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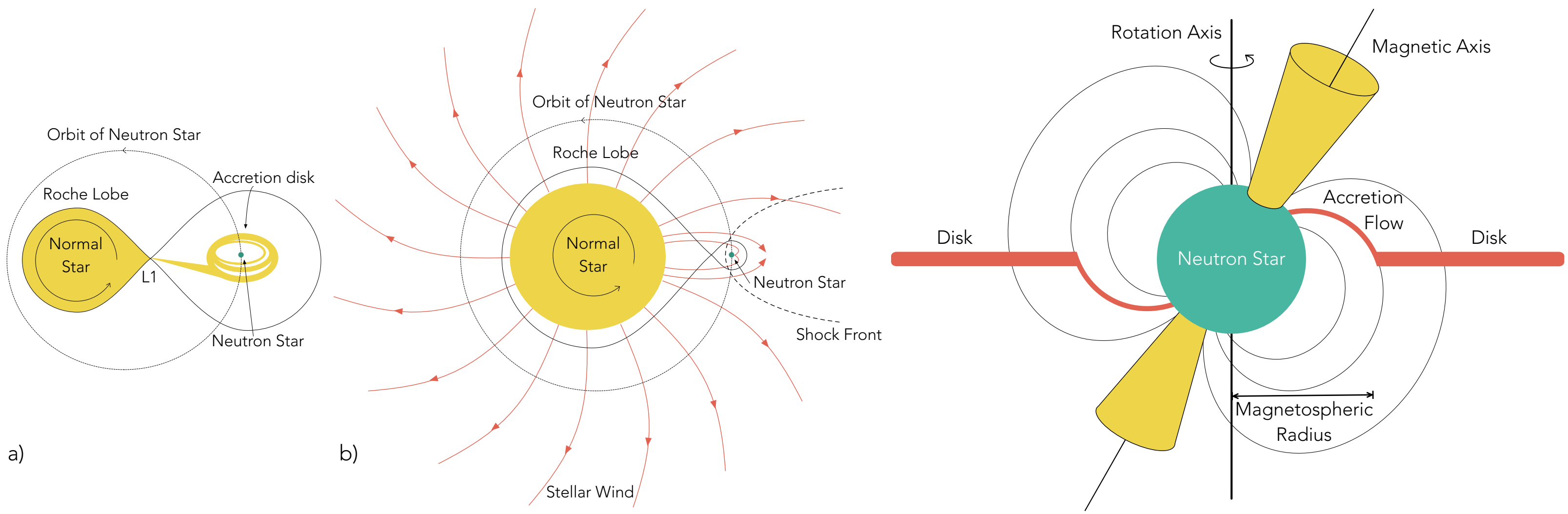


Exploring Time Variability Properties of X-ray Pulsars through Accretion Torque Models

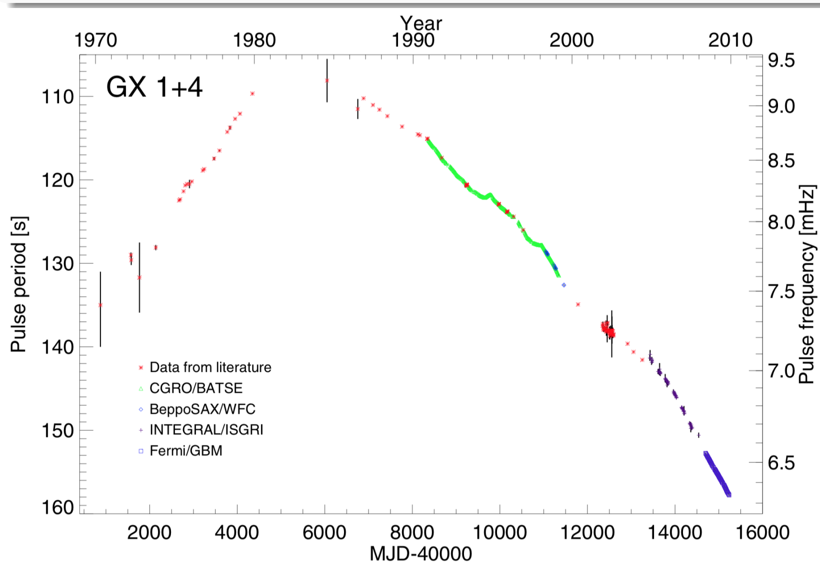
Advisors:
Dr. Lorenzo Ducci, Prof. Dott. Andrea Santangelo

HEA Group Meeting | April 26, 2019 | Inga Saathoff

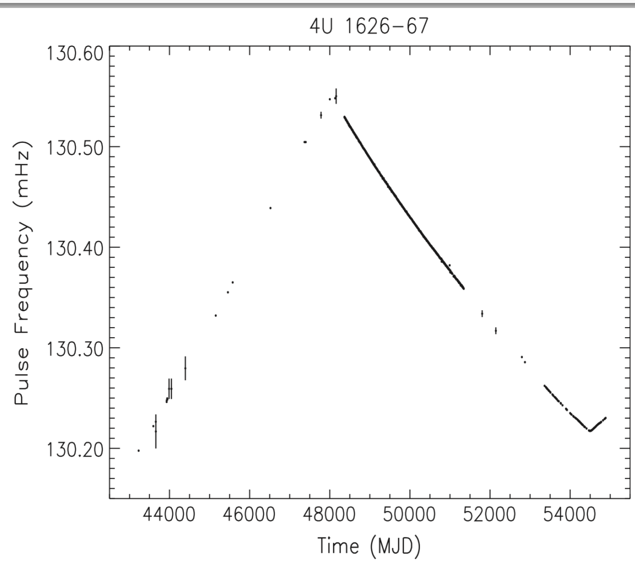
Motivation

Observations & Models: Accreting X-ray Pulsars

- Spin reversals (e.g. in GX 1+4, 4U 1626-67 and OAO 1657-415)



Gonzáles-Galán et al. 2012



Camero-Arranz et al. 2010

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Observations & Models: Accreting X-ray Pulsars

- Spin reversals (e.g. in GX 1+4, 4U 1626-67 and OAO 1657-415)
- Models don't account for these reversals, need fine tuning or pose other problems

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Observations & Models: Accreting X-ray Pulsars

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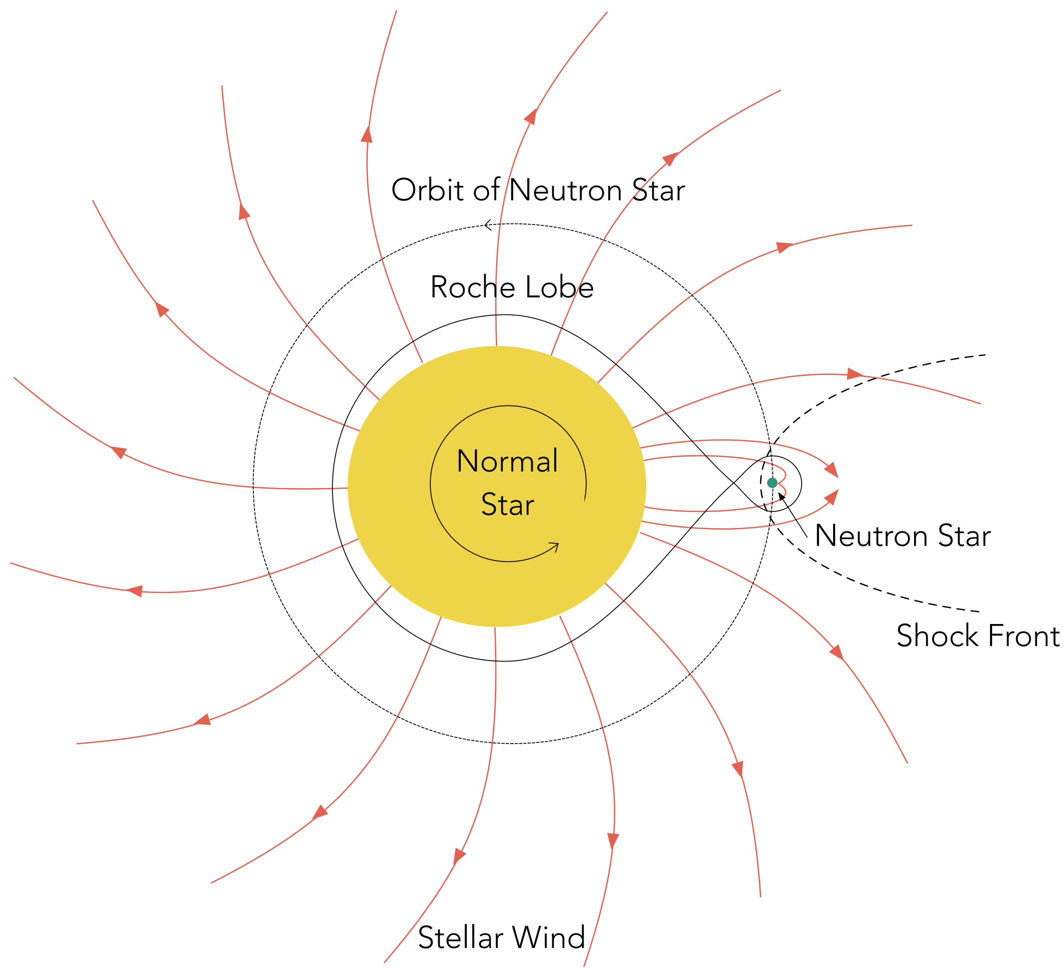
$\Downarrow$

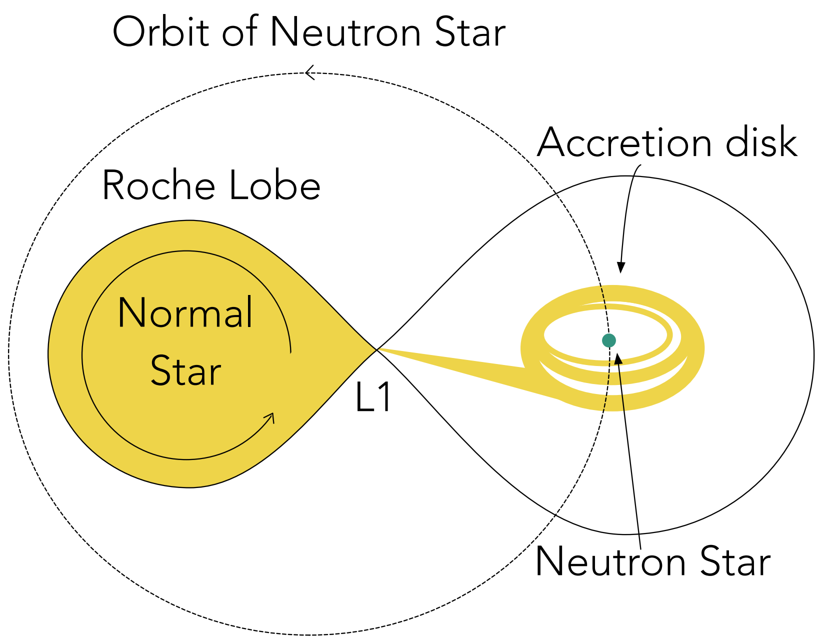
Study the Pulsar in OAO 1657-415

- Investigate if an inclined rotator model can explain the observations in this particular pulsar.
- Examine over 10 years of data from *Fermi*/GBM and *Swift*/BAT to increase the understanding of this source.

Accretion Mechanisms and Classification of XRBs



Accretion Mechanisms and Classification of XRBs



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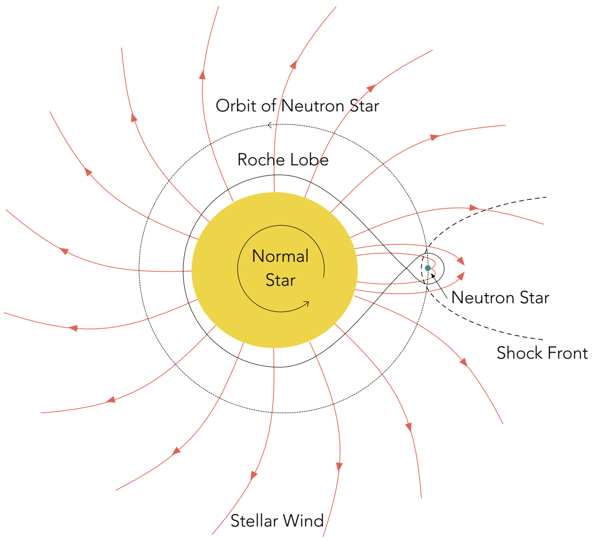

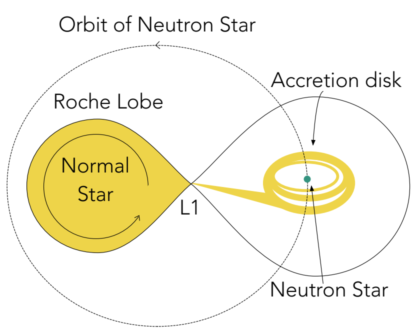

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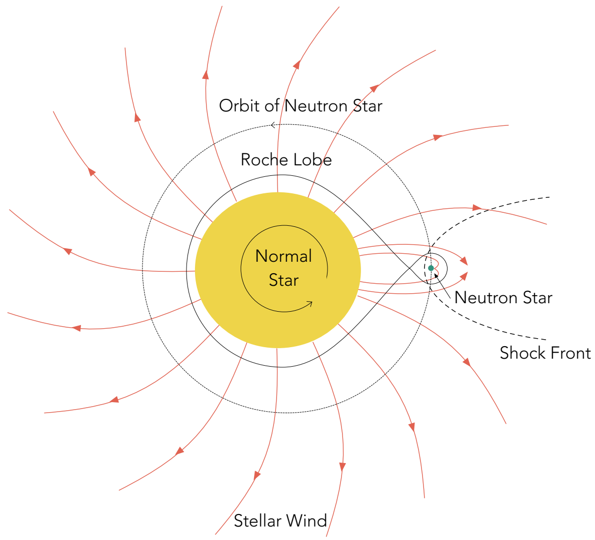
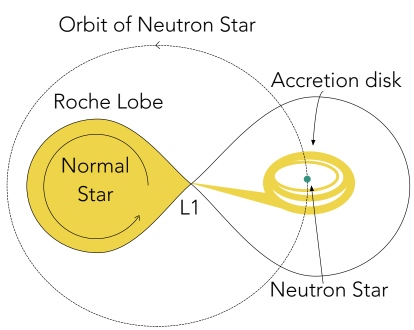
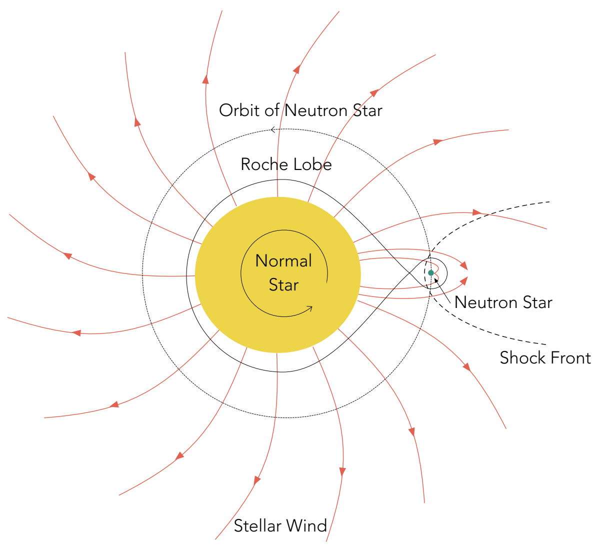


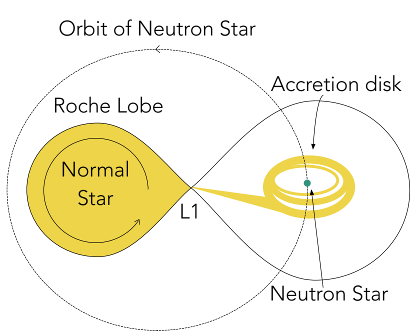


High Mass X-ray Binaries (HMXBs)

- Compact object: Neutron Star, White Dwarf or Black Hole
- Companion: Early type star (O-B) with $M > 5\,M_\odot$
- Strong magnetic field ($\sim 10^{12}$ G)

Accretion Mechanisms and Classification of XRBs





High Mass X-ray Binaries (HMXBs)

- Compact object: Neutron Star, White Dwarf or Black Hole
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- Strong magnetic field ($\sim 10^{12}$ G)

Low Mass X-ray Binaries (LMXBs)

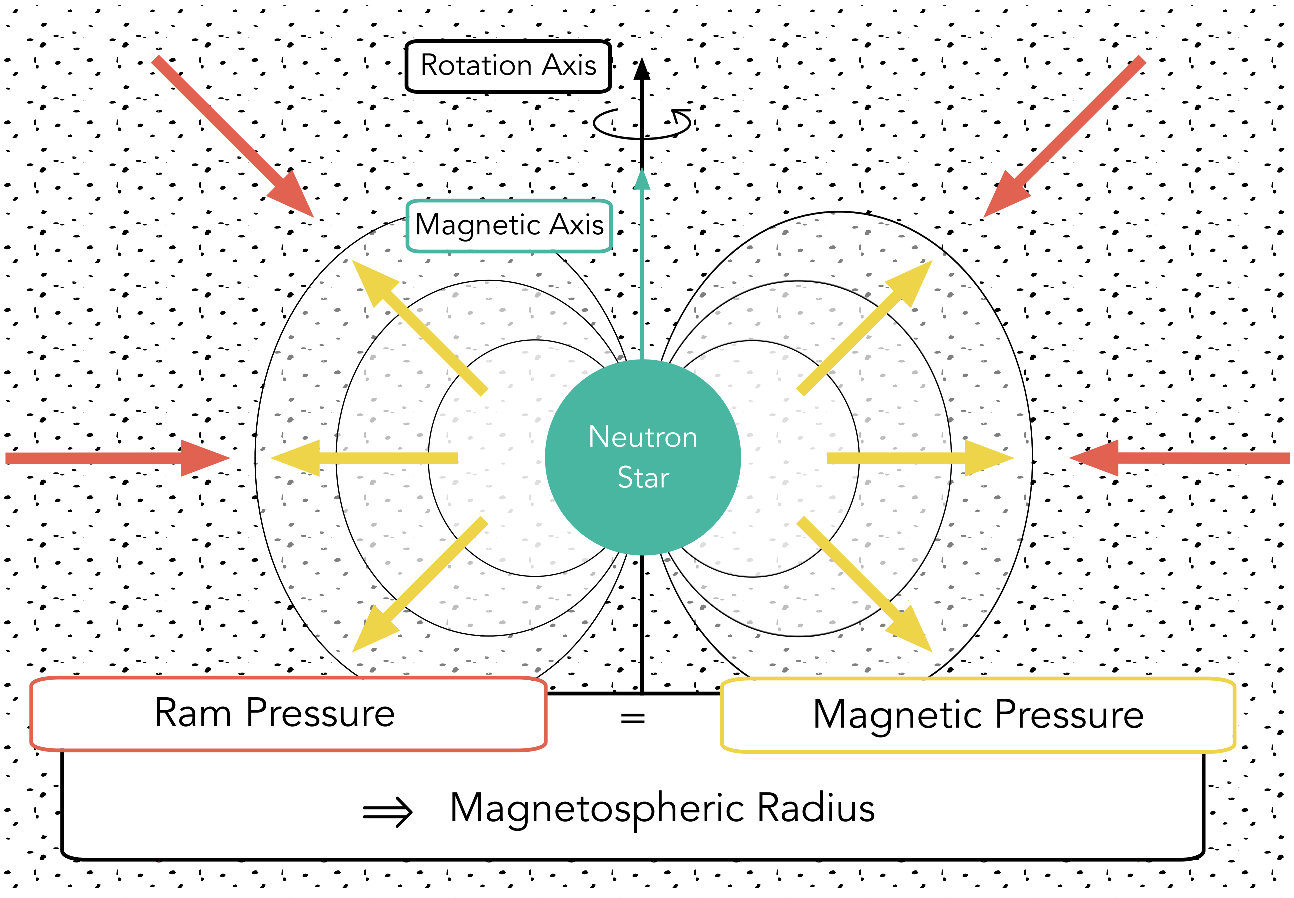
- Compact object: Neutron Star or Black Hole
- Companion: Late type star (M-K) with $M < 1\ M\odot$
- Low magnetic field ($\sim 10^{9}$ G)

Characteristic Radii

- Corotation Radius: The radius, where the Keplerian frequency of the orbiting matter is equal to the NS spin frequency Ω_0:

$$R_{\text{co}} = \left(\frac{GM}{\Omega_0^2} \right)^{1/3}$$

Characteristic Radii



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- Magnetospheric Radius: $(B \approx \mu/r^3)$

$$\frac{1}{2}\rho v_{\mathrm{ff}}^2 = \frac{B^2}{8\pi}$$

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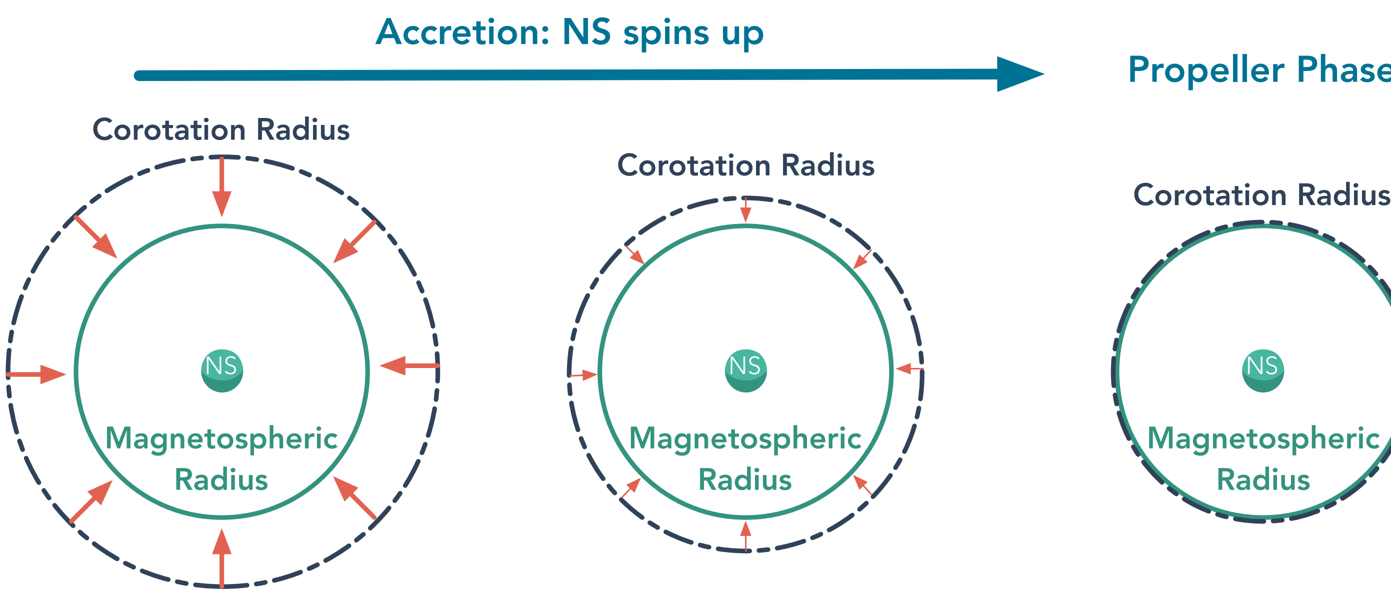
If $R_{\text{M}} < R_{\text{co}}$, matter can be accreted.
If $R_{\text{M}} > R_{\text{co}}$, matter is propelled away.

Models: Early Works

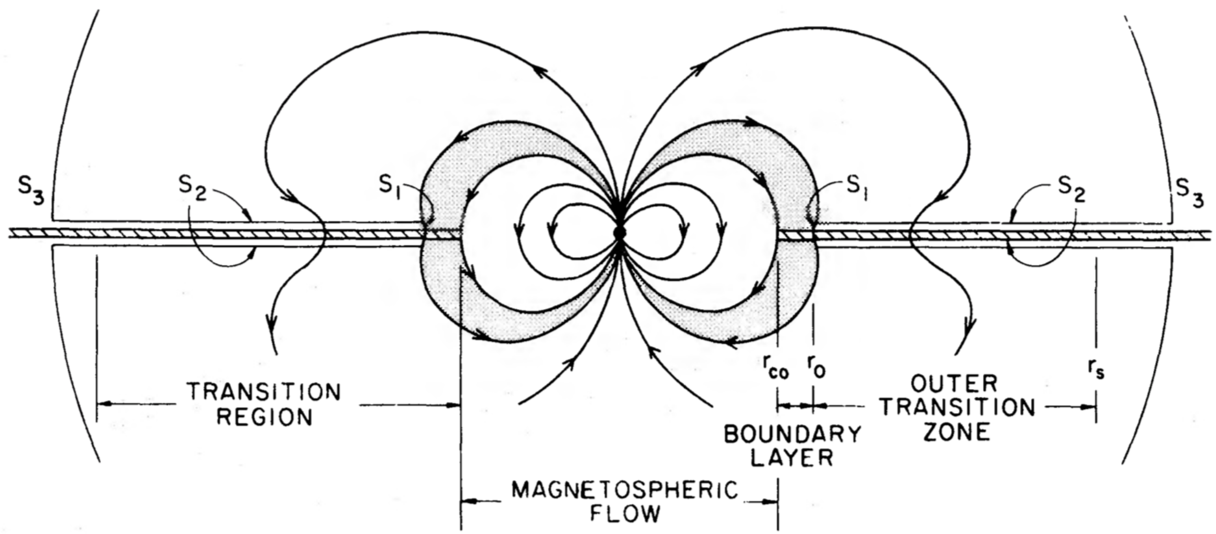
Angular momentum transferred by accreting matter from the disk to the star through the magnetosphere-disk interaction
$\rightarrow$ NS spins up.

Reminder: $R_{co} \propto \Omega_0^{-2/3}$



$\Rightarrow$ Does not account for observed spin-reversals!

Models: Ghosh & Lamb 1978, 1979a,b



Ghosh & Lamb 1979

The interaction between the magnetosphere and the disk can be divided into:

- Boundary Layer: material torque
- Transition Region: toroidal component of the magnetic field

Models: Ghosh & Lamb 1978, 1979a,b

$$-\dot{P} = 5 \times 10^{-5} \mu_{30}^{2/7} n(\omega_s) S_1(M) (P L_{37}^{3/7})^2 \,\mathrm{s\,yr^{-1}}$$

$$\omega_s = 1.35\, \mu_{30}^{6/7} S_2(M) (P L_{37}^{3/7})^2 \,\mathrm{s\,yr^{-1}}$$

$$S_1(M) = R_6^{6/7} (M/M_\odot)^{-3/7} I_{45}^{-1}$$

$$S_2(M) = R_6^{-3/7} (M/M_\odot)^{-2/7}$$

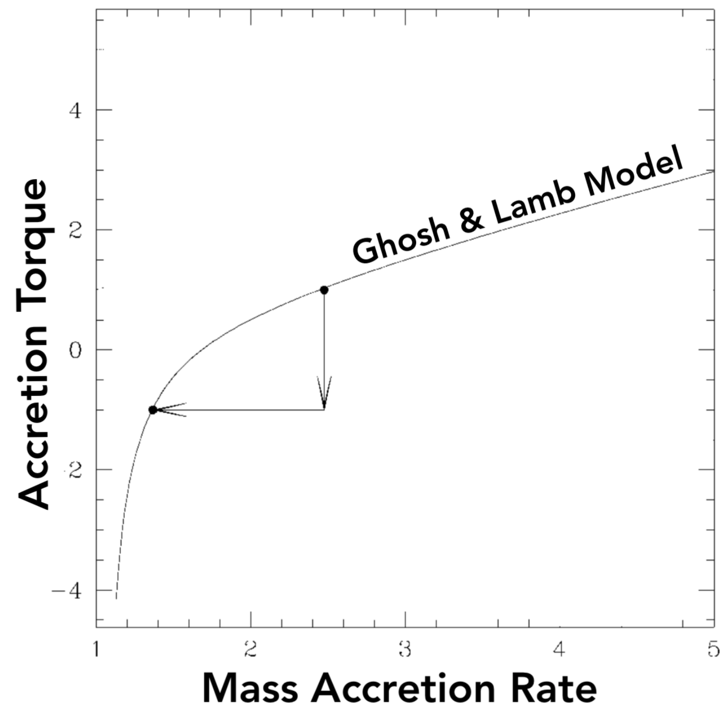
Models: Ghosh & Lamb 1978, 1979a,b

$$N = n(\omega)\dot{M}\sqrt{GMR_{\mathrm{M}}}$$
$$\omega \propto \dot{M}^{-3/7}$$
$$R_{\mathrm{M}} \propto \dot{M}^{-2/7}$$

- Torque is a function of $\dot{M}$
- Smooth and monotonically increasing

$\Rightarrow$ Spin reversals with $\dot{\nu}$ of the same magnitude but opposite sign requires fine tuning!

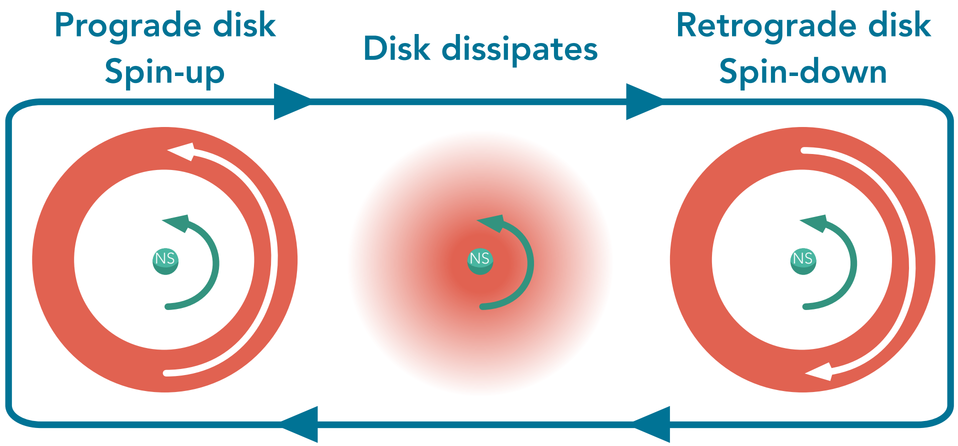
$\Rightarrow$ In spin-down, L is expected to be low $\lightning$ observations



Nelson 1997

Models: Retrograde Accretion Disk

- In GL model: correlation between torque and luminosity during spin-up; no anti-correlation during spin-down.

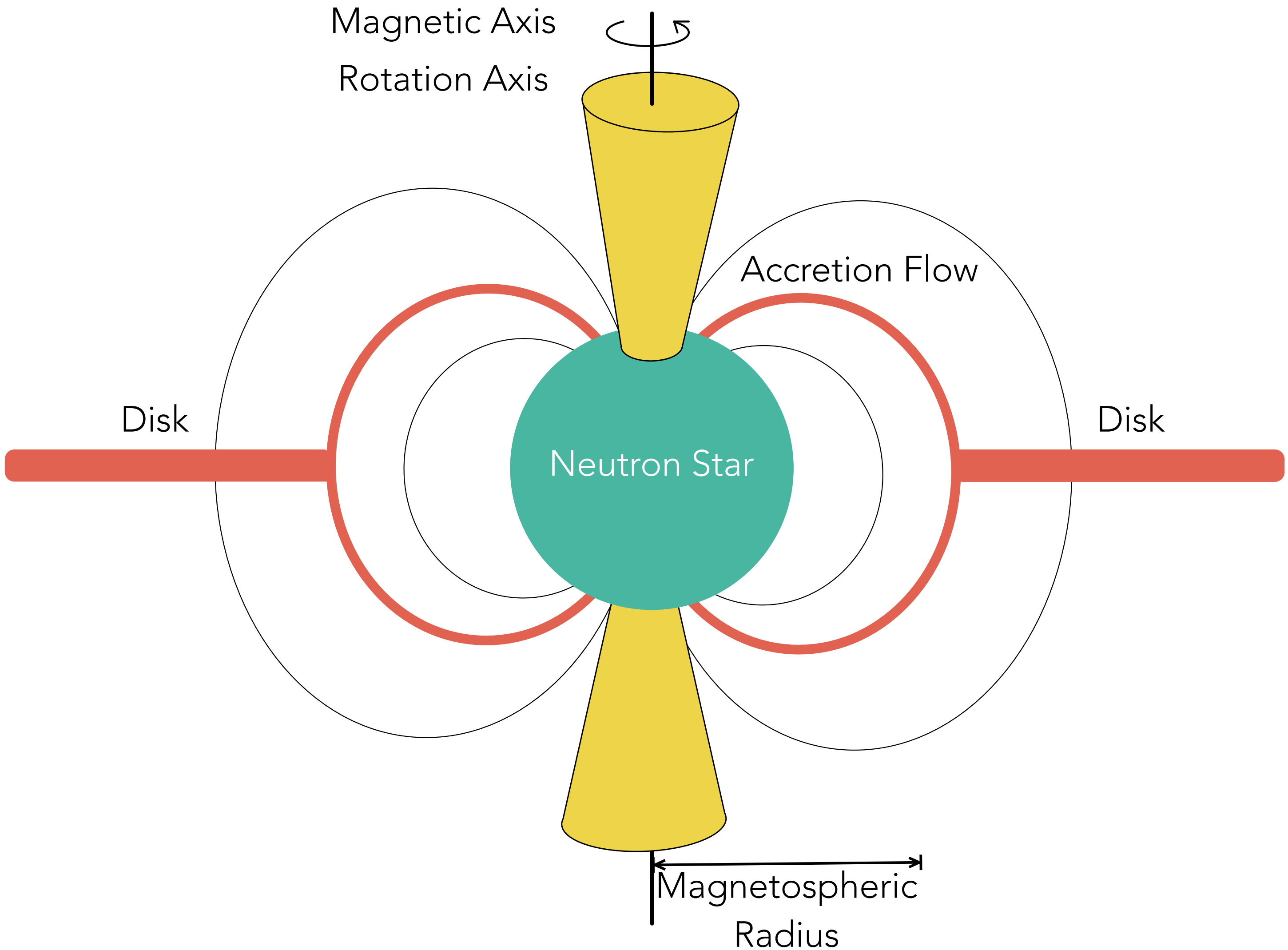


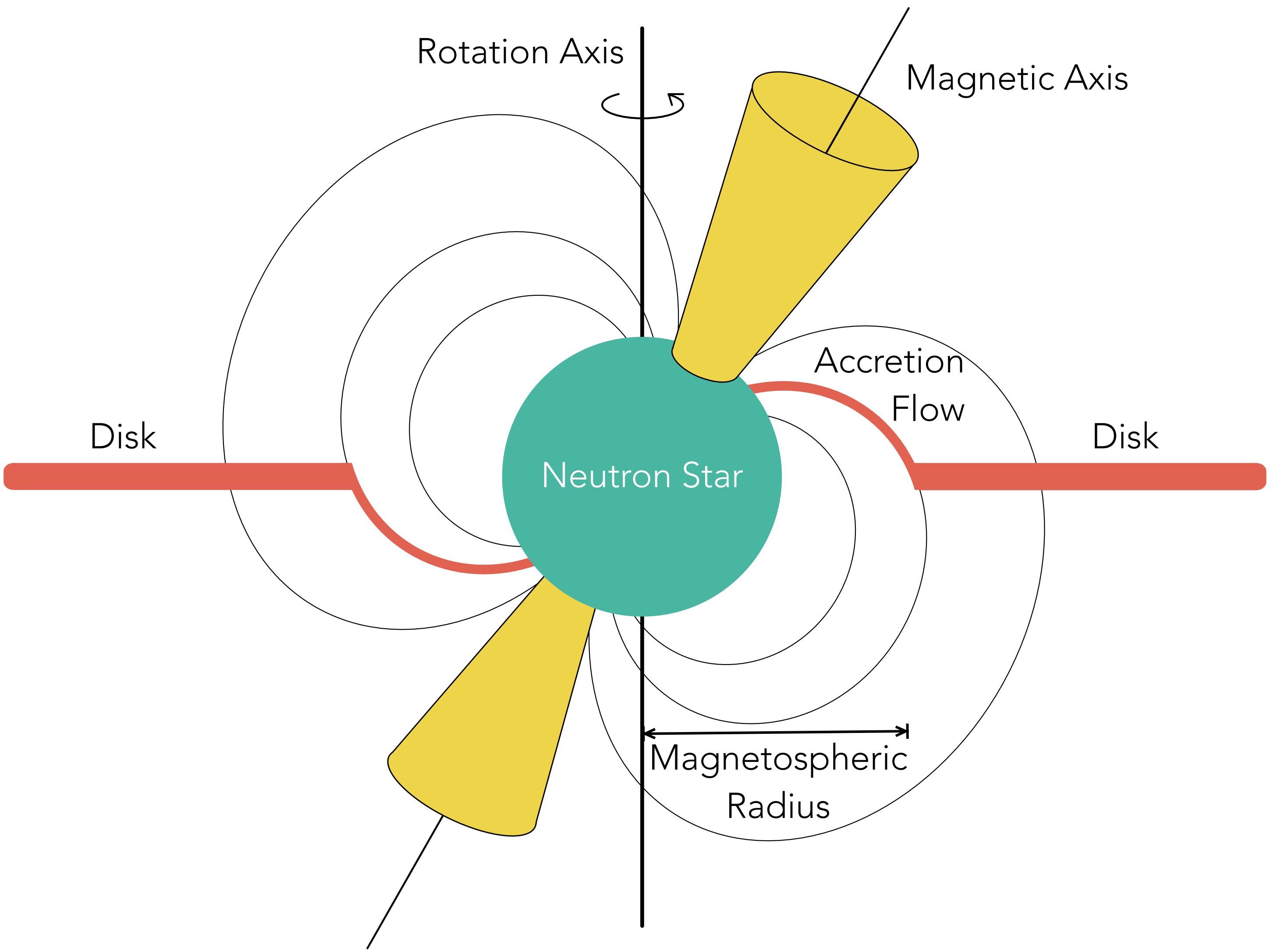
- Hydrodynamic calculations showed that a retrograde-rotating disk can form in wind-fed systems
  $\rightarrow$ NS spins down (negative accreted angular momentum).
- Chakrabarty et al. (1997) found anti-correlation in GX 1+4
  $\rightarrow$ indication for retrograde accretion disk.

Aims

Study the Inclined Rotator Model (Perna et al. 2006):

- Explore the model and investigate the influence of different parameters (B, χ, β).
- Introduce a new component to obtain a long-term spin-up or spin-down, which is superposed on the cyclic spin reversals.
- Apply the model to the X-ray pulsar in OAO 1657-415 to constrain some of the parameters.


Magnetic Axis
Rotation Axis
Accretion Flow
Disk
Neutron Star
Disk
Magnetospheric
Radius


Rotation Axis
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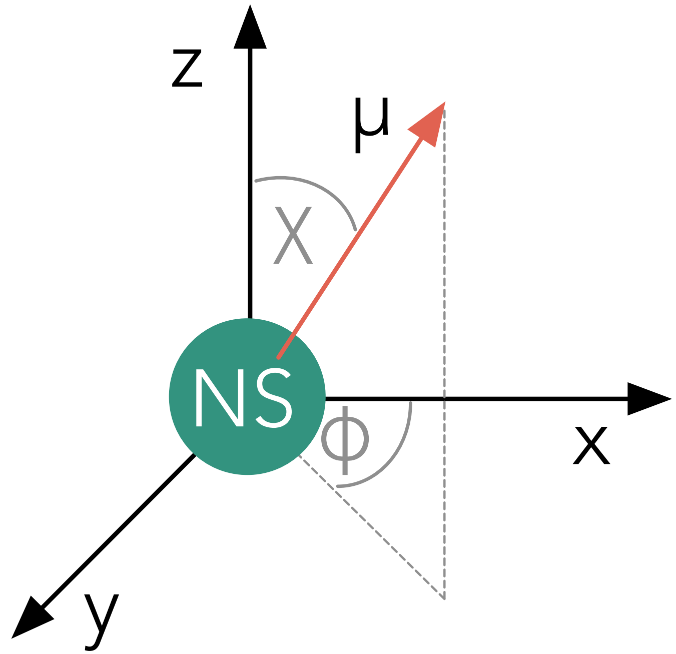
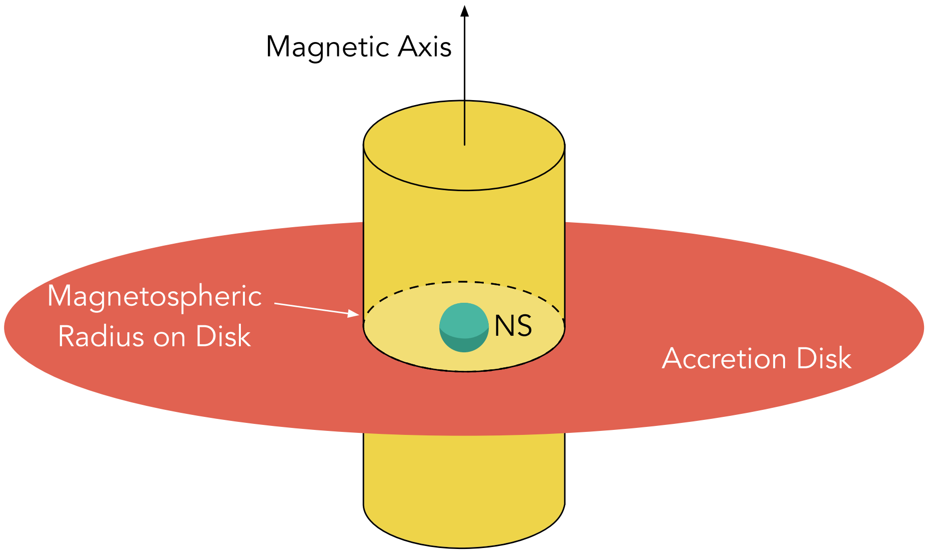
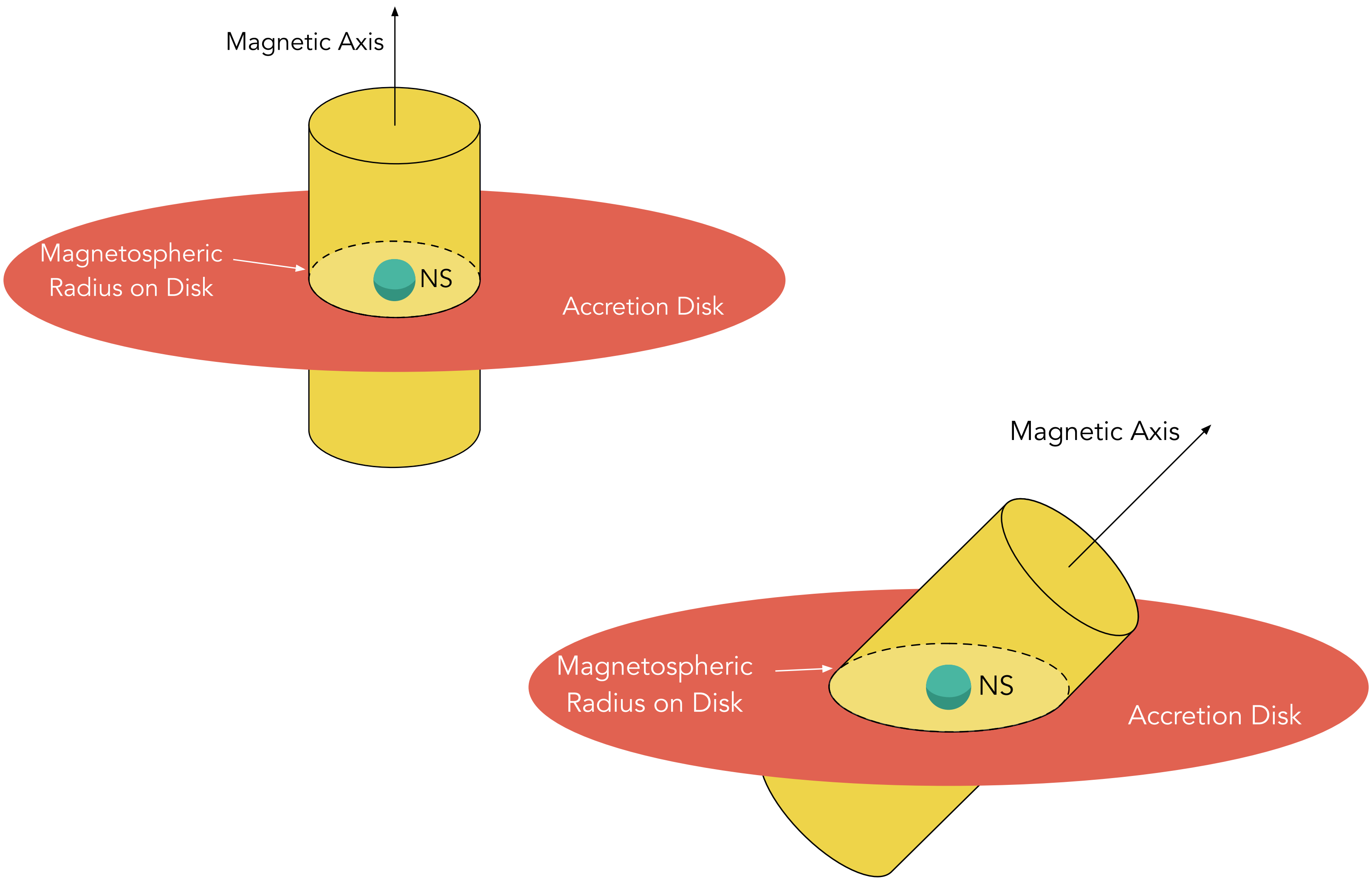
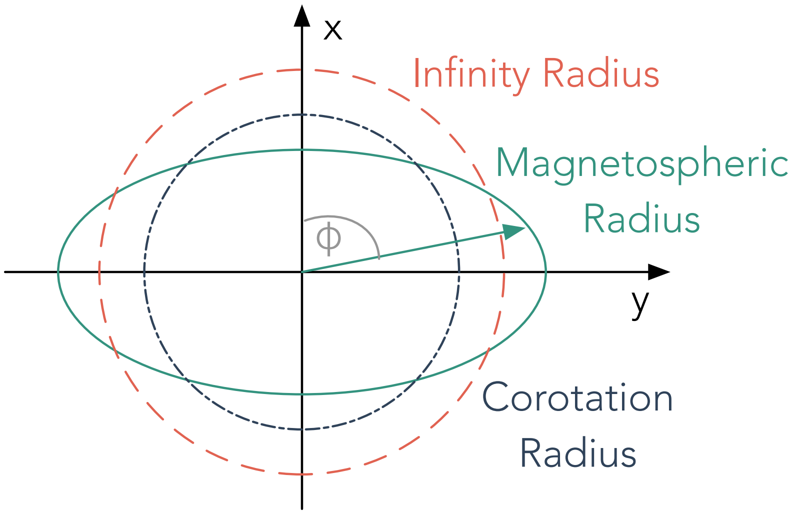
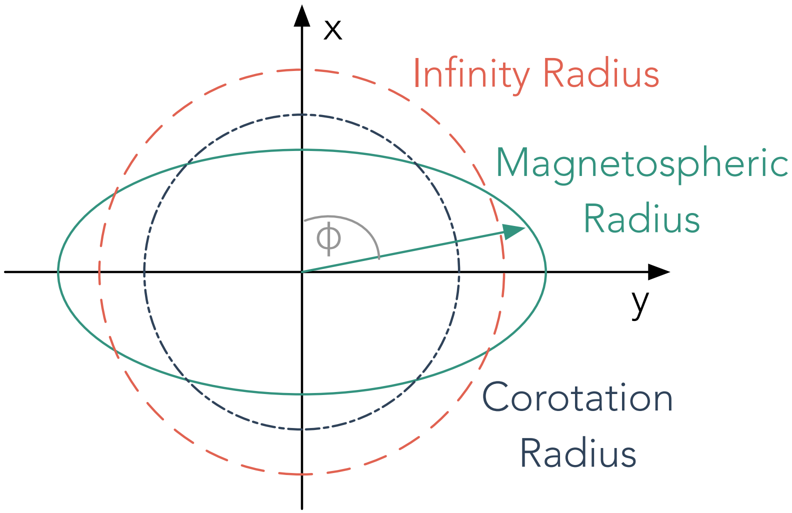


$$B^2 = \frac{\mu^2}{r^6}[1 + 3(\sin\chi\sin\phi)^2]$$

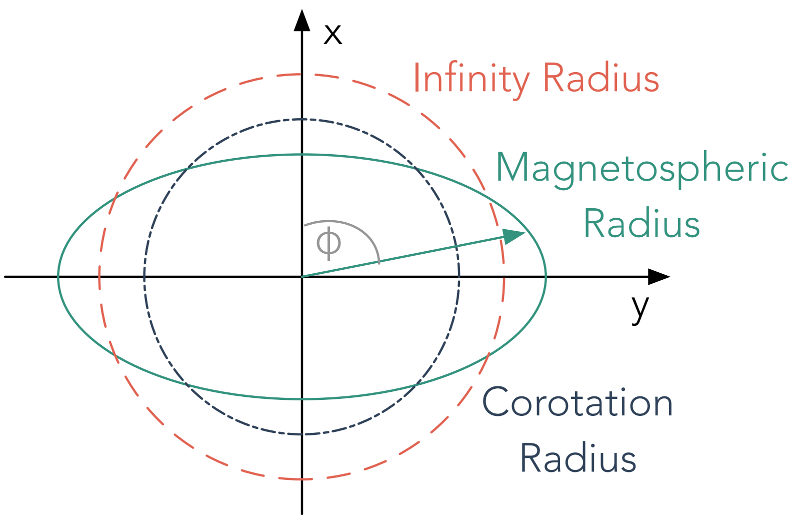

Magnetic Axis
Magnetospheric
Radius on Disk
NS
Accretion Disk


Magnetic Axis
Magnetospheric Radius on Disk
NS
Accretion Disk
Magnetic Axis
Magnetospheric Radius on Disk
NS
Accretion Disk


x
Infinity Radius
Magnetospheric
Radius
ϕ
y
Corotation
Radius



$$R_M(\phi) = 3.2 \times 10^8 \mu_{30}^{4/7} M_1^{-1/7} \dot{M}_{17}^{-2/7} [1 + 3(\sin\chi \sin\phi)^2]^{2/7}\,\mathrm{cm}$$



- $R_M(\phi) < R_{co}$: accretion
- $R_{co} < R_M(\phi) < R_{inf}$: recycling
- $R_M(\phi) > R_{inf}$: ejection

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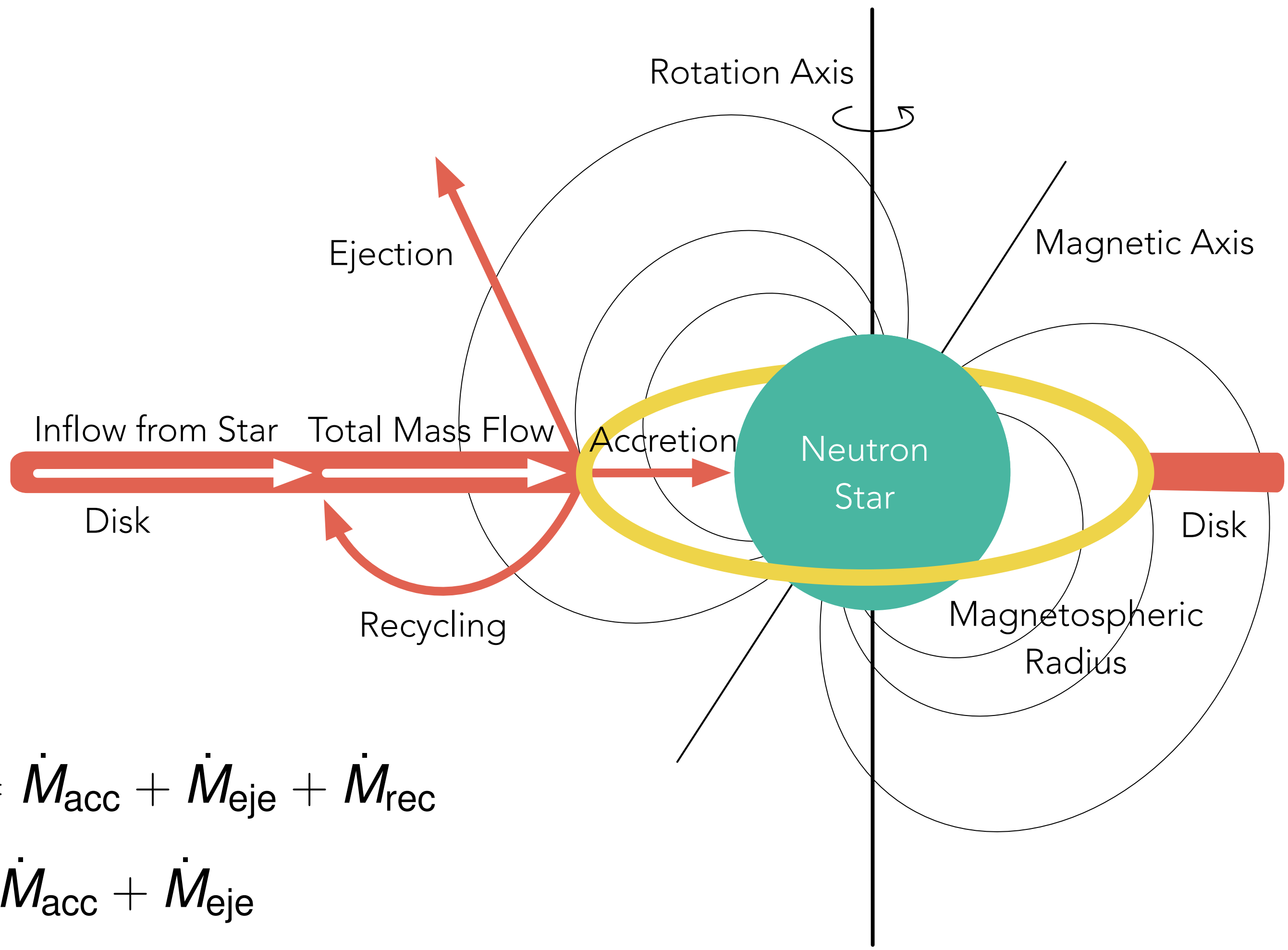
Contributions to $\dot{M}_{\text{tot}}$



$$\dot{M}_{\text{tot}} = \dot{M}_{\text{acc}} + \dot{M}_{\text{eje}} + \dot{M}_{\text{rec}}$$

$$\dot{M}_{*} = \dot{M}_{\text{acc}} + \dot{M}_{\text{eje}}$$

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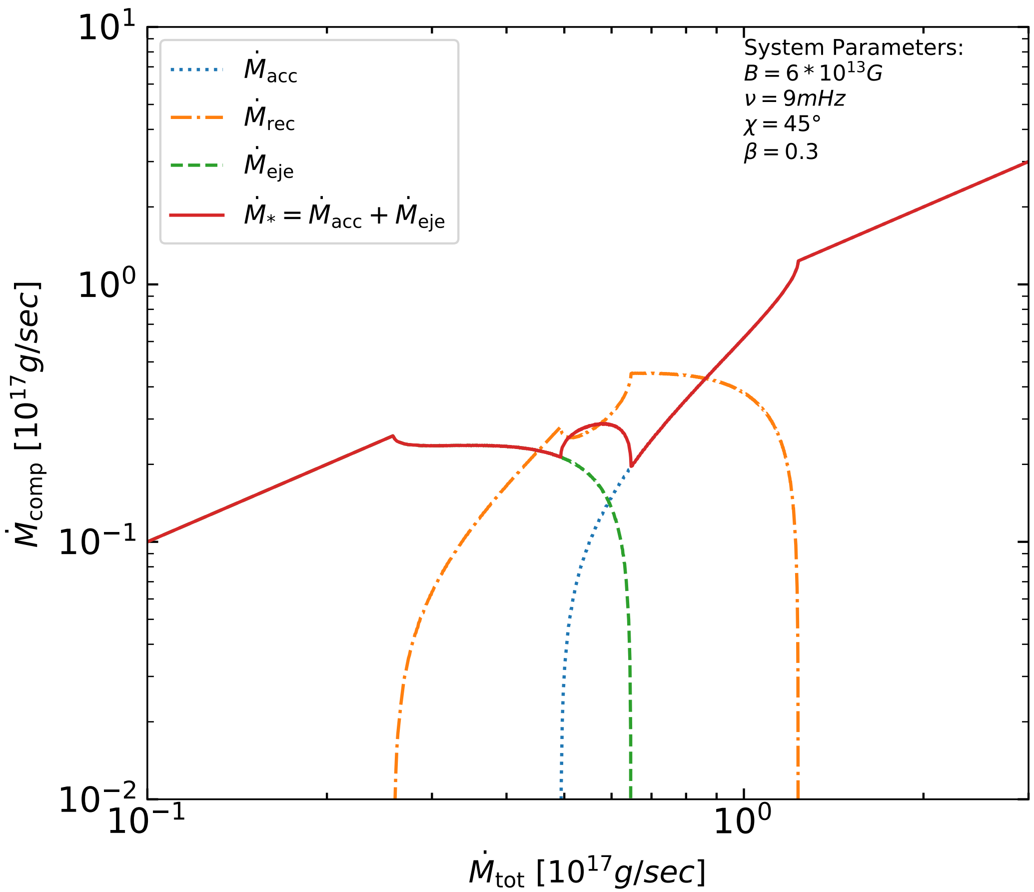
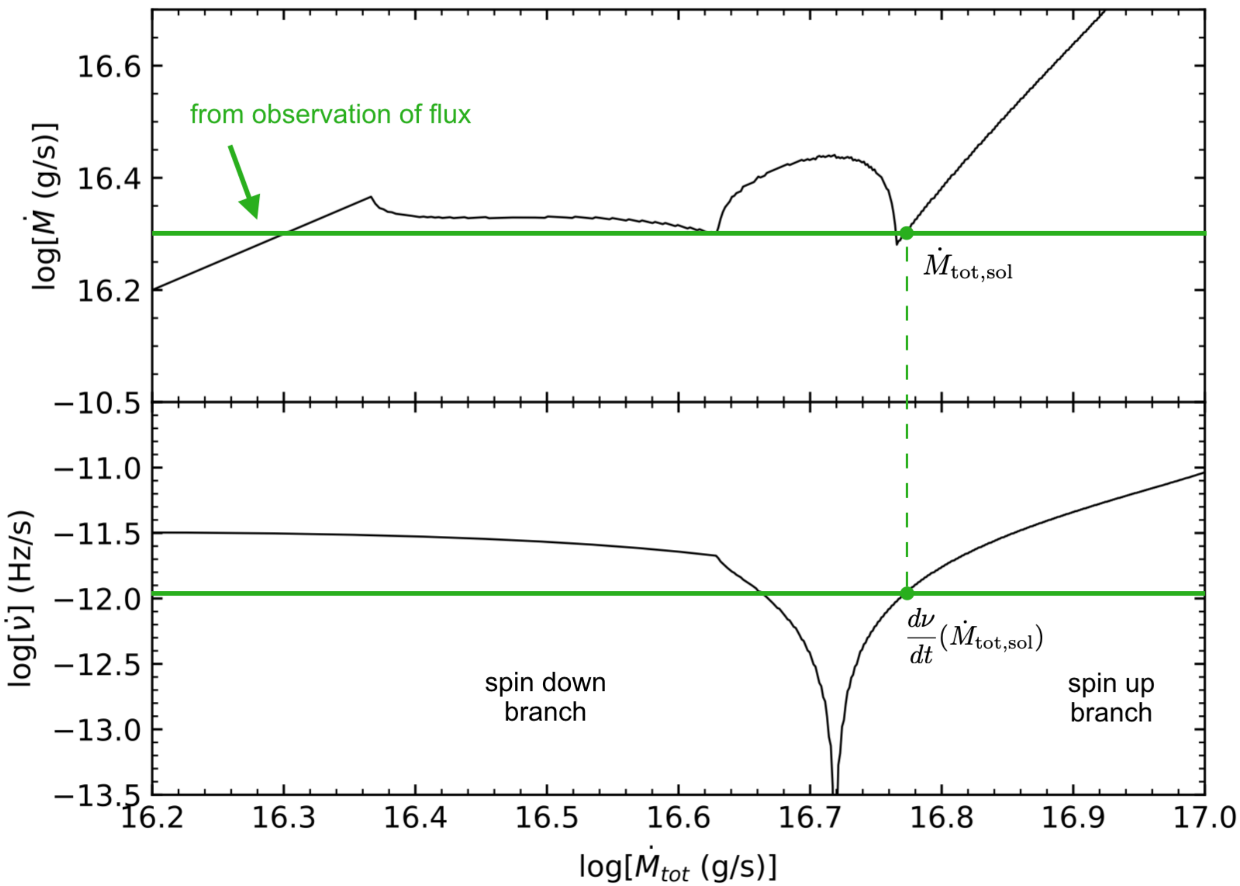


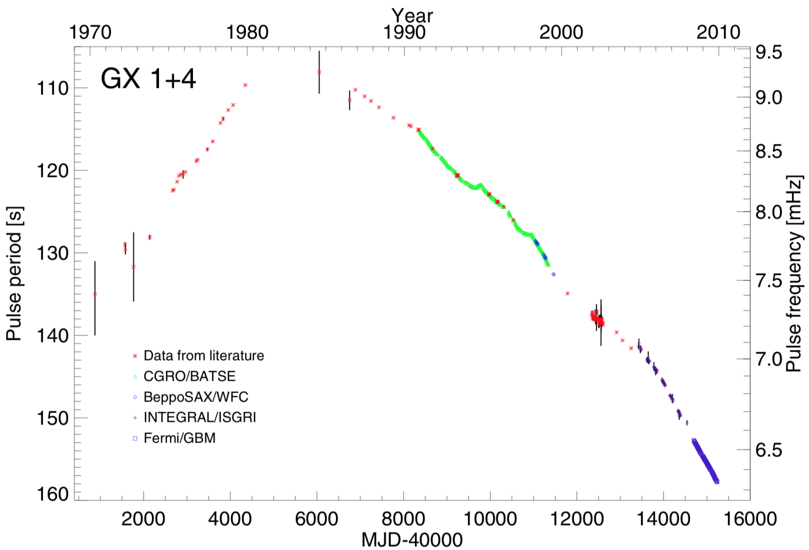
Hysteresis Limit Cycle

$$L_X = GM\dot{M}/R = 4\pi d^2 F_X$$

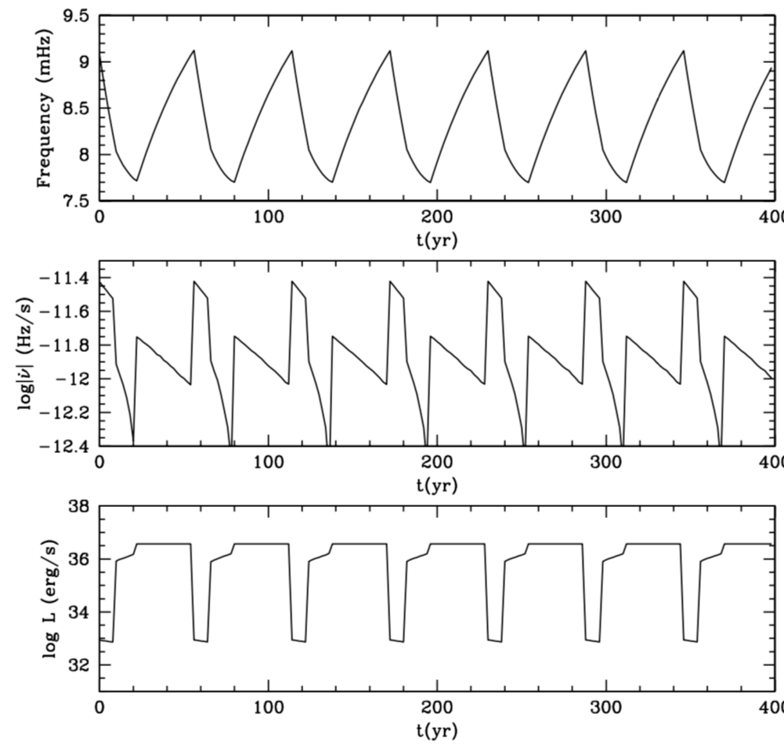
$$\nu(t+dt) = \nu(t) + \frac{d\nu}{dt}(\dot{M}_{\text{tot, sol}})$$



Time Evolution: GX 1+4



Gonzáles-Galán et al. 2012



Perna et al. 2006

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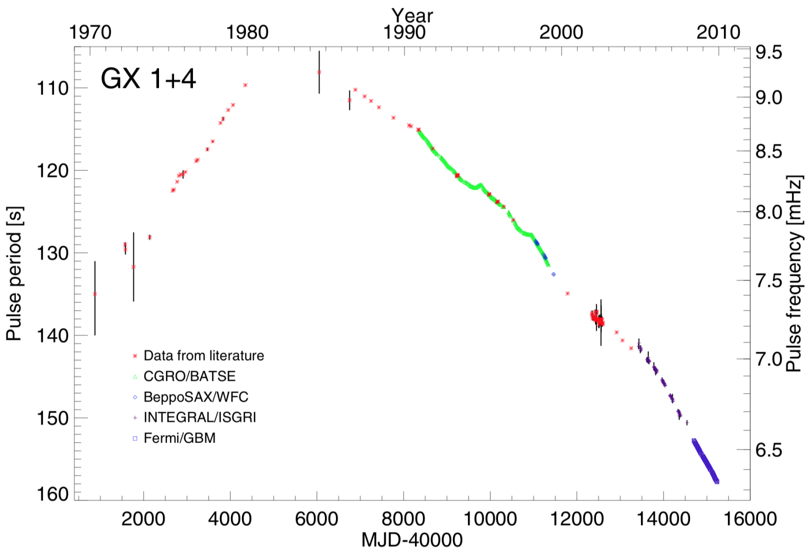

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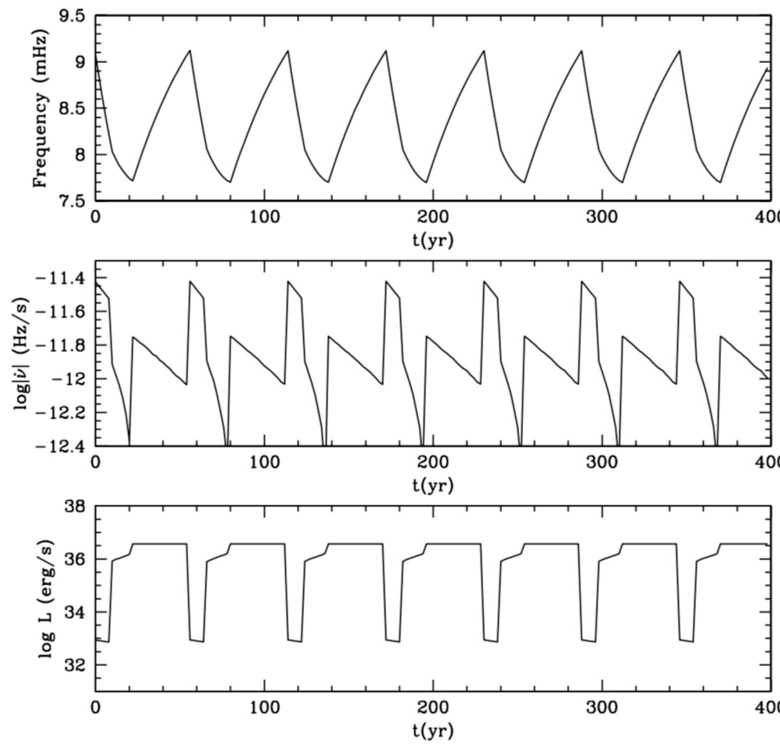
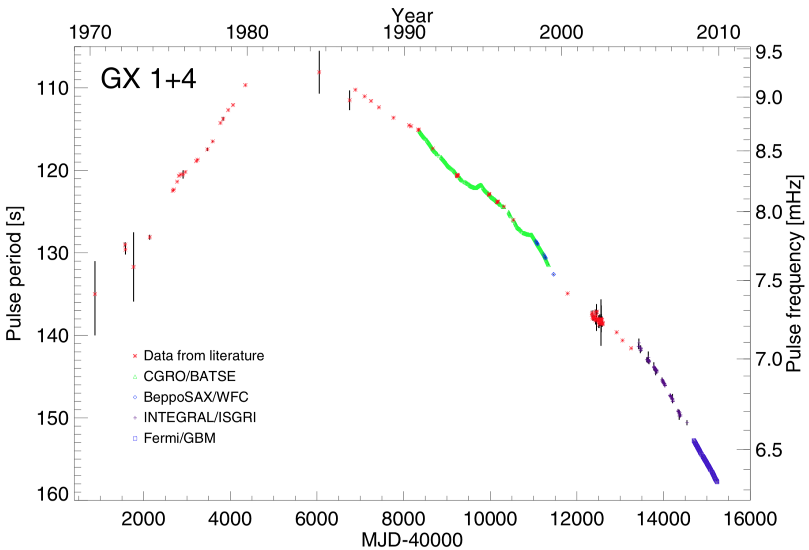


Perna et al. 2006

Parameters

- $B = 6 \times 10^{13}\,\text{G}, \quad \chi = 45^\circ, \quad \beta = 0.3$ (elasticity parameter: a measure of how efficiently the KE of the NS is converted into KE of the ejected matter)

Time Evolution: GX 1+4



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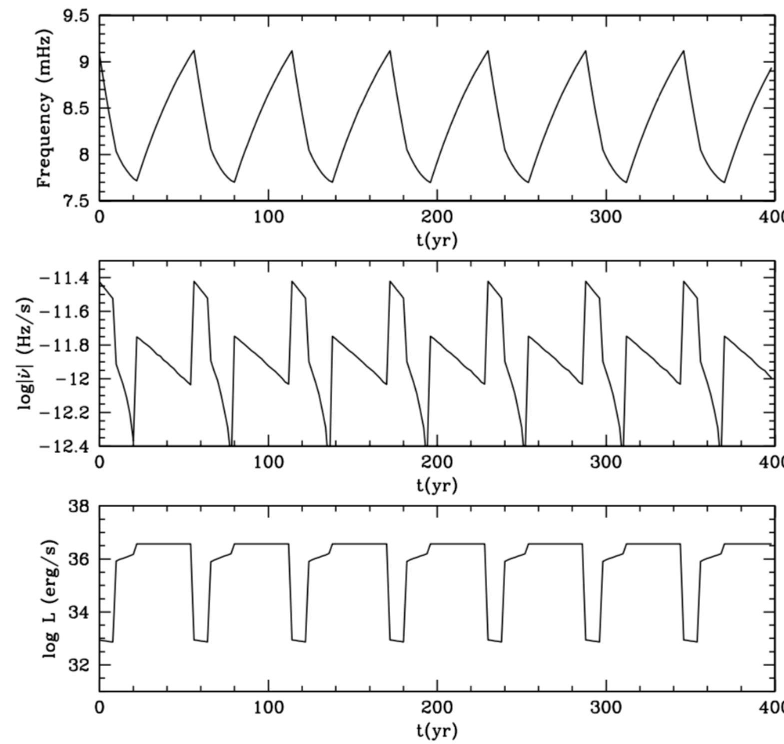
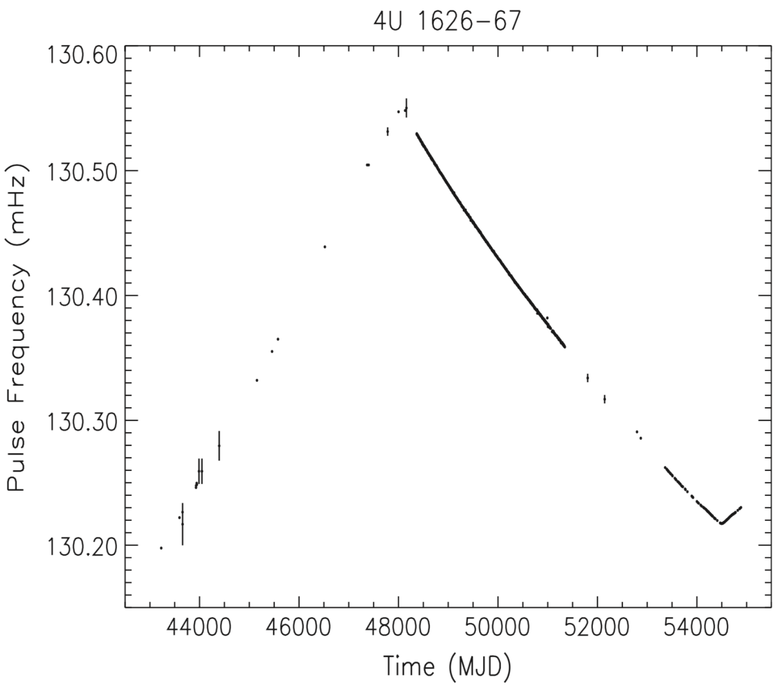


Perna et al. 2006

Parameters

- $B = 6 \times 10^{13}\,\mathrm{G}, \quad \chi = 45^\circ, \quad \beta = 0.3$
- Frequency ✓, Frequency amplitude ✓, Luminosity change ✓

Time Evolution: 4U 1626-67



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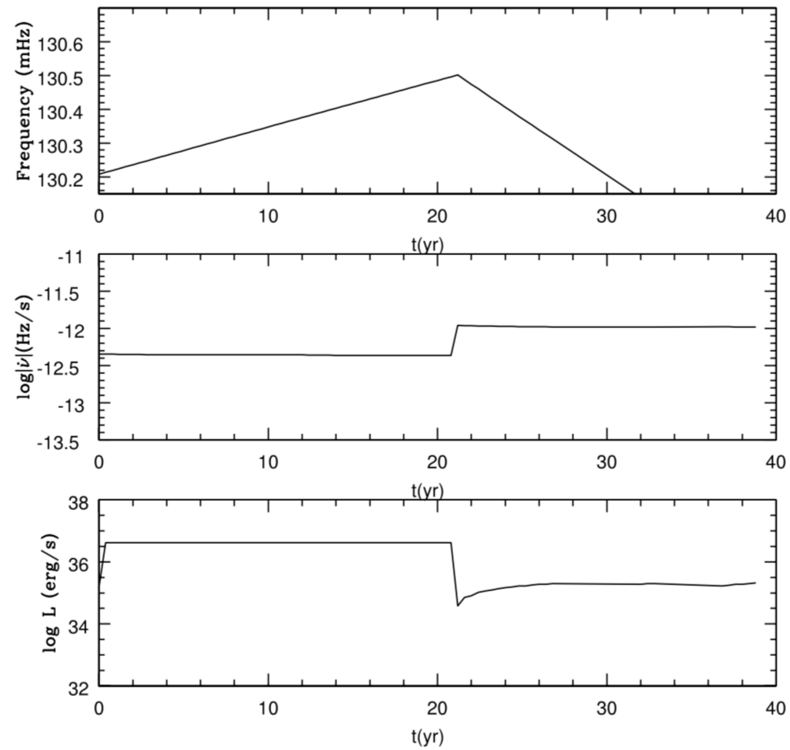
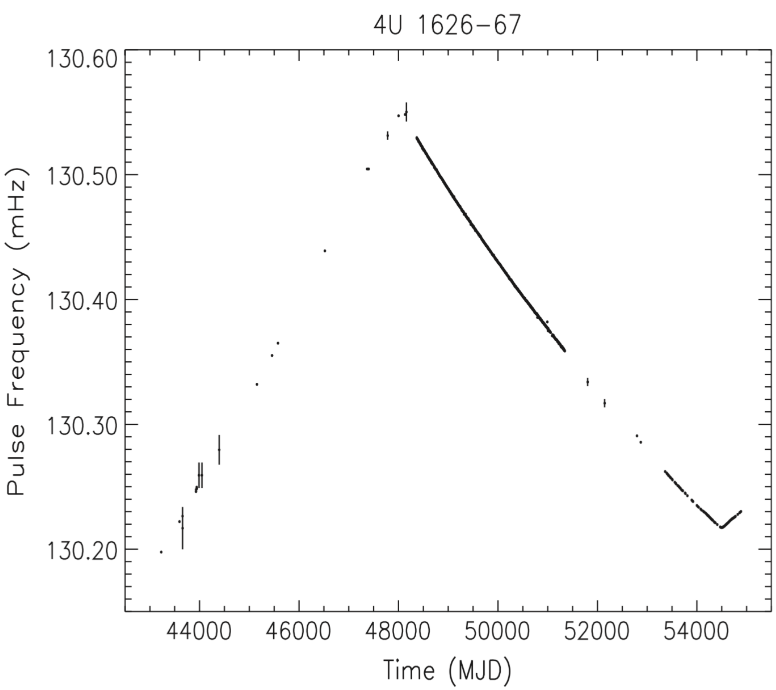


Perna et al. 2006

Time Evolution: 4U 1626-67



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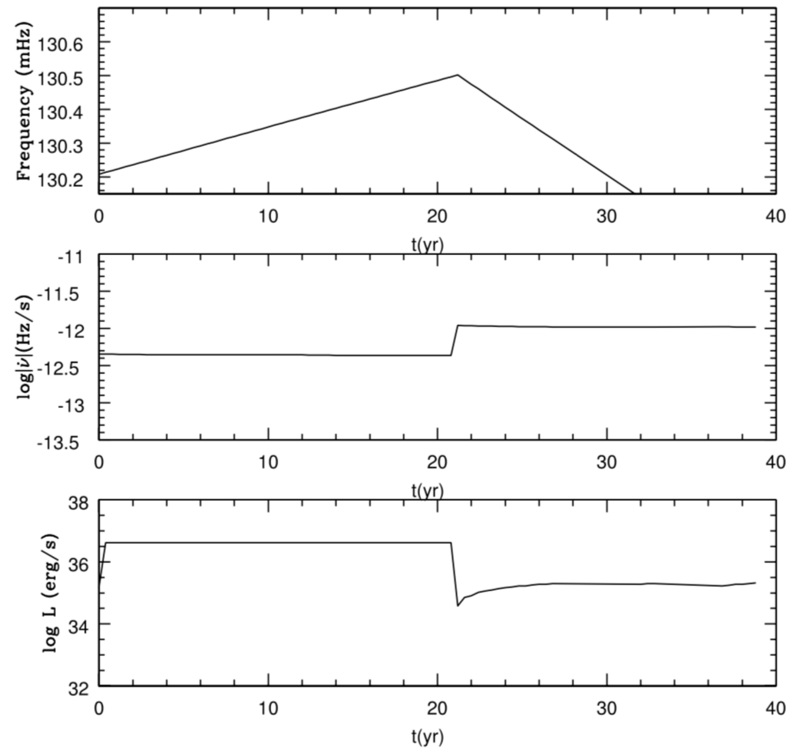
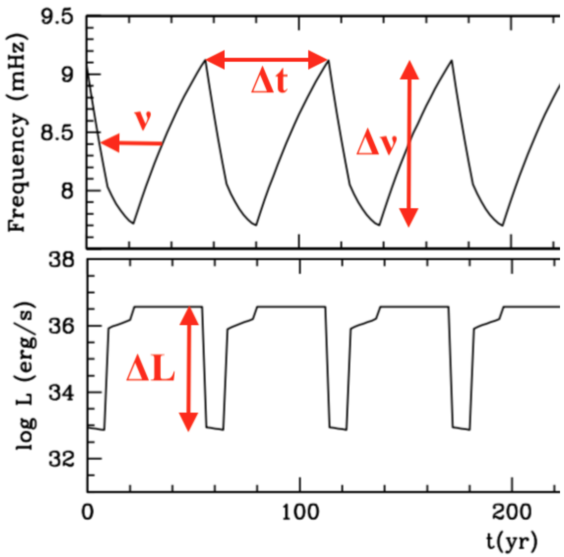


Perna et al. 2006

Parameters

- $B = 2.5 \times 10^{12}$ G, $\chi = 68^{\circ}$, $\beta = 0.0$
- Frequency ✓, Frequency amplitude ✓, Luminosity change ✓

Influence of the Parameters B, β, χ



- ν: "equilibrium" frequency: average between frequencies of torque reversals
- $\Delta\nu$: amplitude between reversals
- Δt: time between reversals
- ΔL: luminosity variation (amplitude)

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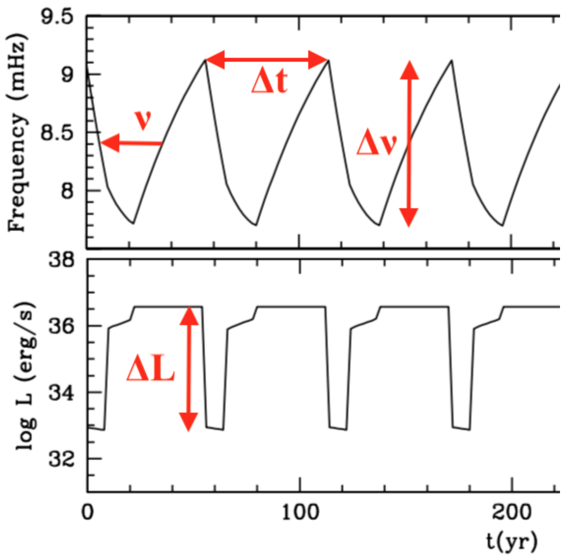

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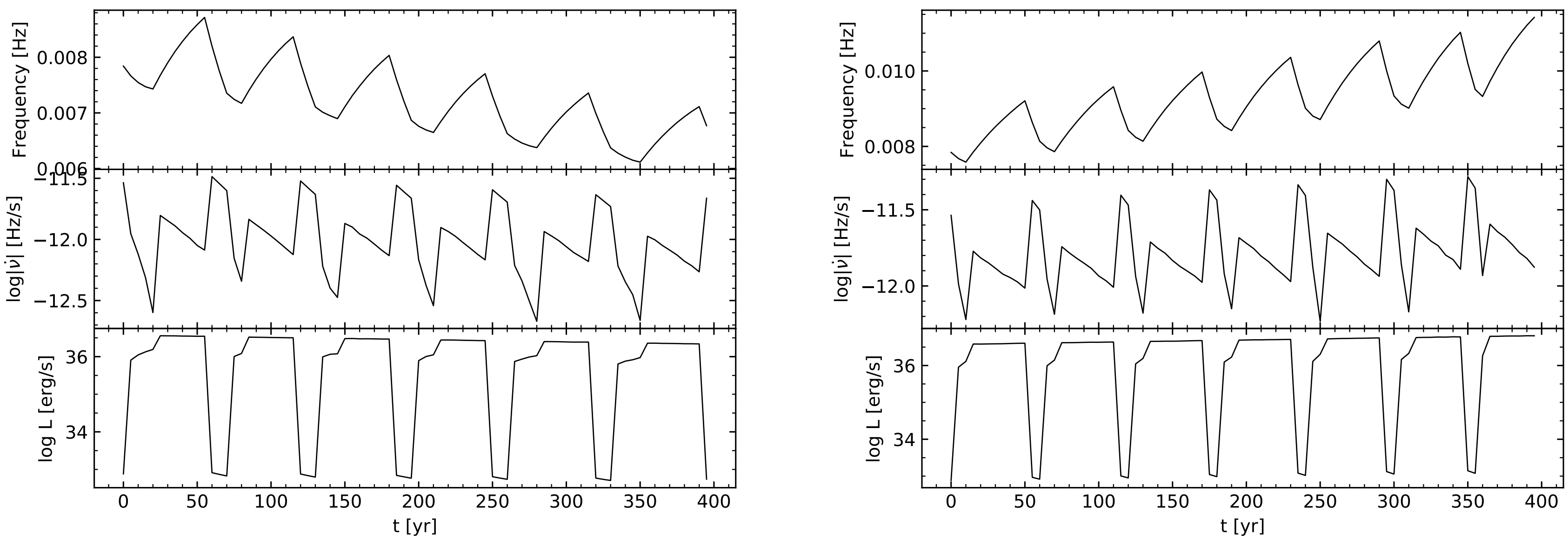
- ΔL: luminosity variation (amplitude)

Parameters	ν	$\Delta\nu$	Δt	ΔL
$B \uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	const.
$\beta \downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
$\chi \uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$

Time Variable $\dot{M}_*$ – Feasibility Test based on GX 1+4



Parameters

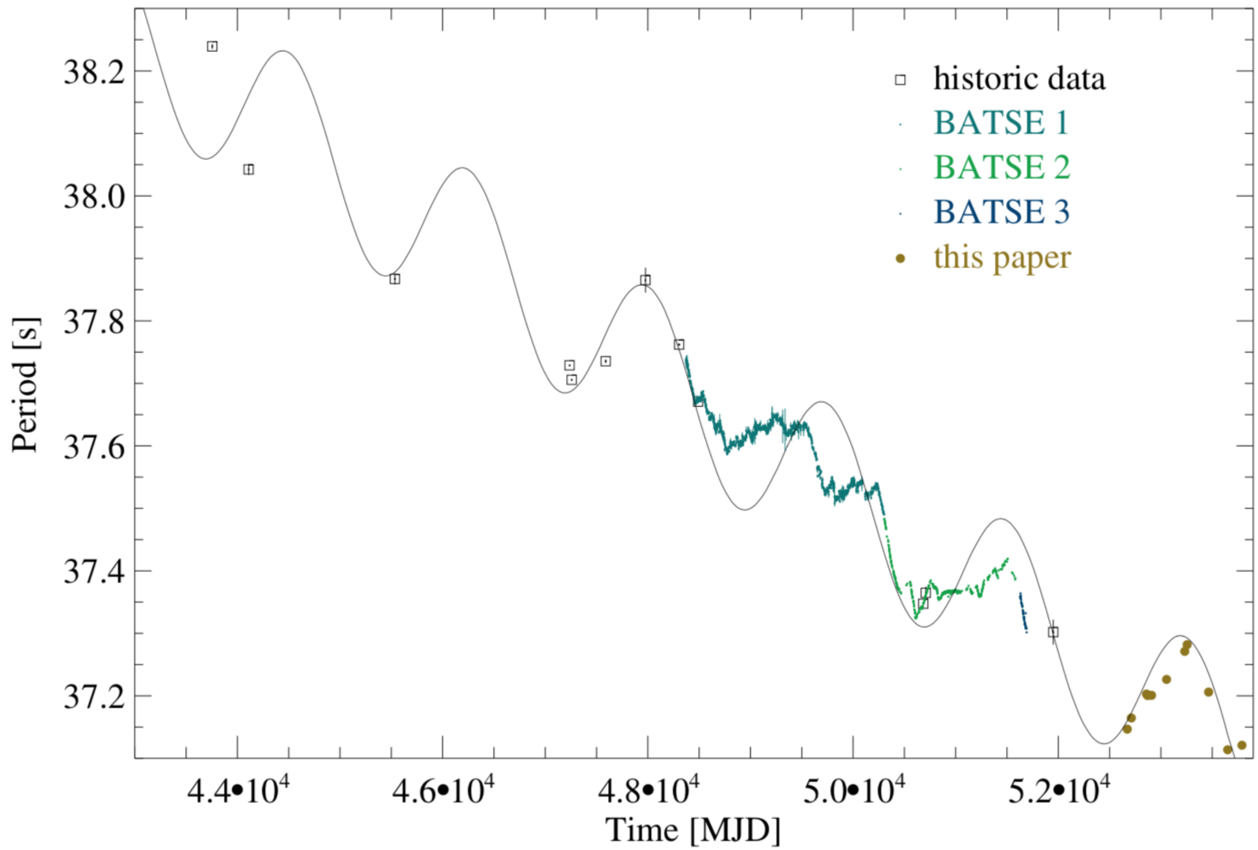
- Spin-down: $d\dot{M}/dt = -2.12 \times 10^{13}\,\mathrm{g\,s^{-1}\,yr^{-1}}$
- Spin-up: $d\dot{M}/dt = 3.68 \times 10^{13}\,\mathrm{g\,s^{-1}\,yr^{-1}}$

OAO 1657-415: Introduction and Observations

Parameters

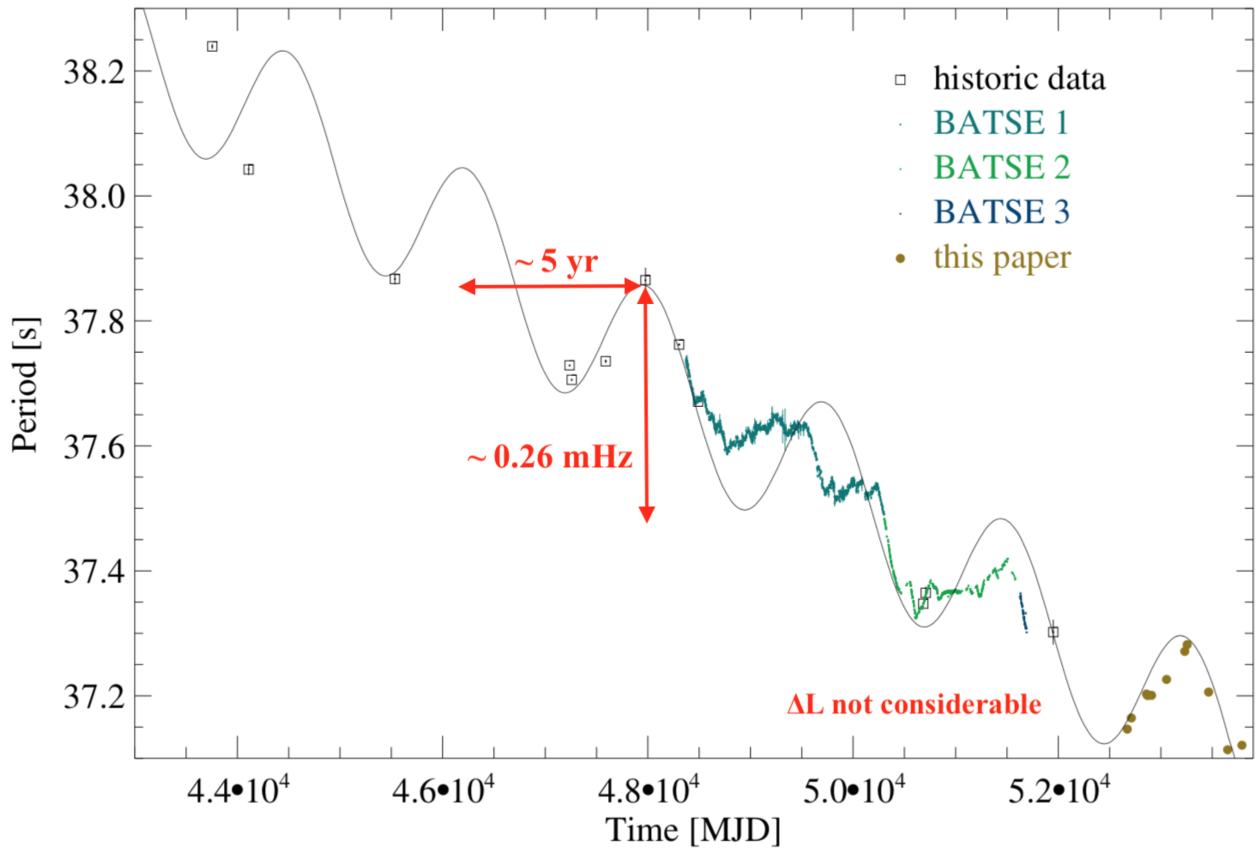
- HMXB
- Companion: Ofpe supergiant
- $M_{\text{NS}} = 1.74\,\text{M}_{\odot}$ (Falanga et al. 2006)
- $M_{\text{opt}} = 17.5\,\text{M}_{\odot}$ (Falanga et al. 2006)
- $R_{\text{opt}} = 25\,\text{R}_{\odot}$ (Falanga et al. 2006)
- $d = 7.1 \pm 1.3\,\text{kpc}$ (Audley et al. 2006)
- $P \approx 37 - 38\,\text{s}$ (Barnstedt et al. 2008)

OAO 1657-415: Introduction and Observations



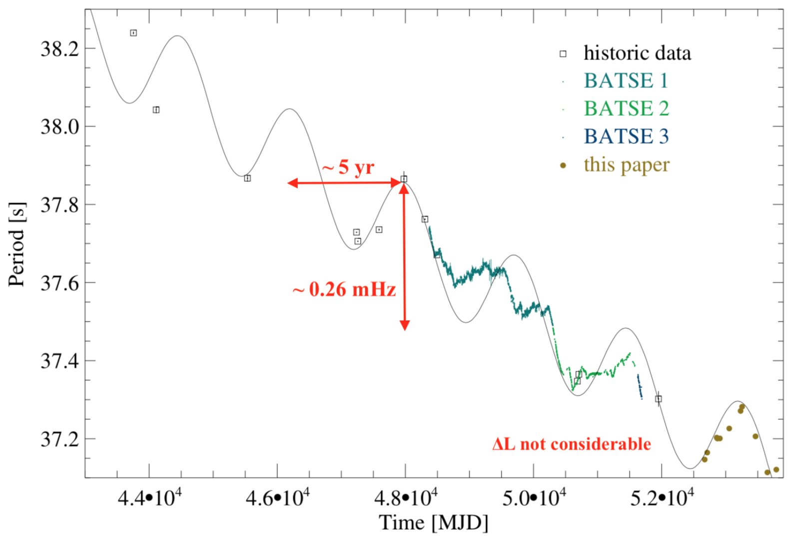
Barnstedt et al. 2008

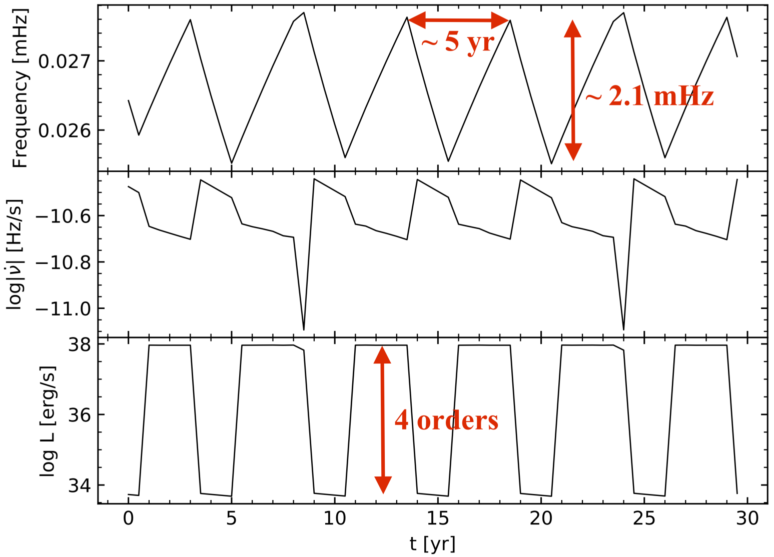
OAO 1657-415: Introduction and Observations



Barnstedt et al. 2008

Application of the Model





Parameters

- $B = 7 \times 10^{13}$ G, $\chi = 36^\circ$, $\beta = 0.8$
- Frequency ✓, Frequency amplitude ✗, Luminosity change ✗

Aims

Study the Inclined Rotator Model (Perna et al. 2006):

✓ Explore the model and investigate the influence of different parameters (B, χ, β).

Influence of parameters:

Parameters	ν	$\Delta\nu$	Δt	ΔL
$B\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	const.
$\beta\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
$\chi\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$

Aims

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$\chi\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$

Aims

Study the Inclined Rotator Model (Perna et al. 2006):

- ✓ Explore the model and investigate the influence of different parameters (B, χ, β).
- ✓ Introduce a new component to obtain a long-term spin-up or spin-down, which is superposed on the cyclic spin reversals.
- (✓) Apply the model to the X-ray pulsar in OAO 1657-415 to constrain some of the parameters.

Influence of parameters:

Parameters	ν	$\Delta\nu$	Δt	ΔL
$B\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	const.
$\beta\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
$\chi\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$

Parameters OAO 1657-415:

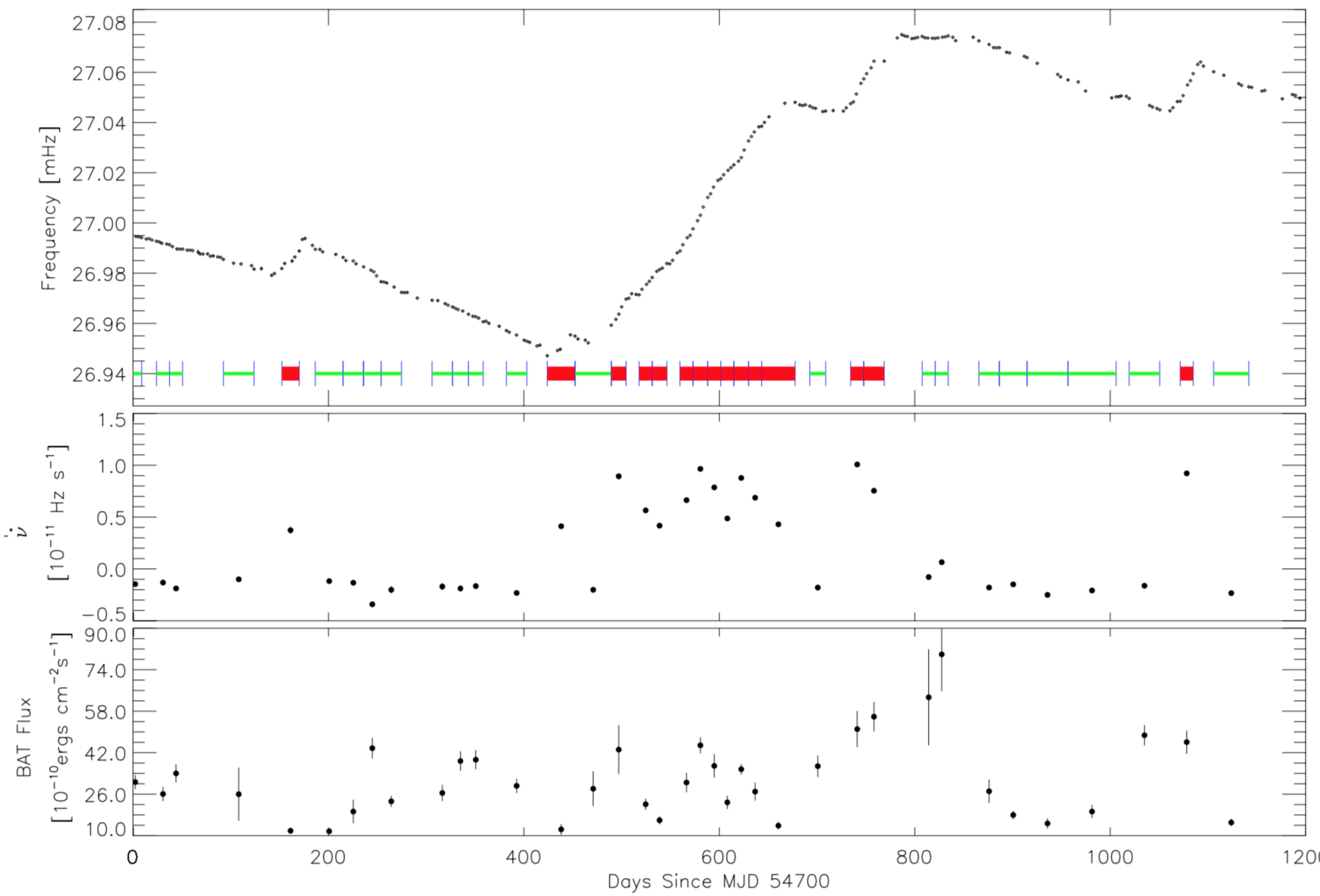
- $B = 7 \times 10^{13}$ G
- $\chi = 36^\circ$, $\beta = 0.8$
- Frequency ✓
- Frequency amplitude ✗
- Luminosity change ✗

Aims

Examine the Frequency and Flux History of OAO 1657-415 *Fermi*/GBM and *Swift*/BAT data:

- Investigate over 10 years of data (2008 - 2018).
- Study the Torque-Flux correlation.
- Constrain the magnetic field and distance.

Previous Work by Jenke et al. 2012



Jenke et al. 2012

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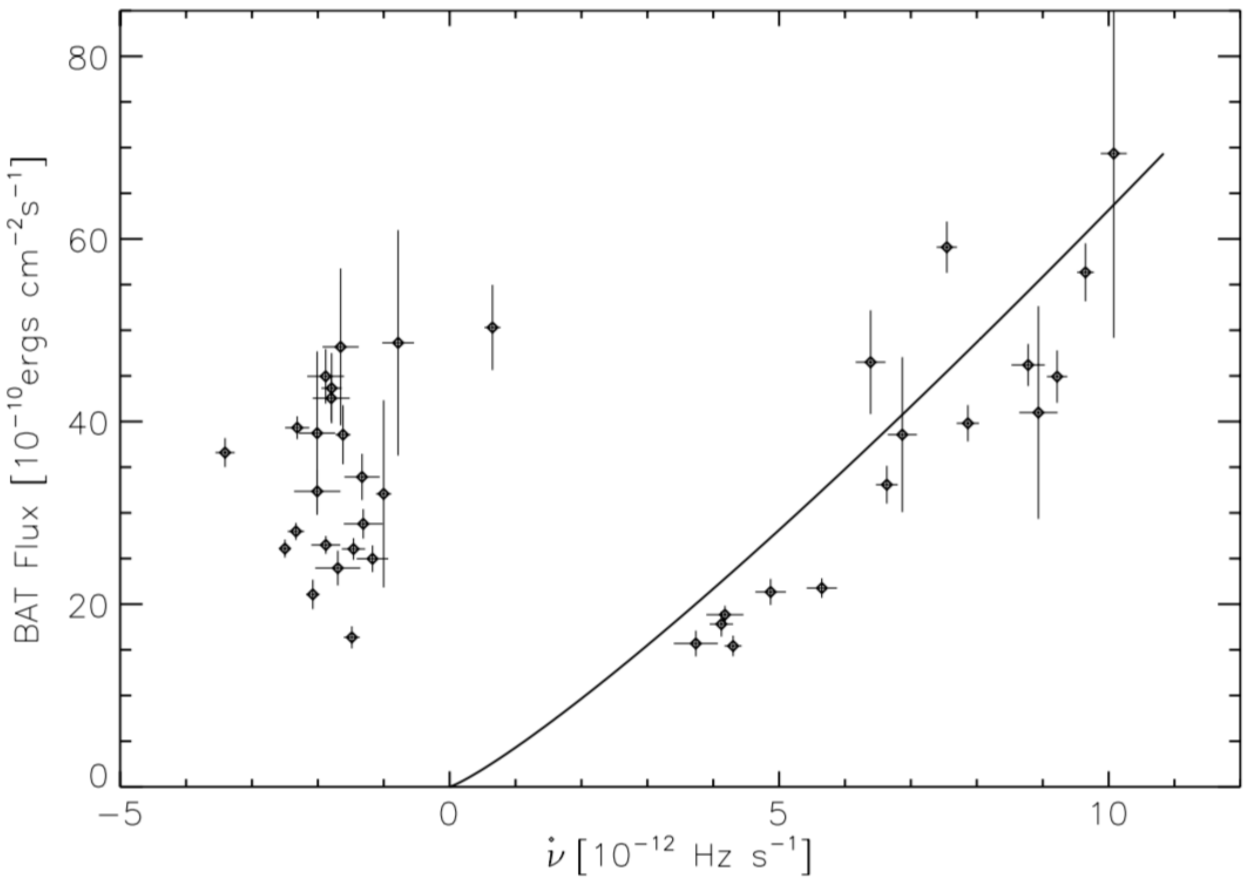
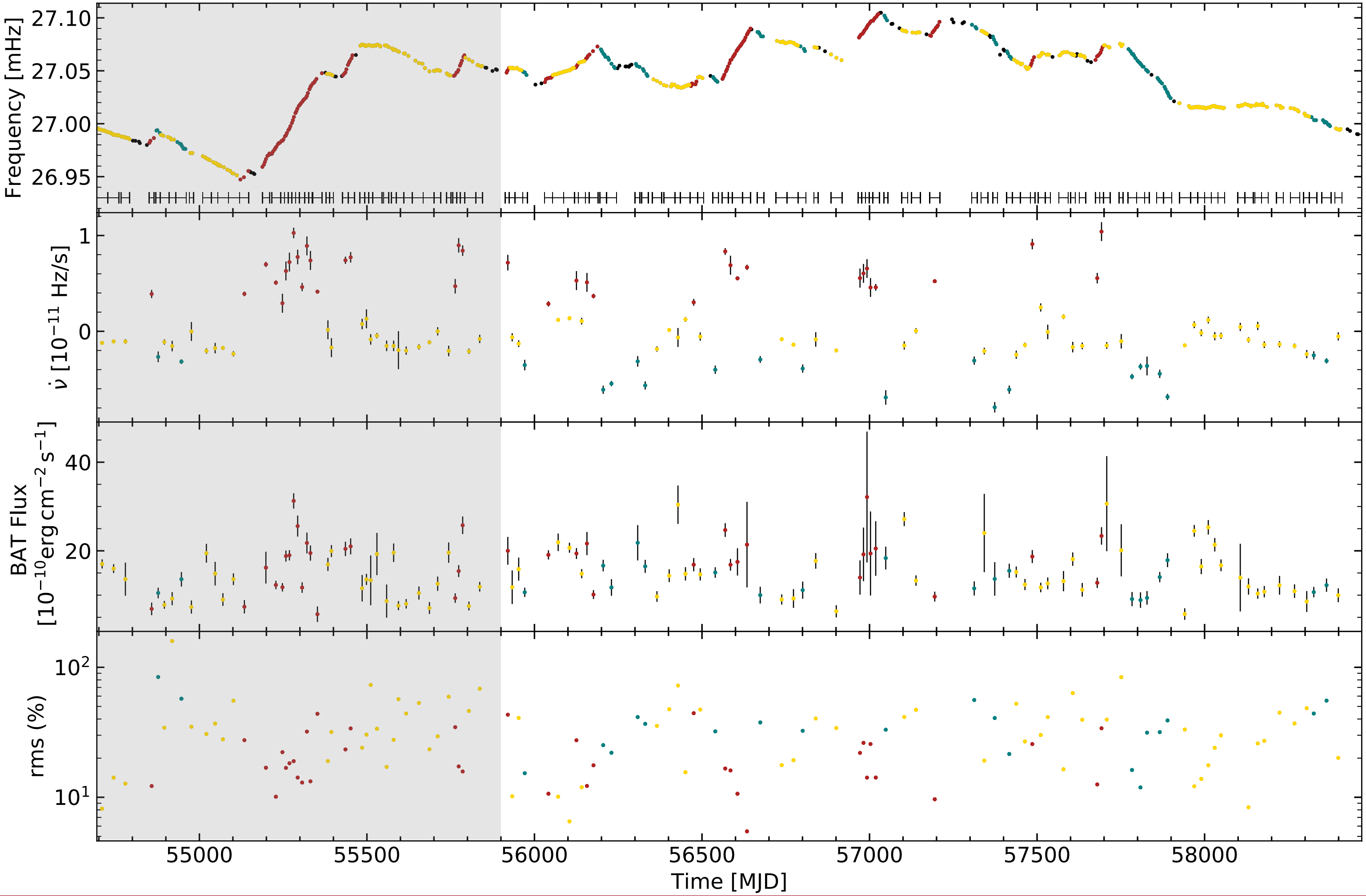
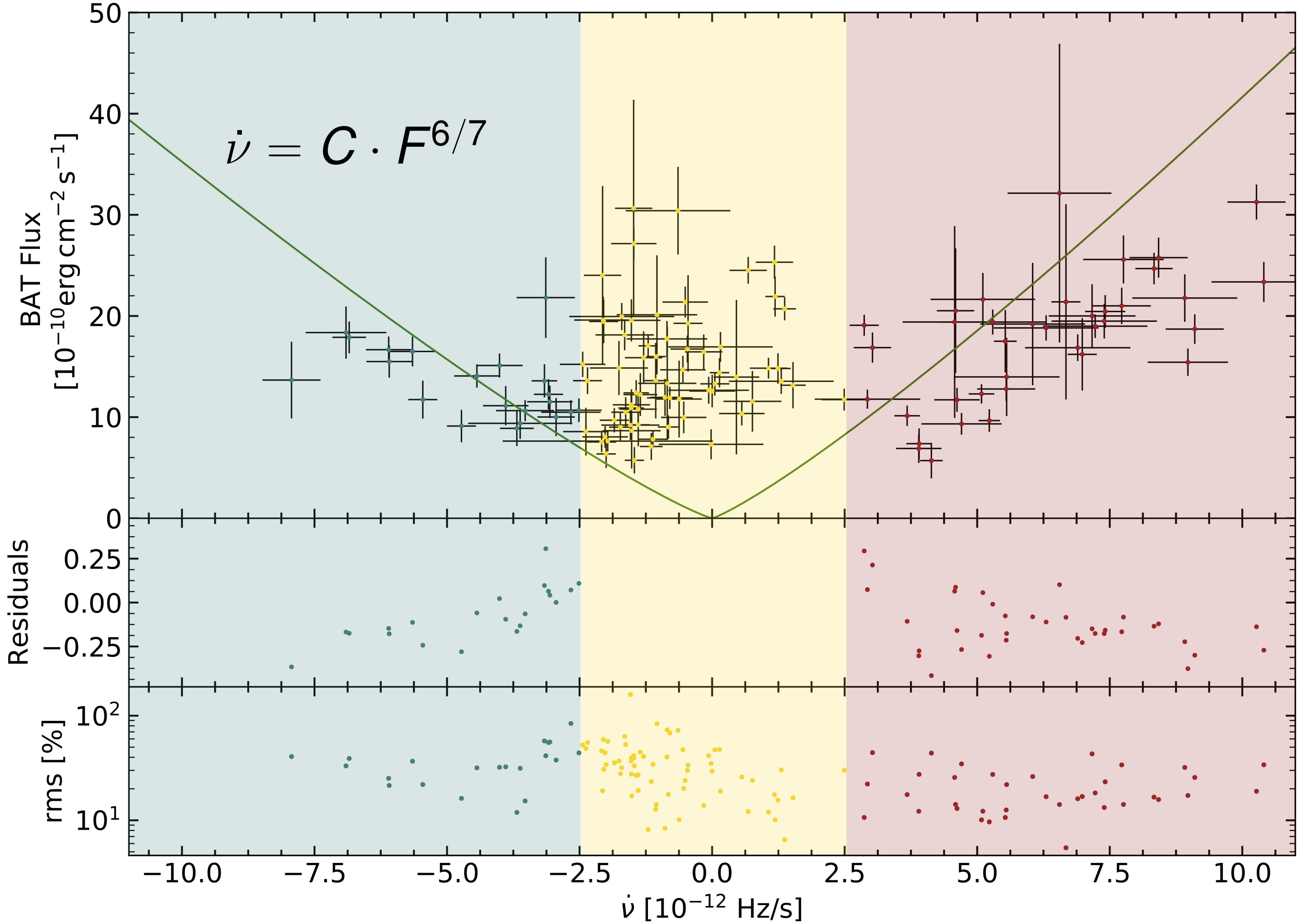


Jenke et al. 2012

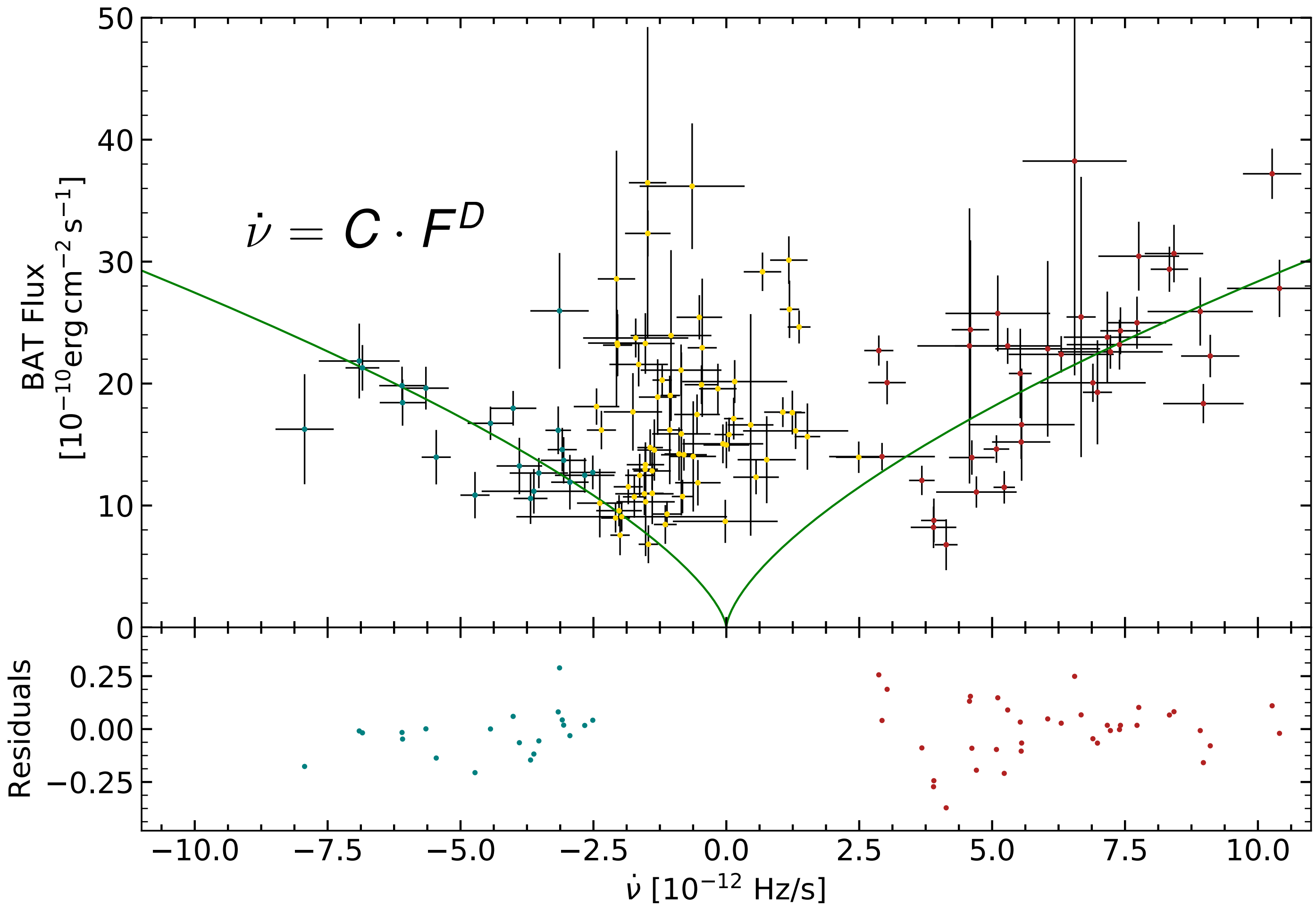
Frequency and Flux History



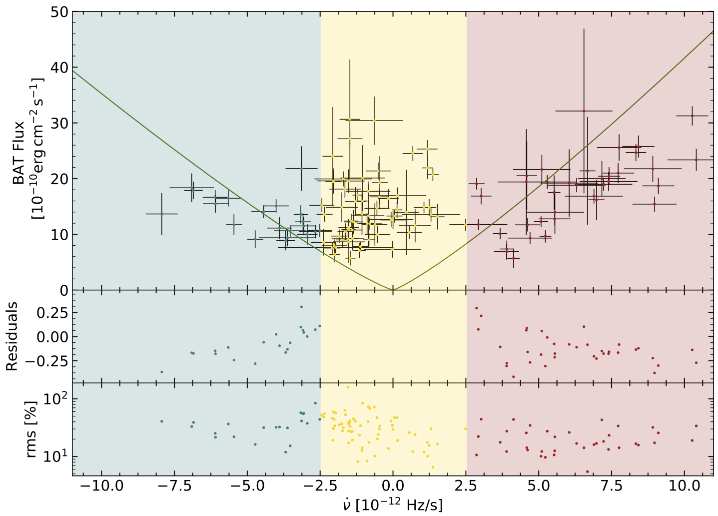
Torque-Flux Correlation of OAO 1657-415



Torque-Flux Correlation of OAO 1657-415



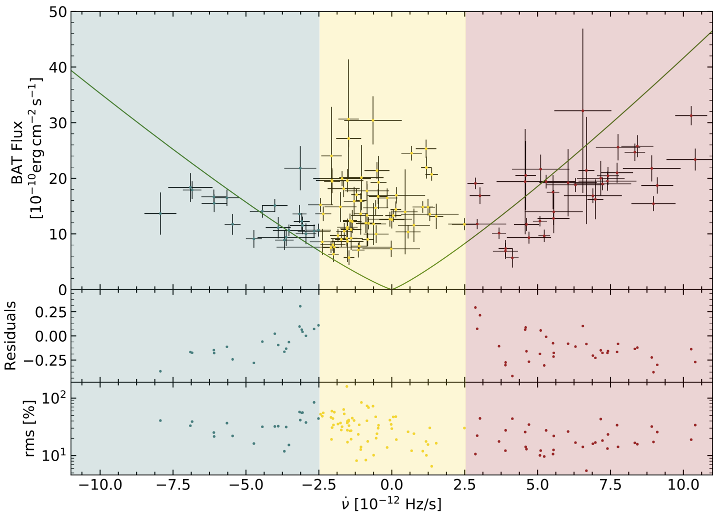
Torque-Flux Correlation of OAO 1657-415: rms

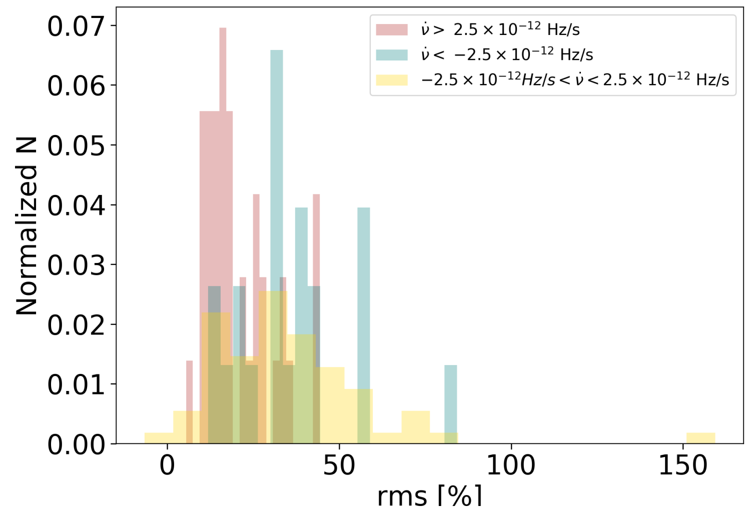


rms averages:

- Spin-up ($\dot{\nu} > 2.5 \times 10^{-12}\,\mathrm{Hz\,s^{-1}}$): 20.9 ± 3.3 %
- Spin-down ($\dot{\nu} < -2.5 \times 10^{-12}\,\mathrm{Hz\,s^{-1}}$): 36.5 ± 7.4 %
- In-between: 34.8 ± 5.9 %

Torque-Flux Correlation of OAO 1657-415: rms





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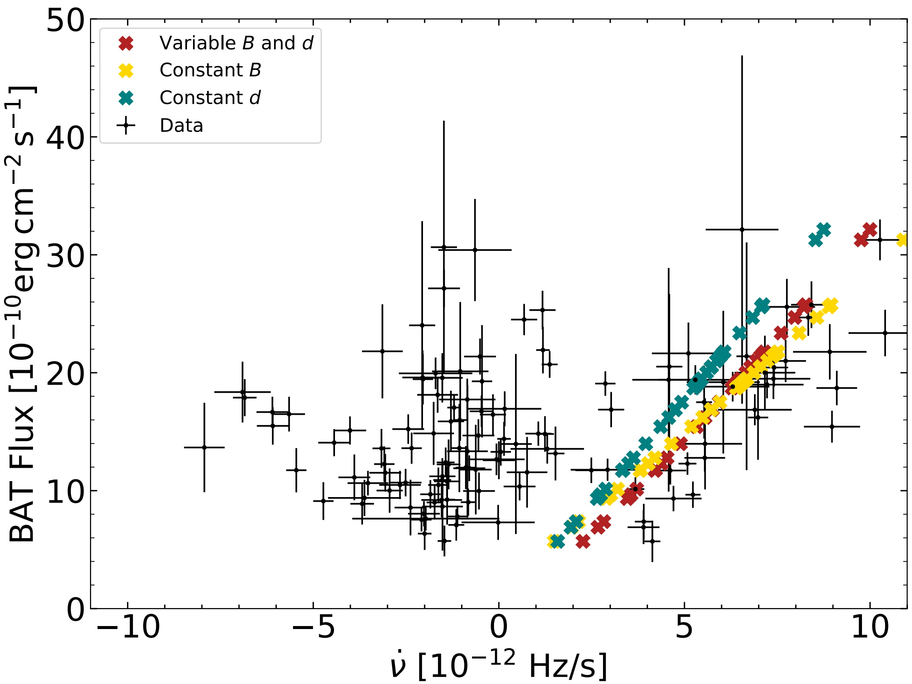
Distance and Magnetic Field Calculation



Ghosh & Lamb model:

$$-\dot{P} \propto \mu_{30}^{2/7} n(\omega_s)(PL_{37}^{3/7})^2$$

$$\omega_s \propto \mu_{30}^{6/7}(PL_{37}^{3/7})^2$$

Least-χ^2 fit results:

- with constant $d = 7.1$ kpc: $B = 2 \times 10^{12}$ G
- with constant $B = 4 \times 10^{12}$ G: $d = 8$ kpc
- with both as free parameters: $B = 2 \times 10^{10}$ G, $d = 15$ kpc

Conclusion - Part I: Inclined Rotator

Influence of parameters:

Parameters	ν	$\Delta\nu$	Δt	ΔL
$B\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	const.
$\beta\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
$\chi\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$

Parameters OAO 1657-415:

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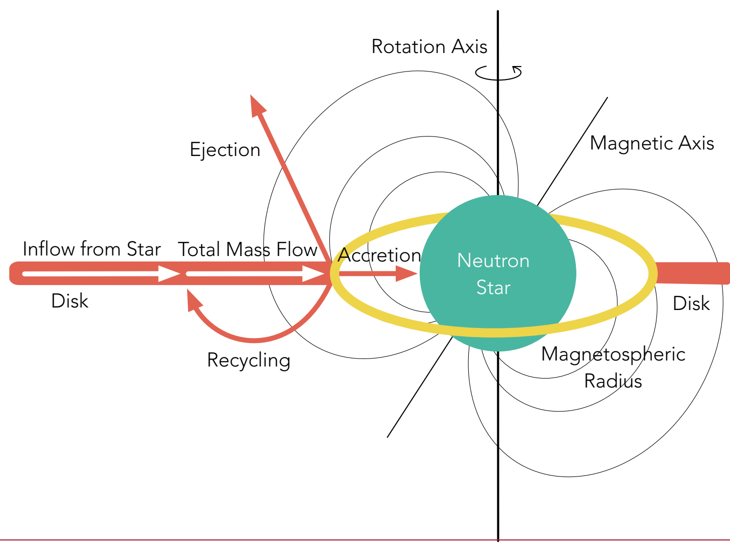
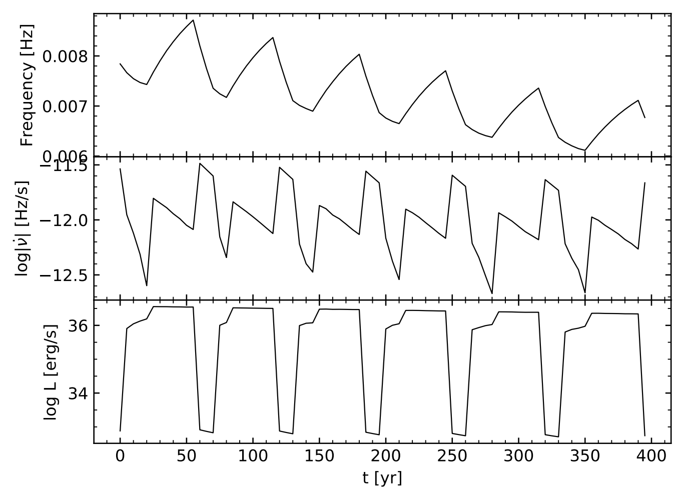
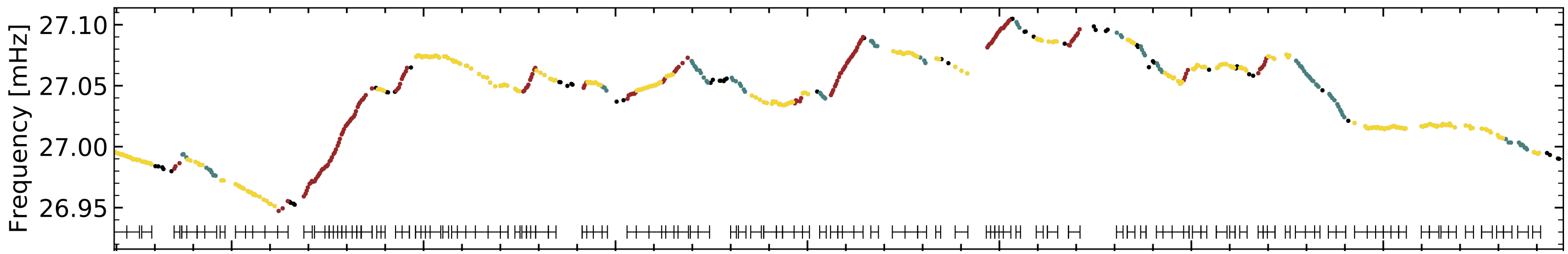
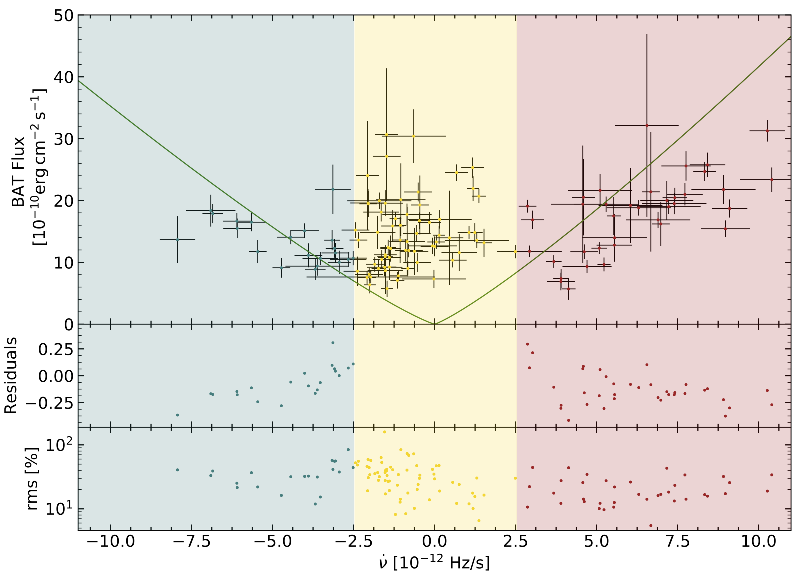




Conclusion - Part II: Torque-Flux Correlation

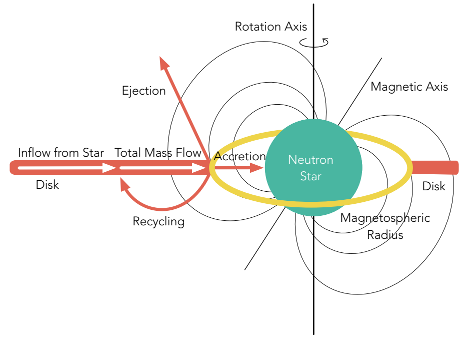




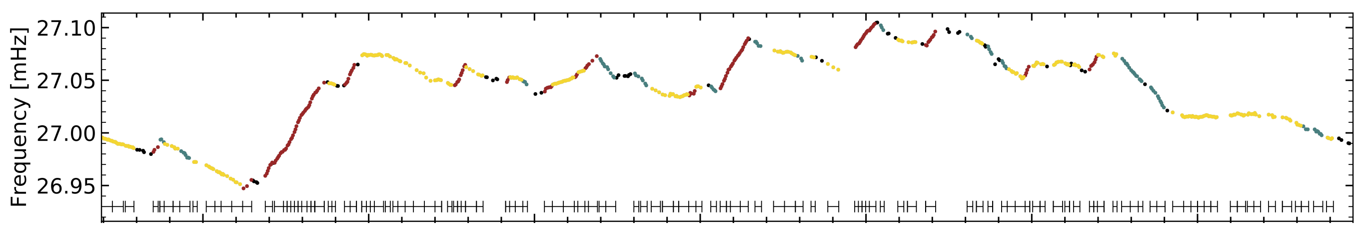
Results:

- Correlation spin-up: ✓
- Correlation spin-down: (✓)
- Low variability on spin-up branch: stable accretion disk
- Variability + its distribution different in other regions: other process? No disk?
- $B = 2 \times 10^{10}\,\mathrm{G}$ to $2 \times 10^{12}\,\mathrm{G}$
- $d = 8\,\mathrm{kpc}$ to $15\,\mathrm{kpc}$

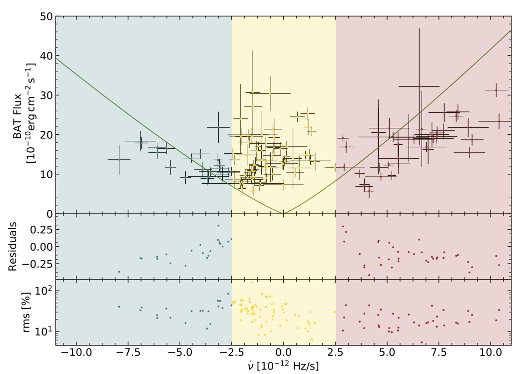
Outlook/Future Work



+ Magnetic torque;
Ghosh & Lamb model



...?



- More data: large spin-down with high flux to support retrograde disk?
- Spectral analysis: same or different processes in different areas? (Combine XRT + BAT?)

Thank you.

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