ГАИШ МГУ
Отдел Релятивистской Астрофизики

Отчёт за пять лет

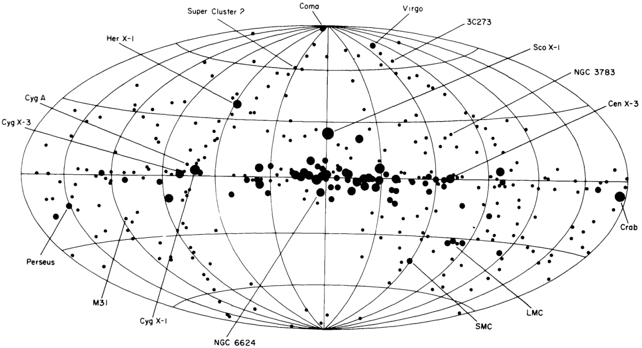
Д. А. Колесников

Основные результаты

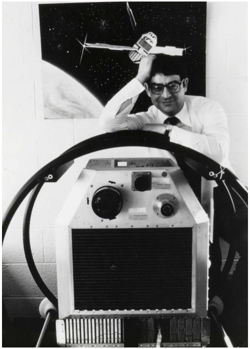
1. Создан код синтеза кривых блеска Discostar для моделирования орбитальных кривых блеска и рентгеновской модуляции потока рентгеновских двойных систем с изгибным аккреционным диском.
2. Объяснена 35-дневная модуляция оптических кривых блеска системы HZ Her/Her X-1 в рамках модели прецессирующего, взаимодействующего с магнитосферой нейтронной звезды, аккреционного диска.
3. Объяснена орбитальная модуляция рентгеновского потока Her X-1 в состоянии минимимума 35-дневного цикла по данным измерений спутника SRG/eROSITA.
4. Объяснена 35-дневная модуляция частоты рентгеновского пульсара Her X-1 по данным измерений спутника Fermi в рамках модели трёхосной свободной прецессии нейтронной звезды.
5. По результатам работы над HZ Her/Her X-1 успешно защищена диссертация на соискание степени кандидата физико-математических наук.

Uhuru: discovery of X-ray source Her X-1 (2U 1705+34)

November, 1971 — first detection of X-ray source in the constellation Hercules[1], $\sim$ 50 years ago



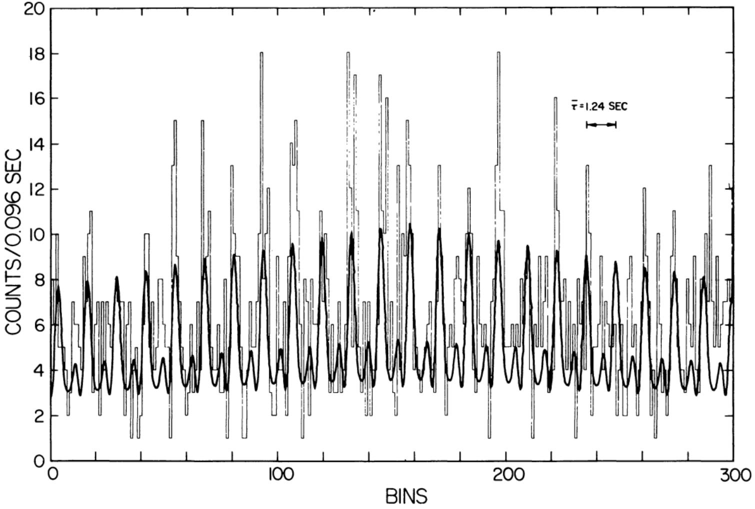
The fourth Uhuru catalog of X-ray sources
Forman et al., 1978



Riccardo Giacconi
and *Uhuru*

[1] Tananbaum et al., 1972

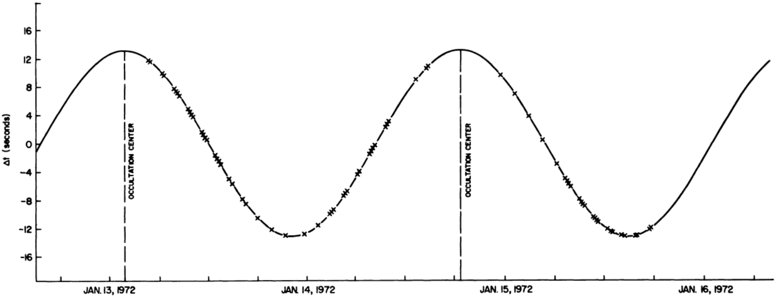
Uhuru: Her X-1 pulsation



The counts accumulated in 0.096-second bins. The heavier curve is a minimum χ^2 fit to the pulsations[2]

[2]Tananbaum et al., 1972

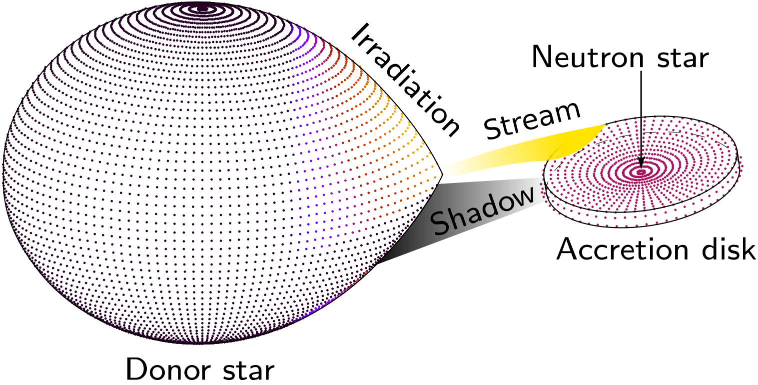
Uhuru: Her X-1 pulse arriving time



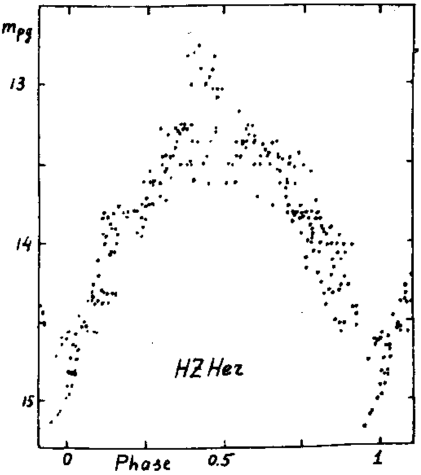
O-C for time of occurrence of a pulse. Orbial period is 1.7 days.[3]

[3] Tananbaum et al., 1972

Scheme of the X-ray binary HZ Her/Her X-1



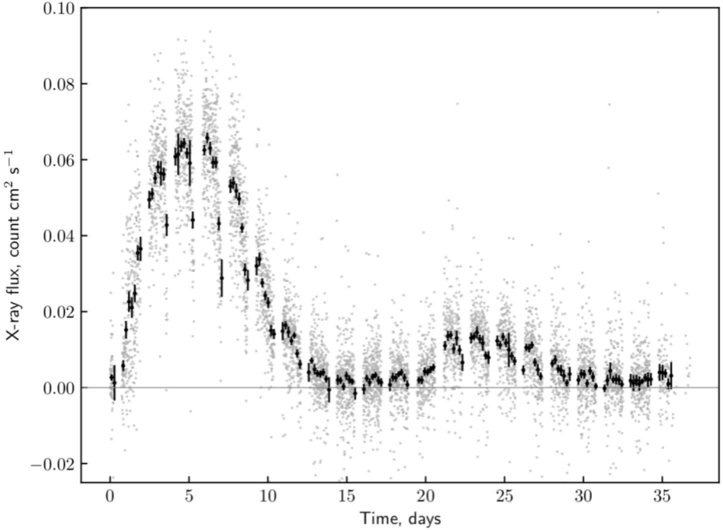
Orbital modulation of the optical flux



First optical light curve by the glass photoplates of the Sternberg Astronomical Institute[4]

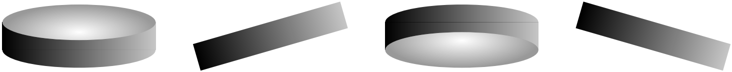
[4] Cherepashchuk et al., 1972

35-day cycle

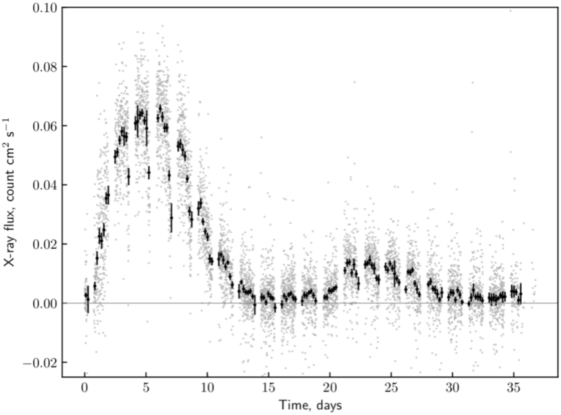


35-day modulation of X-ray flux by *Swift*/BAT

35-day cycle



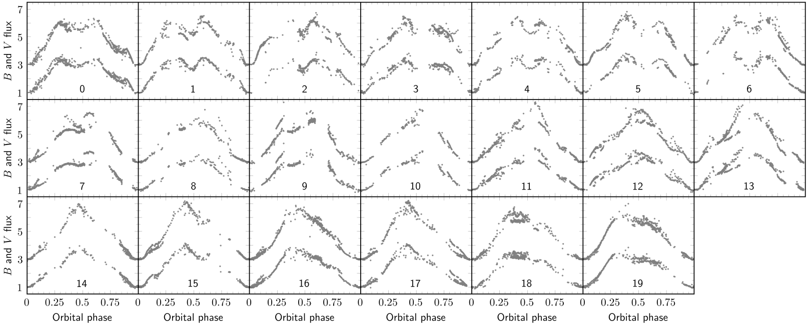
Precession phases of the outer parts of the accretion disk



35-day X-ray flux modulation

Эволюция орбитальных кривых блеска с фазой 35-дневного цикла

Начало главного включения (Main-on) принято за начало 35-дневного цикла (дискретная фаза 0)



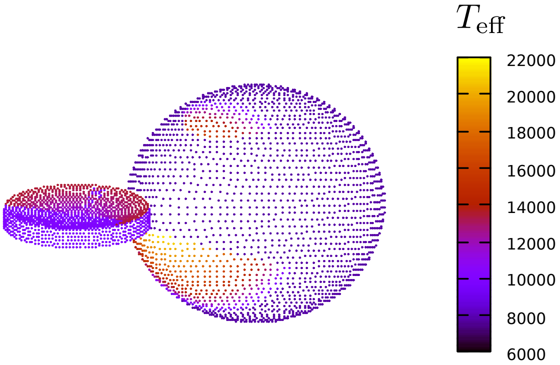
Измеренный относительный поток в фильтре B и V как функция орбитальной фазы, распределённый 20 дискретным фазам 35-дневного цикла (0–19)

I

Modelling of the B and V orbirtal light curves

Код синтеза синтеза кривых блеска

Изгибный, прецессирующий аккреционный диск[5]



Распределение температуры по поверхности звезды-донора и аккреционного диска

[5] `https://github.com/eliseys/discostar`

Модель аккреционного диска

Угол прецессии Φ

Толщина внешнего края H

Наклон внешнего края
к орбитальной плоскости θ_{out}

Наклон внутреннего края
к орбитальной плоскости θ_{in}

Угол между линиями узлов
внешнего и внутреннего края Z

Поток $F_{B,V}$

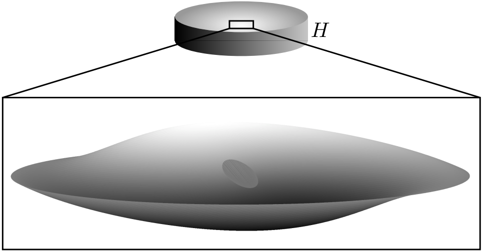


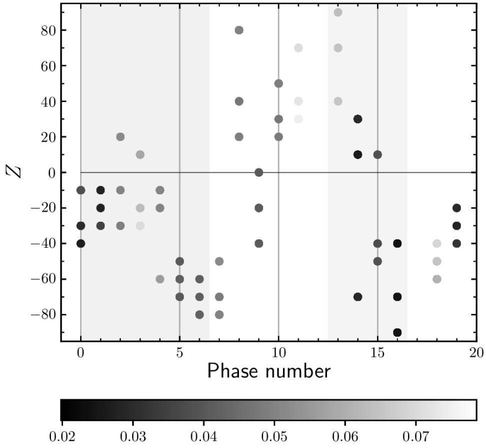
Схема аккреционного диска

Parameters of the disk

Z fixed at descreet values $[-90, \ldots, 90]$

Inclinations θ_{in} and θ_{out} and specific flux $F_{B,V}$ are free parameters

$$\chi^2 = \frac{1}{N - N_{var}} \sum_i^N [y_i - f(x_i)]^2$$

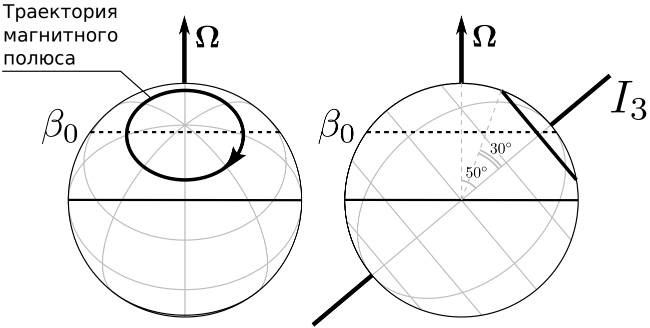


Angle Z as function of 35-day cycle

Magnetic torque, acting on the disk[6]

$$\mathbf{K_m} = \frac{4\mu^2}{3\pi R_d^3}\cos\alpha(3\cos\beta - 1)[\mathbf{n}_\Omega, \mathbf{n}_d]$$

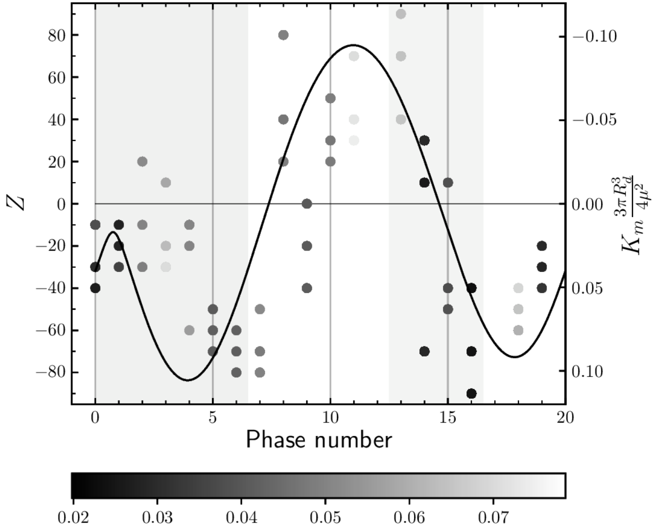
$K_m = 0$:
$\beta_0 = \arccos\sqrt{3}/3 \approx 54.7°$



Two-axial free precession in the model developed by Postnov et al. 2013

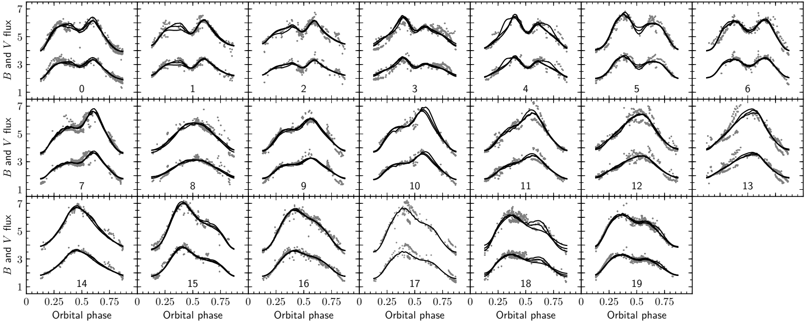
[6] Lipunov & Shakura 1976; Lipunov et al. 1981; Lipunov 1987

Magnetic torque K_m and angle Z



Angle Z and K_m as function of 35-day cycle

Synthetic light curves of HZ Her[7]



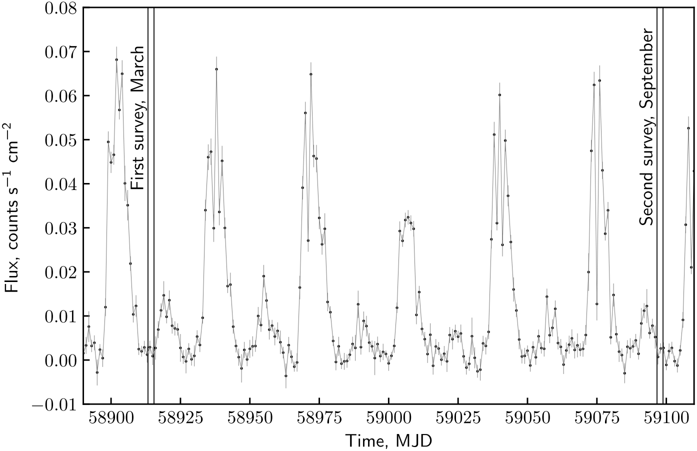
Measured B and V relative flux as function of the orbital phase, distributed over 20 discreet phases of 35-day cycle (poins) and theoreticla light curves (lines)

[7] Kolesnikov et al. 2020

II
Modelling of the orbital modulation of Her X-1 X-ray flux at low state by *SRG*/eROSITA data

First and second X-ray all-sky survey by *SRG*/eROSITA

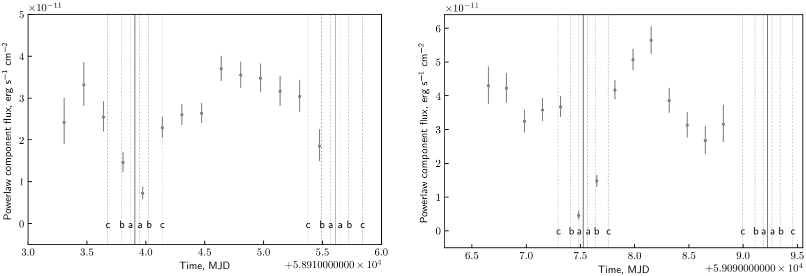
Observations of Her X-1 at first survey occured in 2020 March, 5-7; at second survey in 2020 September, 4-6.



Her X-1 X-ray flux by *Swift*/BAT. Verticla lines — time of *SRG*/eROSITA observations.

Low-state orbital modulation

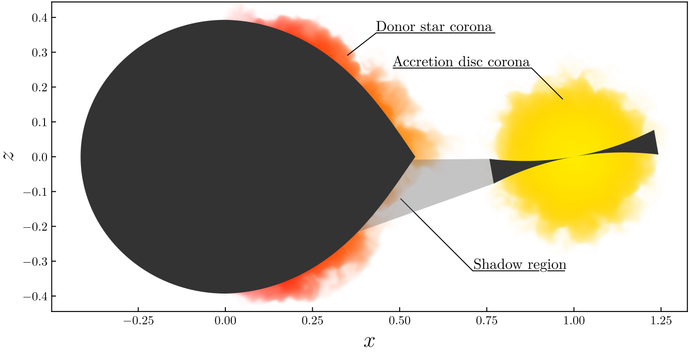
I   II



X-ray flux during the First and Second all-sky survey measured by *SRG*/eROSITA. Solid vertical lines indicate orbital phase 0.

X-ray scattering zones[8]

1. Corona above irradiated part of the donor star
2. Corona above accretion disk
3. Optically thick atmosphere of the donor star

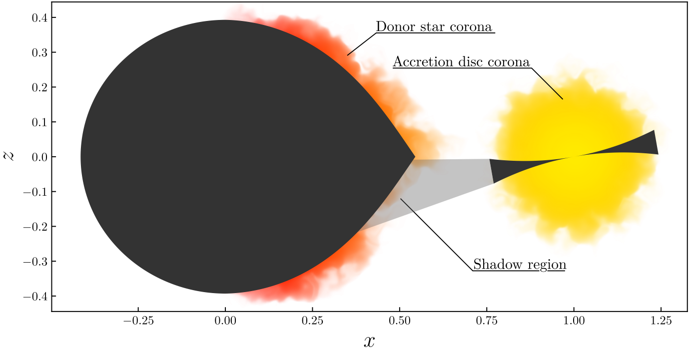


Scheme of HZ Her/Her X-1

[8] Basko & Sunyaev 1973; Basko et al. 1974; Бочкарев 1989; Бочкарев и Карицкая 1992

X-ray scattering zones[9]

1. Corona above irradiated part of the donor star
2. Corona above accretion disk
3. ~~Optically thick atmosphere of the donor star~~

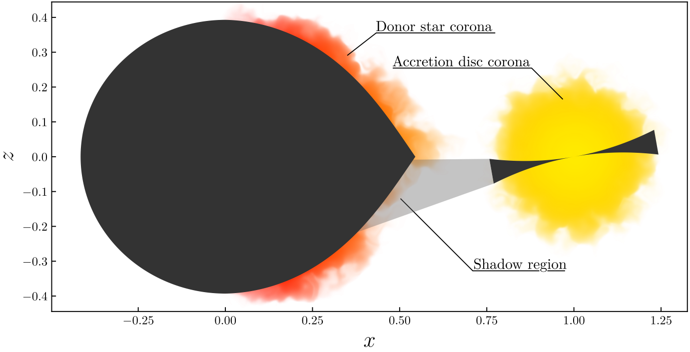


Сечение HZ Her/Her X-1 плоскостью $x - z$ (схема)

[9]Basko & Sunyaev 1973; Basko et al. 1974; Бочкарев 1989; Бочкарев и Карицкая 1992

X-ray scattering zones[10]

1. Corona above irradiated part of the donor star
2. ~~Corona above accretion disk~~ $\longrightarrow$ const
3. ~~Optically thick atmosphere of the donor star~~

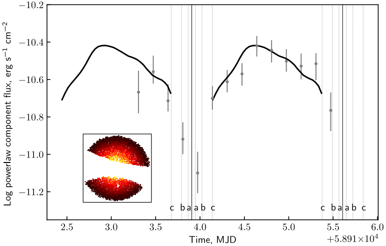


Scheme of HZ Her/Her X-1

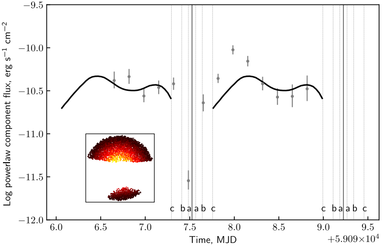
[10] Basko & Sunyaev 1973; Basko et al. 1974; Бочкарев 1989; Бочкарев и Карицкая 1992

Results of the modelling[11]

I



II



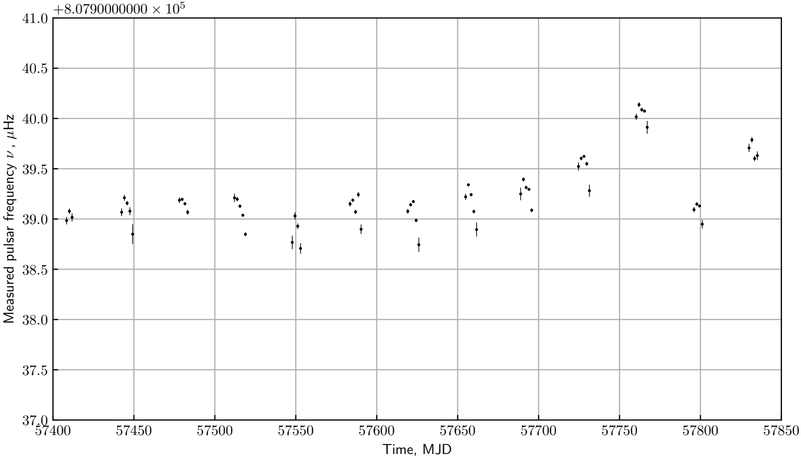
Observed and theoretical X-ray flux as function of orbital phase. In the boxes is synthesized view of the corona above donor star at the orbital phase 0.5

[11] Shakura et al. 2021

III
Evidence for neutron star triaxial free precession in Her X-1 from *Fermi*/GBM pulse period measurements

Her X-1 pulsar frequency measurements

Short-term (∼35 day) amplitude $\frac{\delta\Omega(t)}{2\pi} \sim 0.5\ \mu$Hz

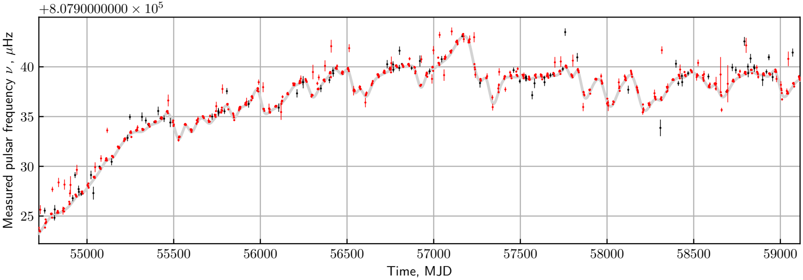


Her X-1 pulsar frequency measured by *Fermi*/GBM

Long-term pulsar frequency measurements

Long-term (4000 days) pulsar frequency variations $\frac{\Omega_0(t)}{2\pi} \sim 5 - 10\ \mu$Hz. The frequency of the pulsar is represented as the sum of the long-term and periodic variations:

$$\Omega(t) = \Omega_0(t) + \delta\Omega(t)$$



Measured *Fermi*/GBM pulsar frequency of Her X-1 during more than 4000 days. Gray line indicate the long-term frequency variations $\frac{\Omega_0(t)}{2\pi}$

Triaxial free precession[12]

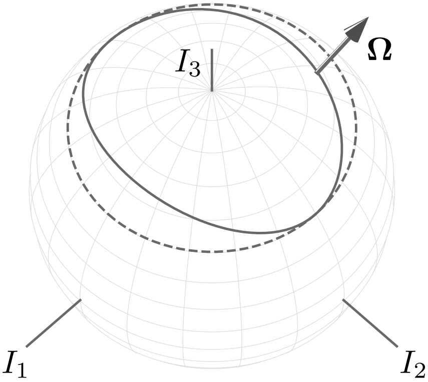
$I_1 < I_2 < I_3$ — principal inertia moments. Path of the vector $\mathbf{\Omega}$ is described by the following equations:

$$\Omega_1 = \sqrt{\frac{2EI_3 - M^2}{I_1(I_3 - I_1)}}\,\mathrm{cn}\tau$$

$$\Omega_2 = \sqrt{\frac{2EI_3 - M^2}{I_2(I_3 - I_2)}}\,\mathrm{sn}\tau$$

$$\Omega_3 = \sqrt{\frac{M^2 - 2EI_1}{I_3(I_3 - I_1)}}\,\mathrm{dn}\tau$$

where $\mathrm{cn}\tau$, $\mathrm{sn}\tau$, $\mathrm{dn}\tau$ — Jacobi elliptic functions, τ — dimentionless time



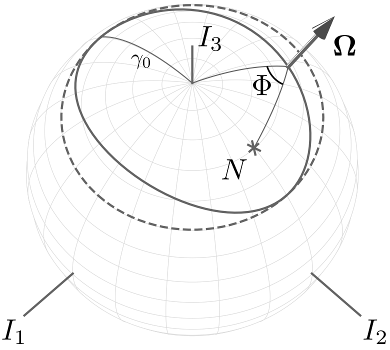
Path of the vector $\mathbf{\Omega}$ on the surface of the NS

[12] Landau & Lifshitz, 1976

Assuming magnetic pole N as the dominating source of X-ray radiation during Main-on:

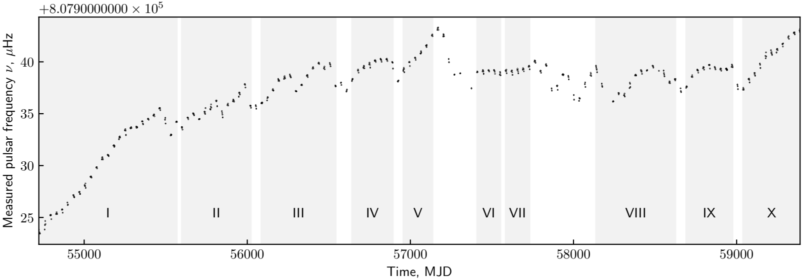
$$\delta\Omega(t) = \frac{d\Phi}{dt},$$

where Φ is precession angle:



Path of the vector $\boldsymbol{\Omega}$ and precession angle Φ

Intervals with constant NS free precession period

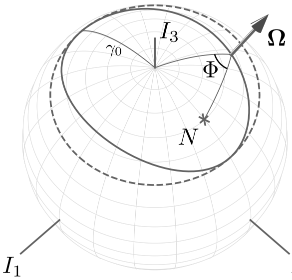


Interval number k	P_k	$\Delta I_3 \times 10^{-7}$	φ_0^*	Reduced χ^2
I	35.14	6.68	−0.45	7.2
II	35.02	6.70	−0.305	9.3
III	34.85	6.73	0.024	4.9
IV	35.25	6.67	−1.13	3.2
V	35.05	6.70	−0.63	4.4
VI	34.83	6.73	0.01	1.8
VII	35.1	6.69	−0.88	4.8
VIII	34.8	6.73	−0.01	4.4
IX	35.01	6.70	0.0	3.6
X	35.0	6.70	−0.015	10.0

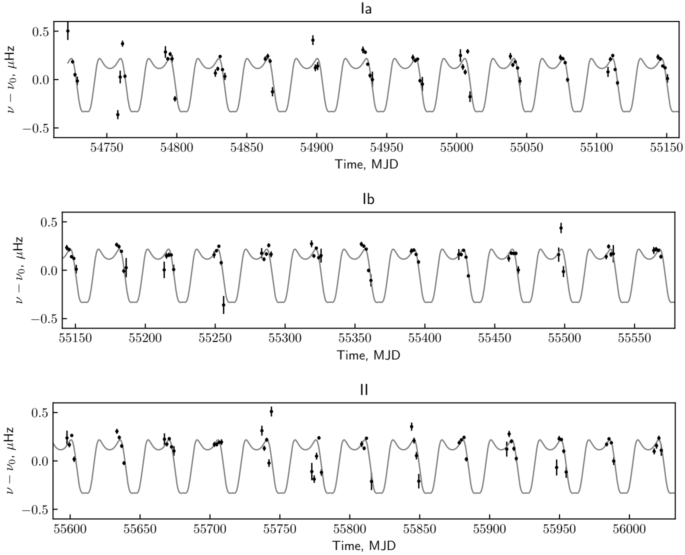
Fixed parameters of the model

Triaxial free precession model parameters fixed during the fitting inside k-th data intervals with constant 35-day cycle duration P_k

Parameter	Symbol	Value
$\mathbf{\Omega}$ and I_3 axis misalignment at zero free precession phase	γ_0	$50°$
Coordinates of the magnetic pole N	N_ϕ N_θ	$90°$ $30°$
Fractional moment inertia difference $(I_2 - I_1)/I_1$	ΔI_2	3×10^{-7}



The best-fit model



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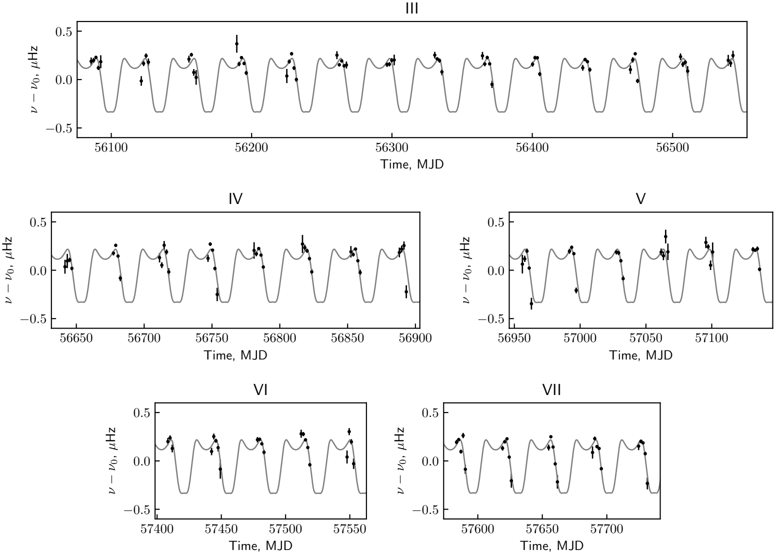
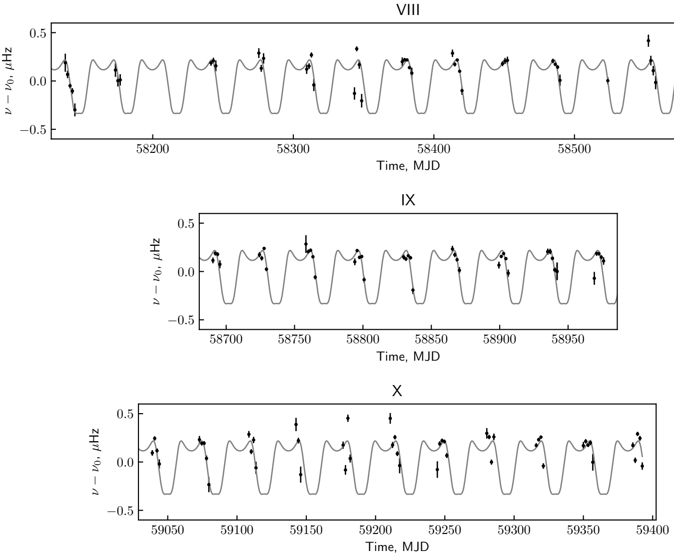


The best-fit model



Спасибо за внимание!

Основные публикации

[1] Dmitry Kolesnikov, et al., Evidence for neutron star triaxial free precession in her x-1 from fermi/gbm pulse period measurements. MNRAS, 2022.

[2] Galina Lipunova, et al., Physical modeling of viscous disc evolution around magnetized neutron star Aql X-1 2013 outburst decay. MNRAS, 2022.

[3] N. I. Shakura, et al., Observations of her x-1 in low states during SRG/eROSITA all-sky survey. A&A, 2021.

[4] D. Kolesnikov, et al., The 35-day cycle in the x-ray binary HZ Her/Her X-1. Contributions of the Astronomical Observatory Skalnate Pleso, 2020.

[5] D. A. Kolesnikov, et al., Modeling of 35-day superorbital cycle of B and V light curves of IMXB HZ Her/Her X-1. MNRAS, 2020.

[6] L. R. Yungelson, et al., Galactic population of black holes in detached binaries with low-mass stripped helium stars: the case of lb-1 (ls v+22 25). MNRAS, 2020.

[7] Nikolai I. Shakura, et al., Accretion processes in astrophysics. Physics Uspekhi, 2019.

[8] K. A. Postnov, et al., Rapidly rotating neutron star progenitors. MNRAS, 2016.