Dynamical features of the tilted precessing accretion disk in Her X-1

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We present the results of the analysis of the dedicated X-ray observations of the binary system Her X-1 and the archival observational data covering the entire history of X-ray studies. Several different types of temporal variability associated with the behavior of the accretion disk in the system have been found.

On August 25–26, 2023, dedicated X-ray observations were carried out with the Mikhail Pavlinsky ART-XC telescope (Revnivtsev et al., A&A, 2025). The observations covered the source in the low state, in which large-scale X-ray flux oscillations with a period of 0.88 days were detected (Fig. 1).

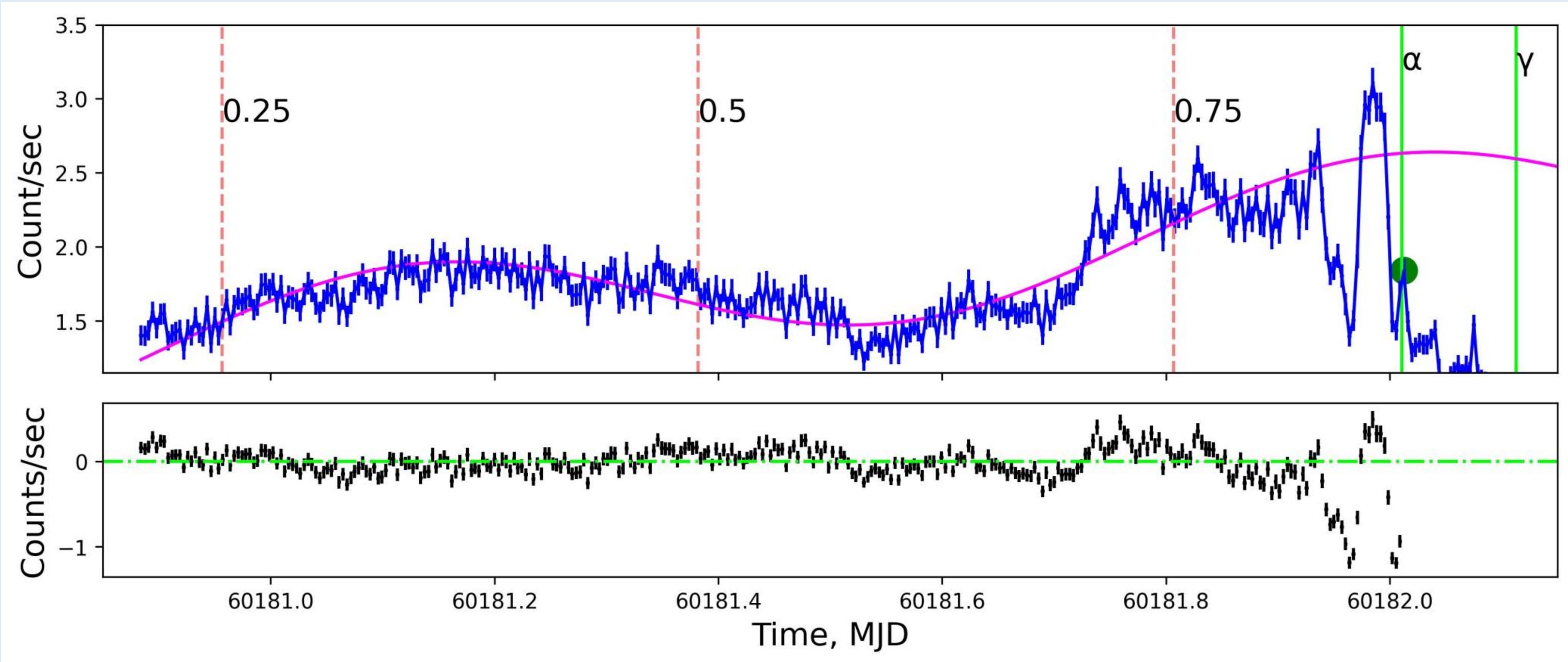

Fig. 1: SRG/ART-XC X-ray light curve (4–12 keV) of the source in the low state. The blue curve represents the data binned with a 300-second bin size; red vertical lines indicate the reference orbital phases; green vertical lines (α and γ) mark the orbital phases at the start of the accretion-disk eclipse and the neutron-star eclipse, respectively; the pink curve is the best fit obtained with a nutating accretion-disk model.

We propose an explanation of this periodicity by the behavior of the accretion disk nutation in the Her X-1 system. The pink line in Fig. 1 corresponds to the model of a nutating accretion disk: $\boldsymbol{F = a * \sin(t * \omega_{obs} - \varphi) + (t - T_0) * k + b}$, where $\boldsymbol{t}$ is the time at a given point, $\boldsymbol{T_0}$ - the start time of the observation, $\boldsymbol{\omega_{obs}}$ - the observed variability frequency $\boldsymbol{\omega_{obs} = 2 * \omega_b + \omega_{pr} - 2 * \omega_{pr}}$, $\boldsymbol{\varphi}$ - the phase of the oscillations, $\boldsymbol{a}$ – the amplitude, $\boldsymbol{b}$ - the value of the function at zero oscillation phase, $\boldsymbol{k}$ - the slope coefficient of the precessional component. We note that the observed frequency is the beat frequency between the accretion disk nutation frequency ($\boldsymbol{2 * \omega_b + \omega_{pr}}$) and the frequency of heating of the optical component by the free precessing neutron star ($\boldsymbol{2 * \omega_{pr}}$). Such a frequency is known for the SS 433, which has similar to Her X-1 dynamics of the accretion disk (Katz ApJ, 1987), but until recently it had not been detected for Her X-1.

We have performed an analysis of the archival X-ray observations of the Her X-1 system. From this analysis, we have compiled a complete catalog of all observed main-on epochs of the X-ray source (Staubert et al., A&A under rev., 2026). Using this catalog, we have identified a bimodal structure in the orbital phase distribution of the main-on times.

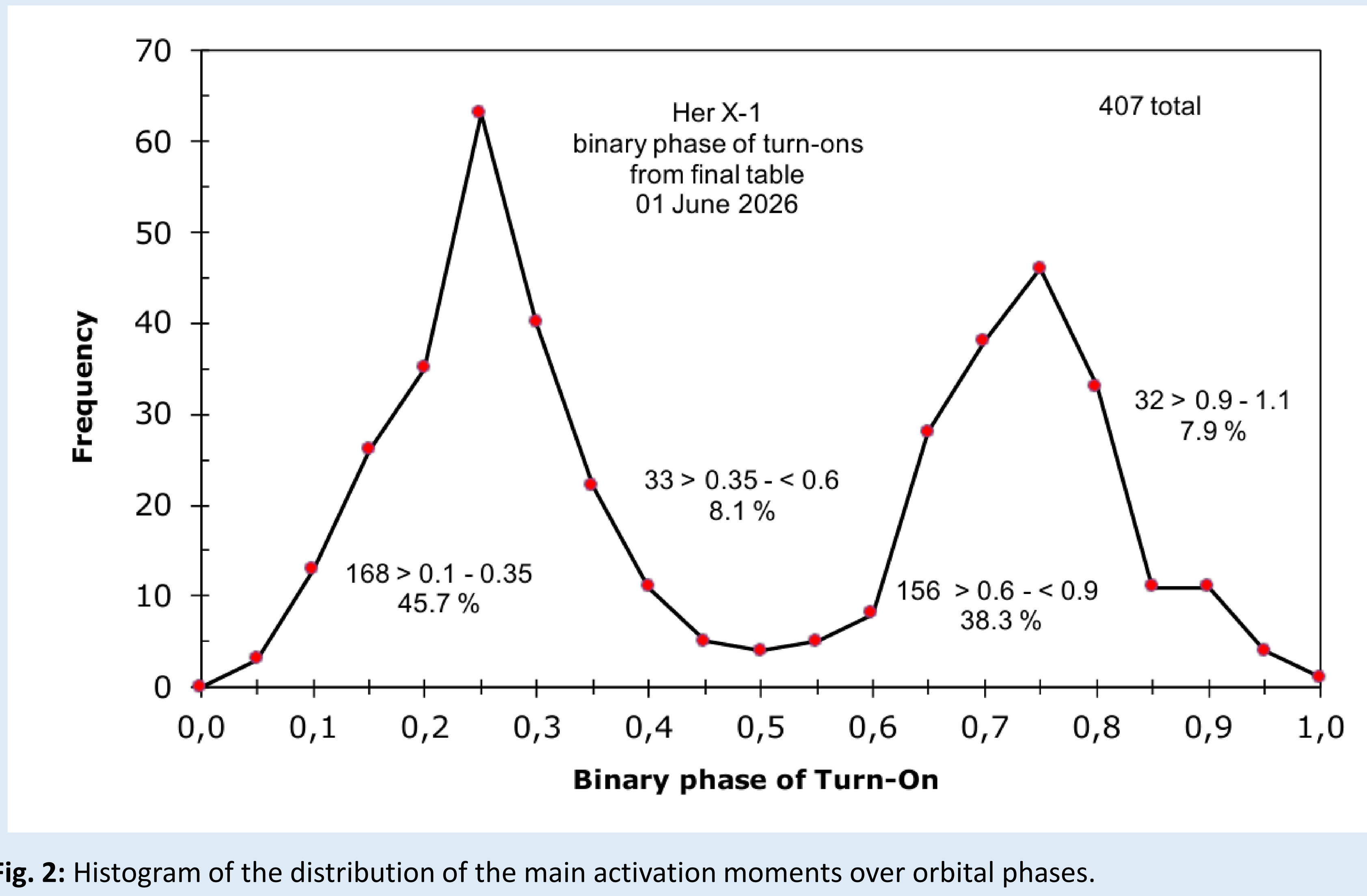

Fig. 2: Histogram of the distribution of the main activation moments over orbital phases.

Such behavior corresponds to the model of a nutating accretion disk (Levine & Jernigan, ApJ, 1982; Shakura et al., MNRAS, 1998). The precessing accretion disk, under the influence of tidal forces from the components of the binary system, should "wobble". This wobbling (nutation) affects the orbital phase of the *Turn-on*, when the eclipse of the neutron star by the accretion disk ends. The grater the amplitude of this wobble, the stronger the tidal influence. The accretion disk experiences the strongest tidal influence near orbital phases 0.25 and 0.75. At these same orbital phases, the probability of the neutron star emerging from the eclipse by the accretion disk – i.e., the *Turn-on* – should also be the highest. This is exactly what we can see in Fig. 2.

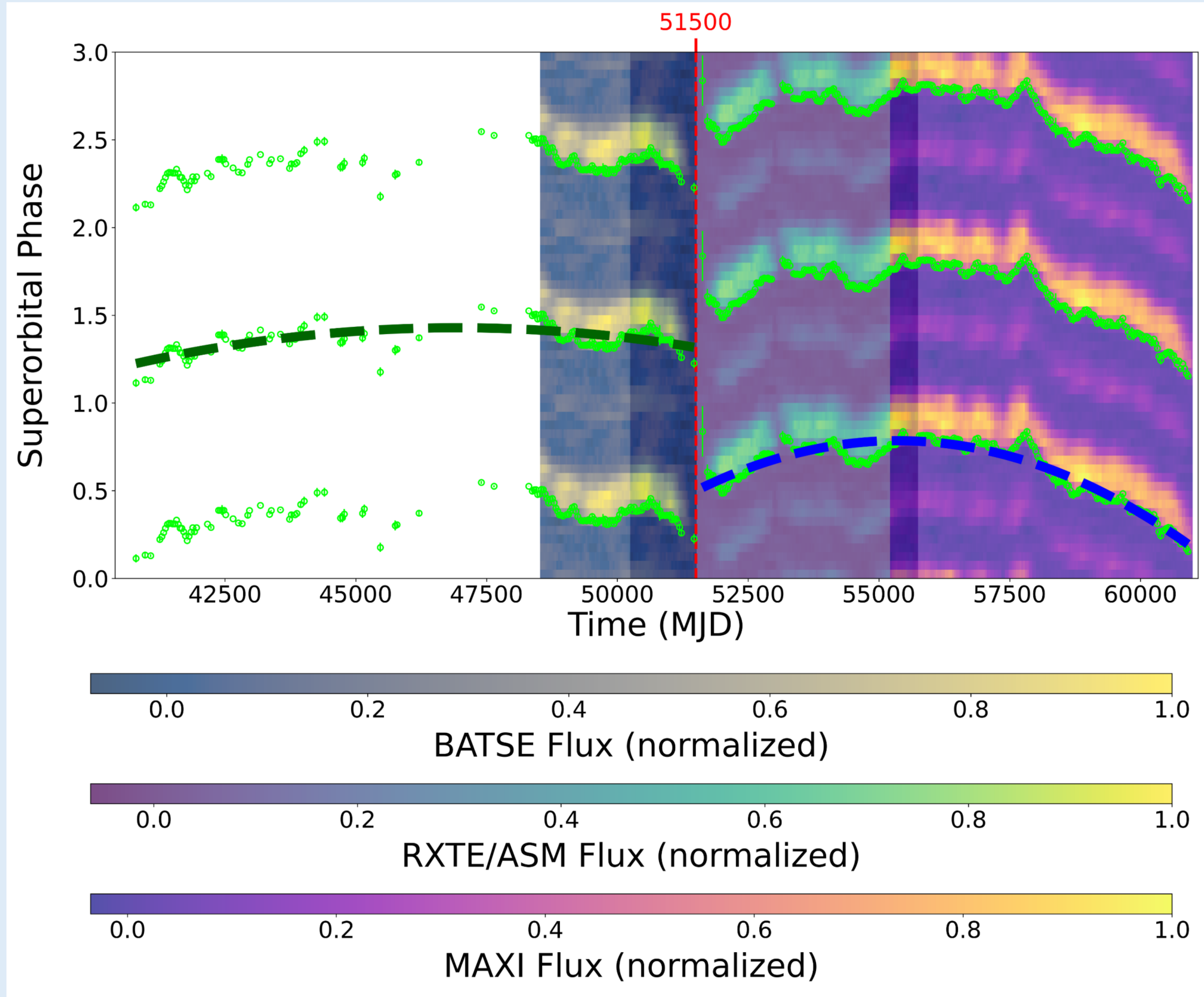

Fig. 3: O–C diagram for Her X-1 ($P_{pr} = 34.85d$; $T_0 = 55000\ MJD$). The «colored» part of the plot corresponds to data from the X-ray monitors: CGRO/BATSE, RXTE/ASM, and MAXI. The «green points» in the plot correspond to the main *Turn-on* epochs of the X-ray source, as determined from archival observations. Two epochs of the secular change in the accretion-disk precession period are distinguished (separated by the line $T = 51500\ MJD$; red vertical dashed line), with the rate of period change indicated by the green dashed line, $\dot{P}_{pr\_1} = 1.4 \times 10^{-5}\ c\ c^{-1}$, and by the blue dashed line, $\dot{P}_{pr\_2} = 4.7 \times 10^{-5}\ c\ c^{-1}$.

Fig. 3 shows an O–C diagram ($P_{pr} = 34.85d$; $T_0 = 55000\ MJD$) in which two distinct parabolic structures can be seen. A parabolic structure in such a plot indicates that the value of the period (assumed constant when constructing the diagram) is changing. We propose to separate these two parabolas by the anomalously low state (marked by the red vertical dashed line). The left (green) parabola corresponds to the value $\dot{P}_{pr\_1} = 1.4 \times 10^{-5}\ c\ c^{-1}$, and the right (blue) parabola to $\dot{P}_{pr\_2} = 4.7 \times 10^{-5}\ c\ c^{-1}$.

A similar rate of change of the precession period ($\dot{P}_{pr} \sim 10^{-5}\ c\ c^{-1}$), as well as a similar behaviour of the deviations of the observed points from the global trend (Fig. 4), is also estimated for the neutron star. This can be considered as an argument in favor of models that link these precessions.

Physical explanation and additional details can be found in our paper currently under review (Revnivtsev et al., A&A, under rev., 2026).

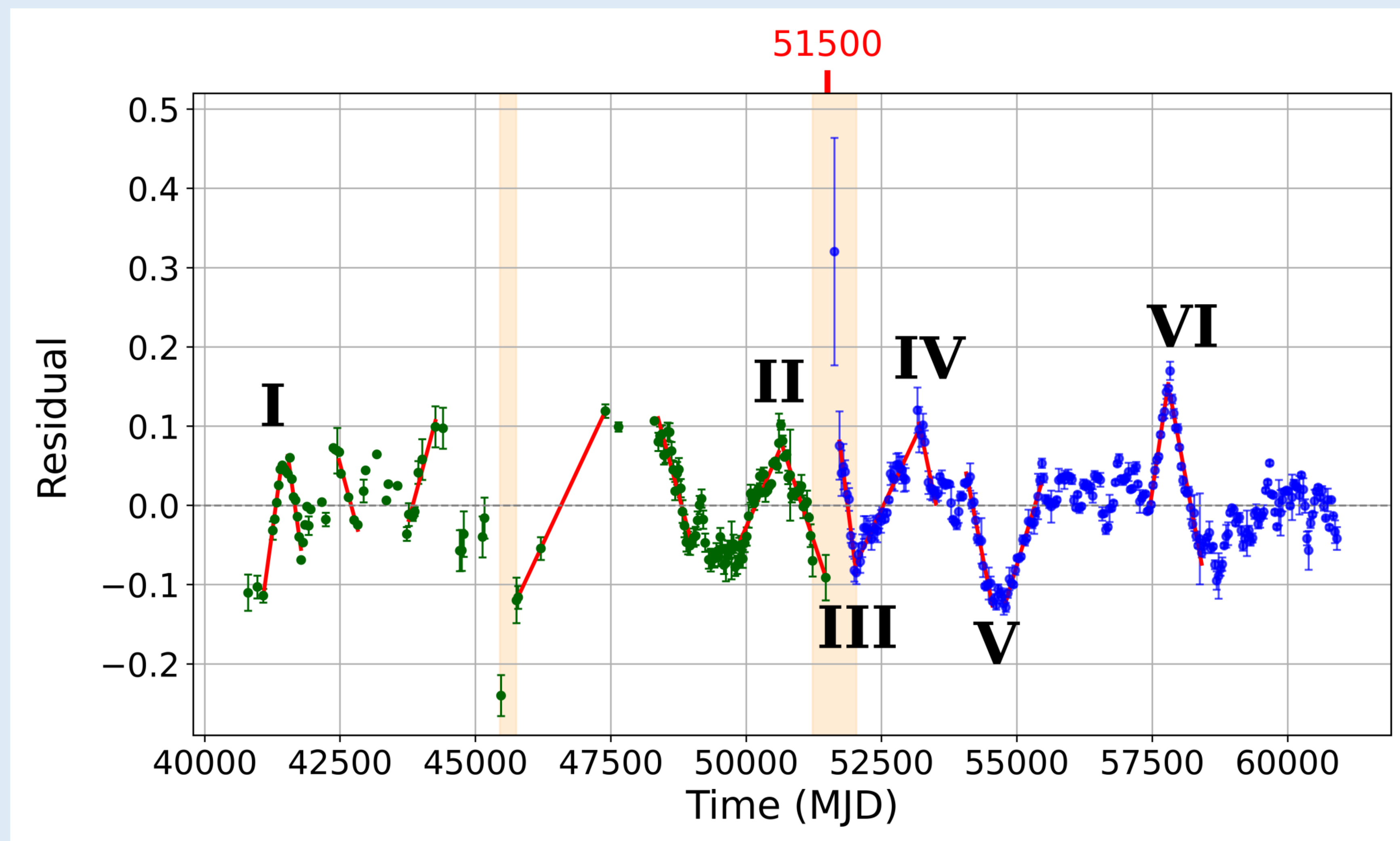

Fig. 4: The residual plot of the observed O–C diagram points from the global trend of the long-term period variation (green and blue dashed lines in Fig. 3). The beige vertical bands correspond to anomalously low states, when the accretion-disk dynamics change and the disk settles into the orbital plane.

Results*:*

1) **A periodicity of 0.88 days of the tilted warped accretion disk in the Her X-1 system has been discovered for the first time.**

2) **A bimodal distribution of the main *Turn-on* epochs of the X-ray source over the orbital phase has been revealed.**

3) **Long-term variability of the accretion-disk precession period has been found. A connection between the variability of the disk precession period and the variability of the neutron-star free-precession period is suggested.**

References*:*

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