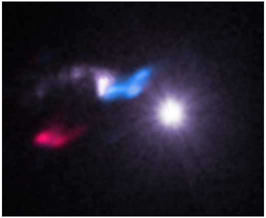


Figure: An artist impression of an X-ray binary. Credit: ESA/Hubble (CC BY 4.0)

- **Microquasars** – X-ray binaries with radio jets

Cyg X-3: a puzzling microquasar

- High-mass XRB
- Nature of the compact object is unknown (**NS/BH ?**)
  - BH hypothesis is favored, but NS is not ruled out
- Donor: Wolf-Rayet (WR) star
  – The only system in the Galaxy consisting of WR star and a compact object
- Masses of components uncertain. $M_* \sim 12 M_\odot$, $M_c \sim 7 M_\odot$?
- Luminous in radio and X-ray. Strong X-ray polarization ~ 25 % (Veledina+23)
- **Shows prominent γ-ray emission**



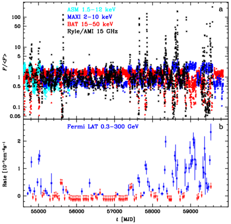


Figure: Top: composite X-ray and radio image of Cyg-X3 (credit: NASA/CXC/SAO/M.McCollough et al, Radio: ASIAA/SAO/SMA). Bottom: multi-band long-term LCs of Cyg X-3 (credit: A.A. Zdziarski)

γ-ray emission from Cyg X-3

Recent enhanced γ-ray activity of the source. Data can provide new clues about the system

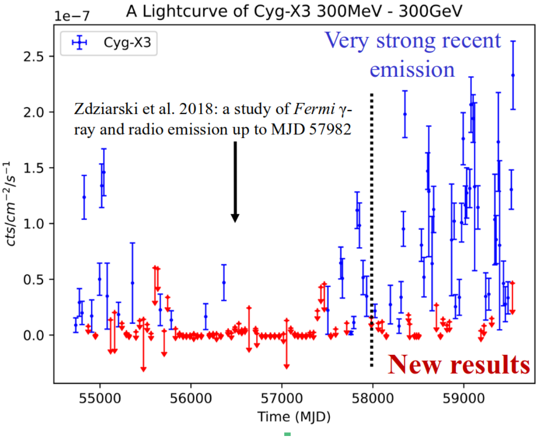
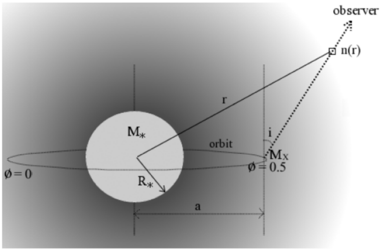
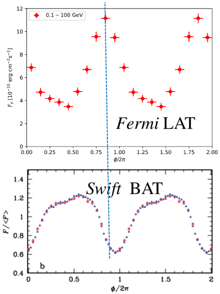


Figure: γ-ray light curve of Cyg X-3 (credit: A.A. Zdziarski)

- γ-rays are strongly **orbitaly modulated** (Fermi LAT Collaboration et al. (2009))
- Modulation: anisotropic Compton scattering of blackbody photons from the donor (Dubus et al. (2010))
- Maximum of the emission expected at superior conjunction (SC) (compact object behind the donor star)
- The data shows an offset of the peak wrt SC $\rightarrow$ signature of **jet misalignment**
- X-rays undergo **wind absorption** $\rightarrow$ their *minimum* is at SC





Left: a scheme visualizing the orbital modulation of X-ray and γ-ray emissions. Right: folded γ (top) and X-ray (bottom) orbital modulation LCs (credit: A.A. Zdziarski)

Motivation of our study: better data and modeling

Motivation of our study

- Previous studies (Dubus et al. (2010), Zdziarski et al. (2018)) use γ-ray data with too limited statistics
- We use recent data with **drastically better quality**
- **Improved modeling:**
  - We take into account **Klein-Nishina** effects for the anisotropic IC
  - Cooled electron population

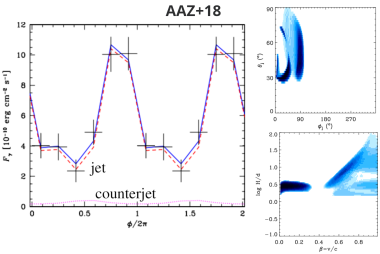


Figure: Modeling old γ-ray Cyg X-3 data (LC modulation) (credit: Zdziarski et al. (2018))

$\Rightarrow$ Much better constraints on the parameters of the system

Outline

Fermi-LAT γ-ray data of Cyg X-3

> **Data analysis**: D. Malyshev

- We analyze *Fermi*-LAT data of Cyg X-3 for MJD 57982 – 59533
- *Spectral analysis*: 0.05 – 500 GeV
- *Timing analysis*: 0.1 - 100 GeV
- Periodicity search: Lomb-Scargle periodogram gives $P_0 = 0.199684622(15)$ d. Full agreement with X-rays

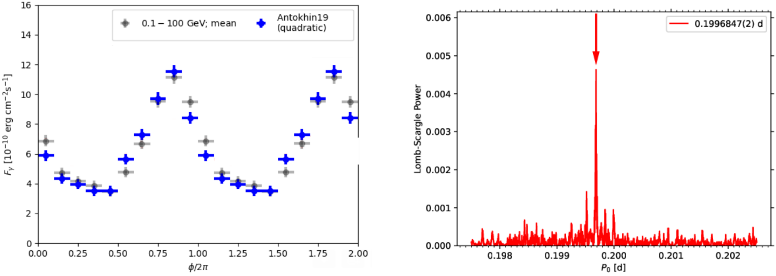


Figure: Left: folded phase LC of Cyg X-3 in γ-ray band based on new data. Right: The Lomb-Scargle analysis determining the modulation period. Credit: D. Malyshev

> **Modeling**: A. Dmytriiev

- **Inverse Compton on stellar photons**:

  Relativistic e^- in the jet Compton upscatter blackbody photons from the donor star to GeV energies (full KN angle-dependent cross-section!)

- **Electron spectrum**:

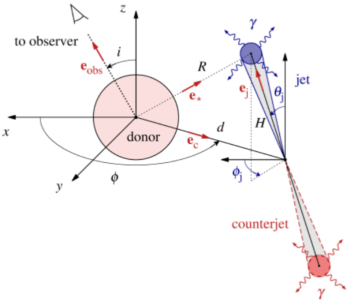
  1. **Power law** with a low- and high-energy cutoffs at γ_1 and γ_2

     $$N_e(\gamma) = K\gamma^{-p}$$

  2. **Cooled population**:

     – $N_e(\gamma) \propto \dot{\gamma}_{\rm cool}(\gamma) \propto \boldsymbol{\gamma}^{-2}$ for $\gamma_{\rm br} < \gamma < \gamma_1$ (radiative cooling)

     – $N_e(\gamma) \propto \boldsymbol{\gamma}^{-1}$ for $\gamma_{\rm min} < \gamma < \gamma_{\rm br}$ (adiabatic losses)



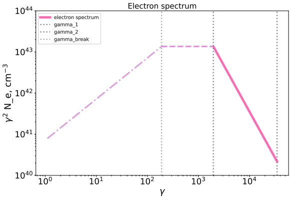


Figure: Top: geometry of anisotropic Compton scattering in Cyg X-3 (Credit: A.A. Zdziarski). Bottom: example of the electron spectrum.

Physical model for γ-ray emission

- Phase-dependent boosting of the stellar emission into the jet frame
- Phase-dependent (anisotropic) Compton scattering
- Boosting of IC emission into the observer frame (jet viewing angle)
- Strongest IC emission when electrons move towards the stellar photons

$\Rightarrow$ **Maximum of γ-rays when jet is behind the star**

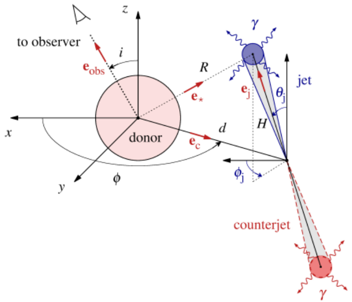


Figure: Geometry of anisotropic Compton scattering in Cyg X-3. Credit: A.A. Zdziarski

Modeling of *Fermi*-LAT γ-ray spectrum of Cyg X-3

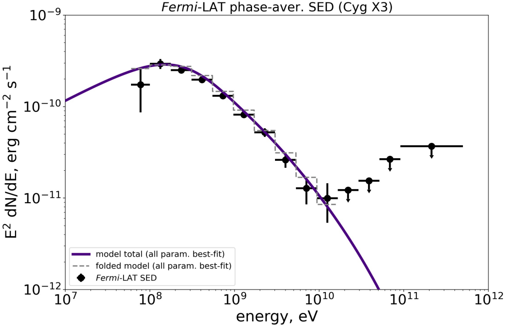
Fitting the phase-averaged SED

We determine

- Total e^- energy content $E_{\mathrm{e,tot}}$
- Spectral index $p = 4.1 \pm 0.1$
- Minimum Lorentz factor $\gamma_1 = 2700 \pm 400$
- Maximum Lorentz factor $\gamma_2 = (1.3 \pm 0.5) \times 10^5$

We assume/fix

- Temperature of the star $T_* = 10^5$ K
- Orbital separation $a = 2.66 \times 10^{11}$ cm
- Distance to Cyg X-3 $D_{\mathrm{sys}} = \mathbf{9}$ kpc (NEW!) (Reid & Miller-Jones (2023))

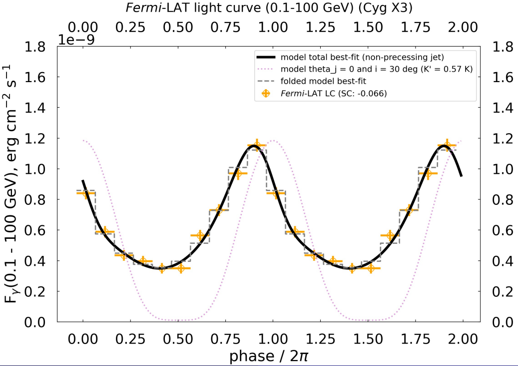


Fitting the phase modulation LC

We determine

- Distance to emitting region along the jet
  $H \approx (1.4 \pm 0.1) \cdot a \sim 10^6 R_g$
- **Jet inclination angle** $\theta_\mathrm{j} = (28 \pm 5)^\circ$
- Jet azimuthal angle $\phi_\mathrm{j} = (194 \pm 3)^\circ$

- Inclination of the system
  $i = (18 \pm 2)^\circ$
- Jet velocity
  $\beta_\mathrm{j} = 0.6 \pm 0.06$
  → relatively slow jet

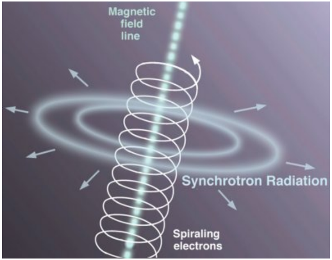


Jet viewing angle: $\boldsymbol{i_\mathrm{j} = 12^\circ}$
compatible with other constraints

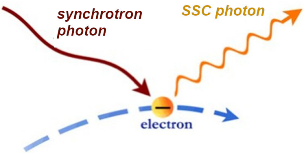
Constraining the magnetic field in the γ-ray emitting zone

We include magnetic field of the jet in the model

- Synchrotron emission (+ self absorption) (radio to X-ray)
- Synchrotron self-Compton (SSC) emission (FULL Klein-Nishina) (X-ray to γ-ray)
- Total γ-ray emission:
  IC on stellar photons + SSC
- Emitting region: cylinder with height $Z \approx (1/3)H$, radius $R = \alpha_{\mathrm{oa,j}} H$
- Jet opening angle $\alpha_{\mathrm{oa,j}}$: **1°** and **5°**
  (Miller-Jones, Fender & Nakar (2006))



SSC process



Constraining the magnetic field in the γ-ray emitting zone

Previous constraint: $B < 100$ G (Zdziarski et al. (2012))

(*only spectra, no LC, no fitting)

Available constraints from data:

- **Submillimeter array (SMA)**: $< F >$ (225 GHz) $\approx$ 300 mJy
  (M. McCollough, private communication)
- **Infrared (IR)**: $F(4.5\mu m) \approx 80$ mJy, $F(11.5\mu m) \approx 70$ mJy (AAZ+12)
- **X-ray**: $F(100$ keV$) \approx 1/2 \times 0.1$ keV cm^{-2} s^{-1} (AAZ+12)
- **γ-ray**: LC minimum flux $F_{\rm LC,min} \approx 3.5 \times 10^{-10}$ erg cm^{-2} s^{-1}
  $\Rightarrow$ **maximum SSC flux**

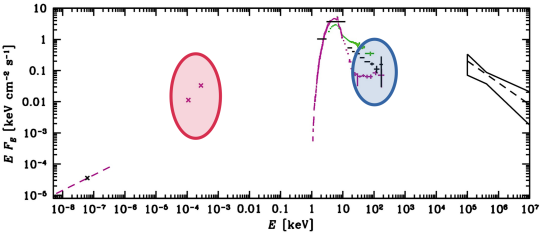


Figure: Available MWL measurements for Cyg X-3 during 2008 and 2009 γ-ray active periods (credit: AAZ+12)

Constraining the magnetic field in the γ-ray emitting zone

We derive:

$\boldsymbol{B < 18}$ **G**, for $\alpha_{\rm oa,j} = 1^\circ$

$\boldsymbol{B < 90}$ **G**, for $\alpha_{\rm oa,j} = 5^\circ$

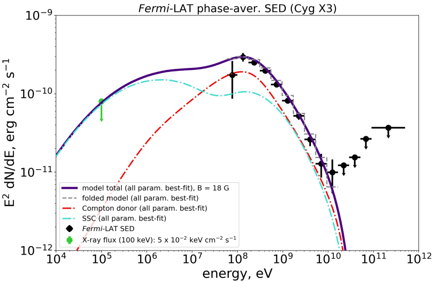
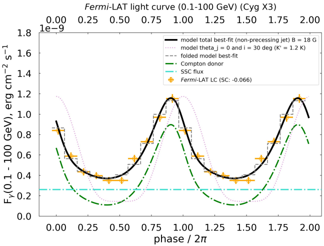


Figure: SED fit. Jet opening angle: 1°, B=18 G



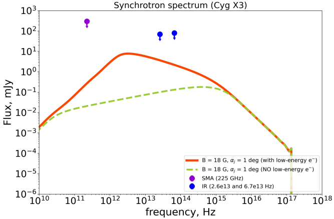


Figure: LC fit and synchrotron emission. Jet opening angle: 1°, B=18 G

Outline

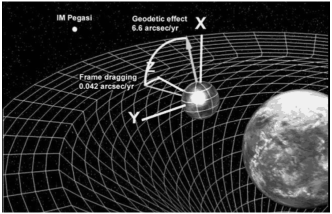
We find evidence of jet misalignment wrt orbital axis. In this situation, the jet should precess due to the effects of **general relativity (GR)**

Precession: **de Sitter** (presence of central mass) and **Lense-Thirring** (rotation of central mass) effect

De Sitter effect dominates in our case. Period of precession for a binary system (Barker & O'Connel 75; Apostolatos+94):

$$P_{\rm prec} = \frac{c^2(M_* + M_{\rm c})^{4/3} P^{5/3}}{(2\pi G)^{2/3}(2 + (3M_*)/(2M_{\rm c}))M_* M_{\rm c}} \quad (1)$$

For Cyg X-3 with $P = 0.2$ d, we get $P_{\rm prec} \approx 50$ yr



(1) Over $P_{\rm prec} \approx 50$ yr, $\phi_{\rm j}$ will change by 360°

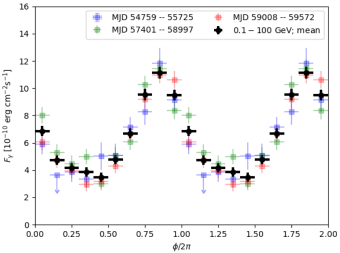
Evolving jet orientation → peak of the modulation moves around.

We see NO variations in the modulation over 5000 d of *Fermi*-LAT monitoring.

(2) Jet precession → jet position angle evolution (angle difference between the projection of the jet and the orbital axis in the plane of the sky)

We see NO changes of this angle in radio data spanning 30 yr.

⇒ **Jet not aligned with the spin axis of the compact object?**



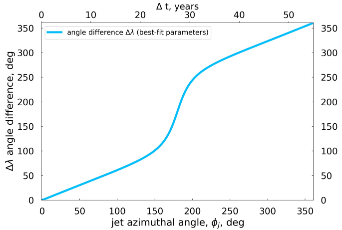


Figure: Top: comparison of γ-ray modulation over different time intervals (credit: D. Malyshev). Bottom: predicted projection angle evolution over 50 years due to jet precession (A. Dmytriiev).

Effect of the stellar wind and Coriolis force

WR star has an intense **stellar wind**, which may lead to the **outward bending** of the jet (Yoon & Heinz 2015; Bosch-Ramon & Barkov 2016).

On top of that, due to orbital rotation, **Coriolis force** may induce **lateral jet bending**.

→ Jet precession at the orbital period (0.2 d)

This can explain X-ray polarization modulation at the orbital period

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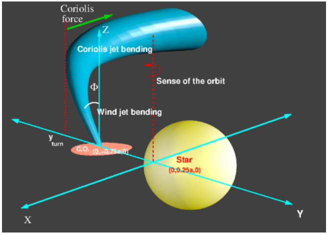
We model the jet bending as:

$$\phi_\mathrm{j} = \phi + \Delta$$

where ϕ is orbital phase and Δ is a Coriolis jet bending angle (fit parameter)



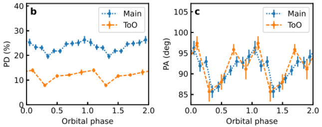


Figure: Top: Illustration of a simulated scenario of jet bending due to wind thrust and Coriolis force in a binary system. Credit: Barkov & Bosch-Ramon (2022). Bottom: X-ray polarization modulation measurements (Veledina+23).

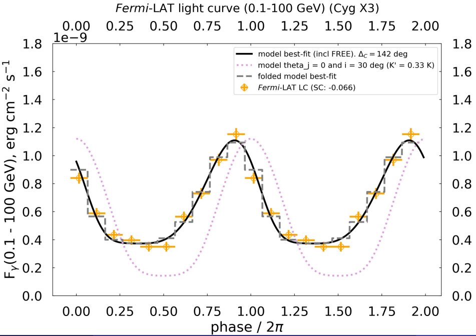
Fitting the phase modulation LC for the bent jet model

We determine

- Distance to emitting region along the jet $H \approx (2.3 \pm 0.3) \cdot a$
- **Jet inclination angle** $\theta_\mathrm{j} = (22 \pm 4)^\circ$
- Coriolis bending angle $\Delta = (142 \pm 3)^\circ$

- Inclination of the system $i = (17 \pm 3)^\circ$
- Jet velocity $\beta_\mathrm{j} = 0.45 \pm 0.19$
  → slow jet

Average jet viewing angle: 27° – problematic



Outline

Summary

- γ-ray emission from Cyg X-3 is compatible with anisotropic Compton scenario (in KN regime) with a PL electron spectrum
- The **jet** has to be **inclined** wrt to the orbital axis
- Substantially tighter constraints on the parameters of the system
- We DO NOT observe a 50 yr **precession** period in γ-ray and radio data: **jet has to be launched off the spin axis**
- We disfavor a scenario with a precessing **jet bent** by the thrust of the stellar wind and the Coriolis force
- Significantly improved constraints on the **magnetic field** in the γ-ray production region:

$$\boldsymbol{B < 18\ \mathrm{G}} \quad (\alpha_{\mathrm{oa,j}} = 1^\circ) \quad \text{and} \quad \boldsymbol{B < 90\ \mathrm{G}} \quad (\alpha_{\mathrm{oa,j}} = 5^\circ)$$

ApJ Letters paper in preparation ! ...

Thank you for your attention!

Back-up slides

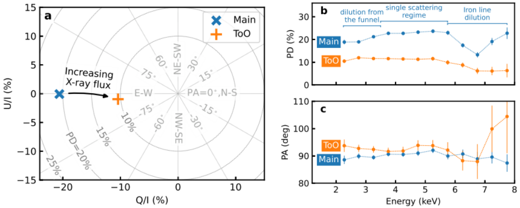


Figure: Orbital-phase averaged polarization properties of Cyg X-3 as measured by IXPE (credit: Veledina+23)

IXPE revealed strong ($\sim$ 25 %) X-ray polarization (Veledina+23):

$\Rightarrow$ The central source is obscured, and we only see X-rays reflected from the inner surface of a narrow *accretion funnel*

The accretion is **super-Eddington** $\rightarrow$ Cyg X-3 is a superluminous X-ray source. The funnel is aligned with the radio jet.

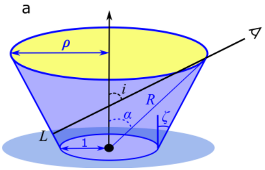


Figure: A schematic representation of the accretion funnel (credit: Veledina+23)