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Multi-frequency long-term observations of Her X-1 — The 35-d cycle

N. Shakura*,[1,2] **D. Kolesnikov,**[1] **K. Postnov,**[1,2] **I. Volkov,**[1,3] **I. Bikmaev,**[2] **T. Irsmambetova,**[1] **R. Staubert,**[4] **J. Wilms,**[5] **E. Irtuganov,**[2] **P. Shurygin,**[2] **P. Golysheva,**[1] **S. Shugarov,**[1,6] **I. Nikolenko,**[3,7] **E. Trunkovsky,**[1] **G. Schonherr,**[8] **A. Schwope,**[8] **D. Klochkov**[4]

[1]*Sternberg Astronomical Institute, Moscow State University, Moscow, Russia*
[2]*Kazan Federal University, Kazan, Russia*
[3]*Institute of Astronomy RAS, Moscow, Russia*
[4]*Institute for Astronomy and Astrophysics, Tubingen, Germany*
[5]*Astronomical Institute of the University of Erlangen-Nuremberg, Bamberg, Germany*
[6]*Astronomical Institute of the Slovak Academy of Scienses, Tatranska Lomnica, Slovakia*
[7]*Crimean Astrophysical Observatory, Nauchny*
[8]*Leibniz Institute for Astrophysics, Potsdam, Germany*

In this work are presented the results of modelling of 35^d superorbital changes of B and V lightcurves and X-ray flux of HZ Her/Her X-1. The model implemented in the new code written in C programming language, with module for parameter optimisation written in Python. The model includes a tilted precessing and warped accretion disc around a freely precessing neutron star. The disc is warped near its inner edge due to interaction with the rotating neutron star magnetosphere. The magnetic torque depends on the precessional phase of the neutron star. The X-ray emission flux from the neutron star also depends on the free precession phase which modulates the X-ray illumination of the optical star atmosphere and the intensity of gas streams. We demonstrate that this model is able to well reproduce both optical observations of HZ Her and the behaviour of the 35-day X-ray cycle

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1. Introduction

HZ Her/Her X-1 is an intermediate mass X-ray binary consisting of a $1.8-2.0 M_\odot$ evolved sub-giant star and an $1.0-1.5\ M_\odot$ neutron star observed as X-ray pulsar [1]. The binary orbital period is $P_b = 1.7$ days, the X-ray pulsar spin period is $P_* = 1.24$ seconds. The optical star fills its Roche lobe and an accretion disk is formed around the neutron star (Fig. 1). Due to X-ray irradiation, the optical flux from HZ Her is strongly modulated with the orbital period, as was first found by the inspection of archive photoplates [2]. Before X-ray observations, HZ Her had been classified as an irregular variable.

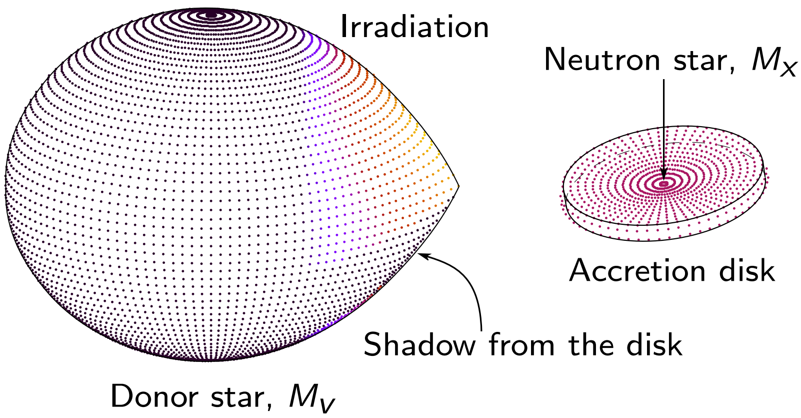

Figure 1: Appearance of the HZ Her/Her X-1. The binary orbital period is $P_b = 1.7^d$, the X-ray pulsar spin period is $P_* = 1.24^s$. The donor star fills its Roche lobe and an accretion disk is formed around the neutron star. Due to X-ray irradiation, the optical flux from HZ Her is strongly modulated with the orbital period.

The X-ray flux curve of Her X-1 is modulated with ≈ 35 day period. The 35^d-day X-ray cycle consists of a 7-orbit "main-on" state and a 5-orbit "short-on" state of lower intensity (Fig 2). The main-on and short-on states are separated by 4-orbit intervals during which the X-ray flux vanishes completely. The X-ray observations can be explained by eclipses of the central source due to the motion of a precessing accretion disk [3]. Also in the last work and in [4] were performed pioneering works for modelling of the superorbiral 35^d-period changes of lightcurves.

Soon after the discovery of the X-ray pulsar, the NS free precession was suggested as a possible explanation to the observed 35^d-day modulation [6]. Later on, the EXOSAT observations of the evolution of X-ray pulse profiles of Her X-1 with the 35-day cycle phase was also interpreted by the NS free precession [7]. Another model, based on the precession of the accretion disk, have been first presented in the paper of [8].

Extensive studies of Her X-1 suggested the presence of a warped tilted accretion disk around NS. Its retrograde precession results in consecutive opening and screening of the central X-ray source [9]. The X-ray light curve is asymmetric between the eclipses due to scattering of X-ray radiation in a hot rarefied corona above the disk. Indeed, the X-ray "turn-on" at the beginning of the "main-on" state is accompanied by a significant decrease in the soft X-ray flux because of strong absorption. No essential spectral change during the X-ray flux decrease is observed, suggesting the photon scattering on free electrons of the hot corona close to the disk inner edge [10, 11, 12, 13].

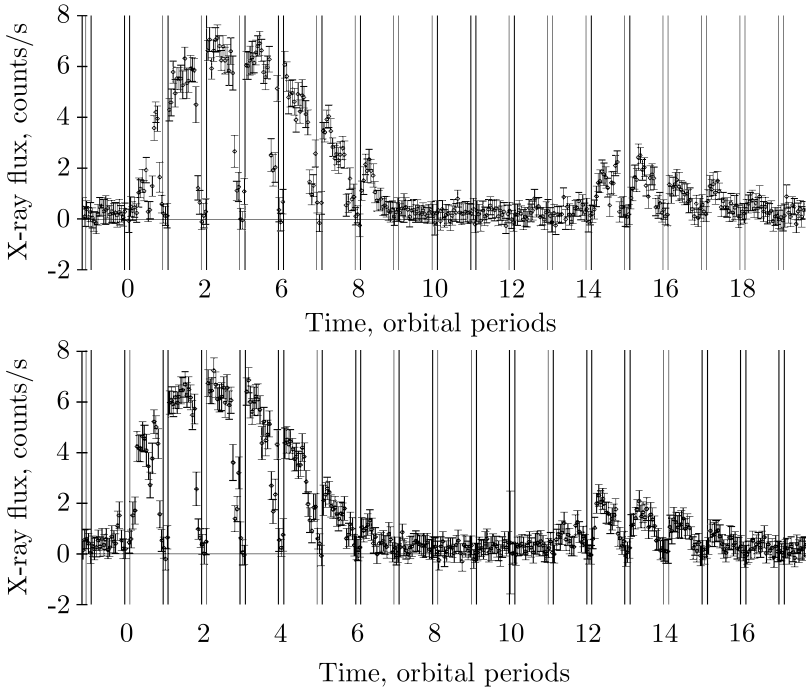

Figure 2: 35^d cycle of X-ray flux of Her X-1. The 35^d X-ray cycle consists of a 7-orbit "main-on" state and a 5-orbit "short-on" state of lower intensity. The 35^d cycle of the Her X-1 is explained by the accretion disk precession in the direction opposite to the orbital motion. Top figure show X-ray flux with the start of the main-on at orbital phase 0.7, bottom one with the start of the main-on at orbital phase 0.2. Figure from [5].

The X-ray pulse profile are observed to strongly vary with the 35^d-day phase [7, 14, 15, 16] differing significantly at the main turn-on and of the short-on states. Such changes are difficult to explain by the precessing disk only. As was shown by [17], the X-ray RXTE/PCA pulse evolution with the 35^d phase can be explained by the NS free precession with a complex magnetic field structure on the NS surface. In this model, in addition to the canonical poles (a dipole magnetic field), arc-like magnetic regions around the magnetic poles are included, which is a consequence of a likely non-dipole surface magnetic field of the neutron star [18, 19].

Longterm observations show that, there was long (up to 1.5 years) off-states of X-ray sourse, but X-ray irradiation remains unchanged [20, 21, 22, 23, 24]. Possibly, that mean accretion disk had layed in the orbital plane and X-ray source was obscured to observer. Till now it is not clearly known which mechanism take disk out of orbital plane and put it back.

History of the optical observations of HZ Her written on glass photoplates, show us long periods of absense of X-ray irradiation [25, 26]. It means in that periods accretion completely vanishes.

In the present work, we have analyzed the nature of 35^d cycle on the base of an extensive optical photometric observations of HZ Her collected from the literature and obtained by the authors. We have found that the the model of precessing tilted and warped accretion disk combined with the free precession of the neutron star with complex surface magnetic field is able to explain a detailed photometric light curve of HZ Her constructed from all observations available.

2. Model

Donor star shape is defined by equipotential surface of the Roche potential. The effective temperature of the donor star varies across the surface due to gravity darkening and X-ray irradiation. The disk in the model warped and tilted (Fig. 3). The disk makes a complex X-ray shadow on the surface of the donor star. We suggest that the disk warped mostly near the neutron star due to magnetic torque. Near the orbital phase 0.5 disk passes in front of the donor star. We use a

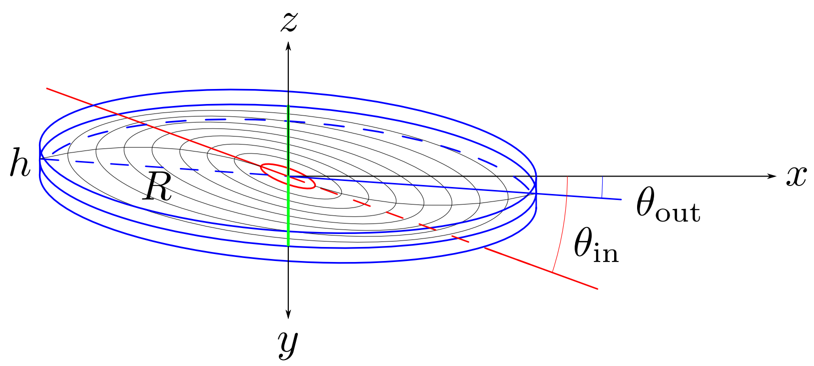

Figure 3: Model of the disk. There are 7 free parameters in the model that completely define the shape and orientation of the disk: θ_{out} — tilt of the outer edge of the disk with respect to the orbital plane, θ_{in} — tilt of the inner edge with respect to the orbital plane, φ_{out} — phase angle of precession motion, Z — angle between the nodal line of the outer edge of the disk and the nodal line of the inner edge of the disk (on the figure $Z = 0$, see green line), inclination i and phase where $\varphi_{out} = 0$. Phase $\varphi_{out} = 0$ corresponds to the maximum opening of the disk. In addition, the width h of the outer edge of the disk was included in the model.

ray-tracing technique to determine which parts of the star's surface are obscured by the disk. We haven't modelled orbital phases near 0.0, where the disk passes behind the donor star. The neutron star's X-ray intensity adopted from [17]. The neutron star is under free precession with a period close to 35^d.

3. Results

Here we show found parameters of the model as a function of the phase of 35^d cycle. Also we show the lightcurves corresponding to the minimum of residuals between model and observations (Fig. 4). The most interesting result that the the angle Z, which defines torsion of the disk, follows the theoretical magnetic torque K_m acting on the disk's inner edge (Fig. 6, Z). Inner edge of the disk tends to be close to the NS's equator when magnetic torque reaches maximal value (Fig. 6, θ_{in}), which was predicted by [27].

Resent XMM-Newton satellite observations showed- the presence of the modulation of disk wind mass outflow rate with 35^d superorbital period [28]. This result is in according to the model of free precession of the neutron star. Wind becomes stronger when the magnetic pole of the neutron star gets the most close to the disk plane.

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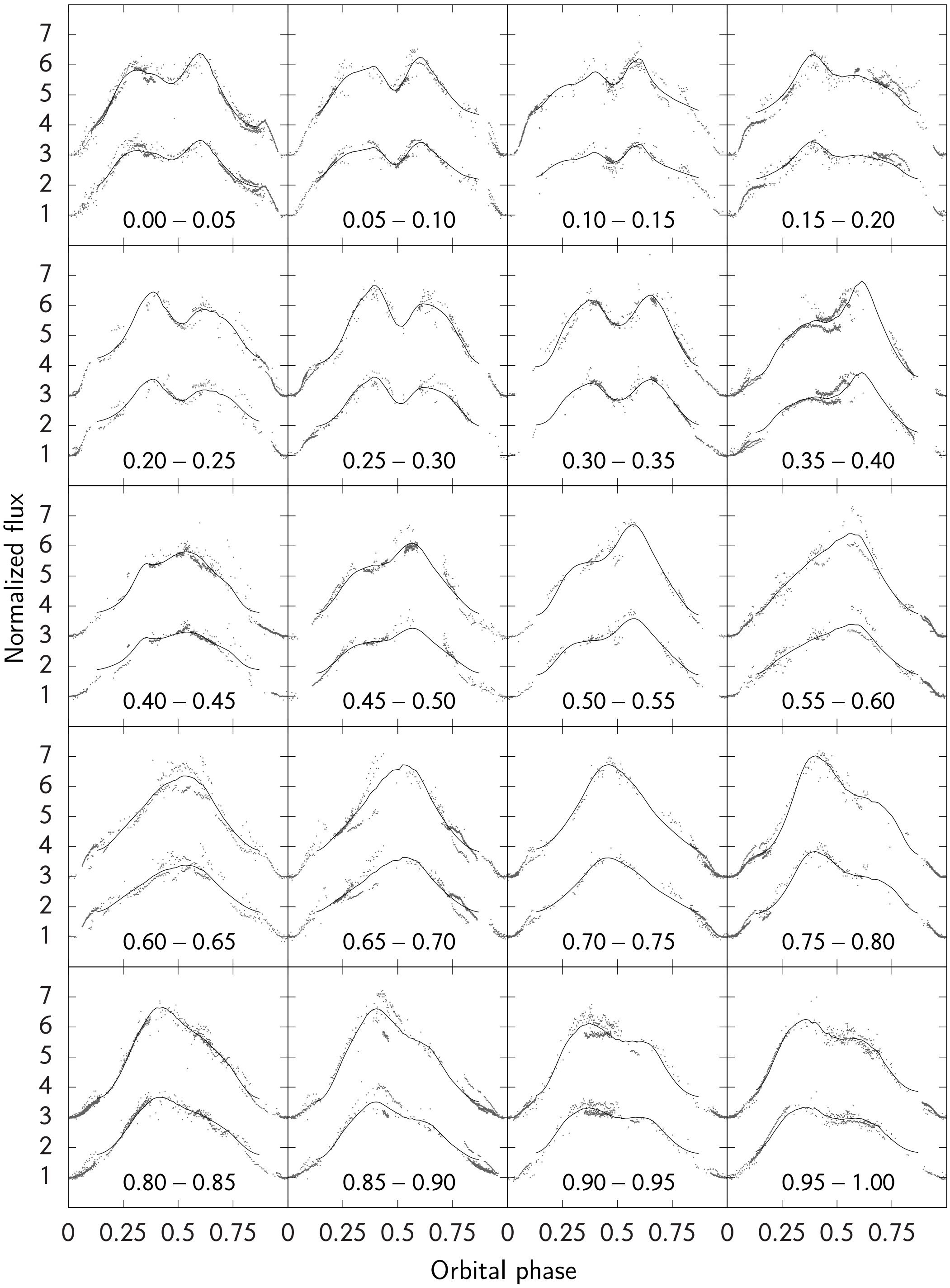

Figure 4: Relative *B* and *V* flux. Observed (points) and theoretical lightcurves (solid lines). The numbers in the cells indicate a phase interval of 35^d cycle. Data in filter *B* is shifted up to 2 units with respect to *V* filter. The optimum theoretical lightcurve for every phase is shown.

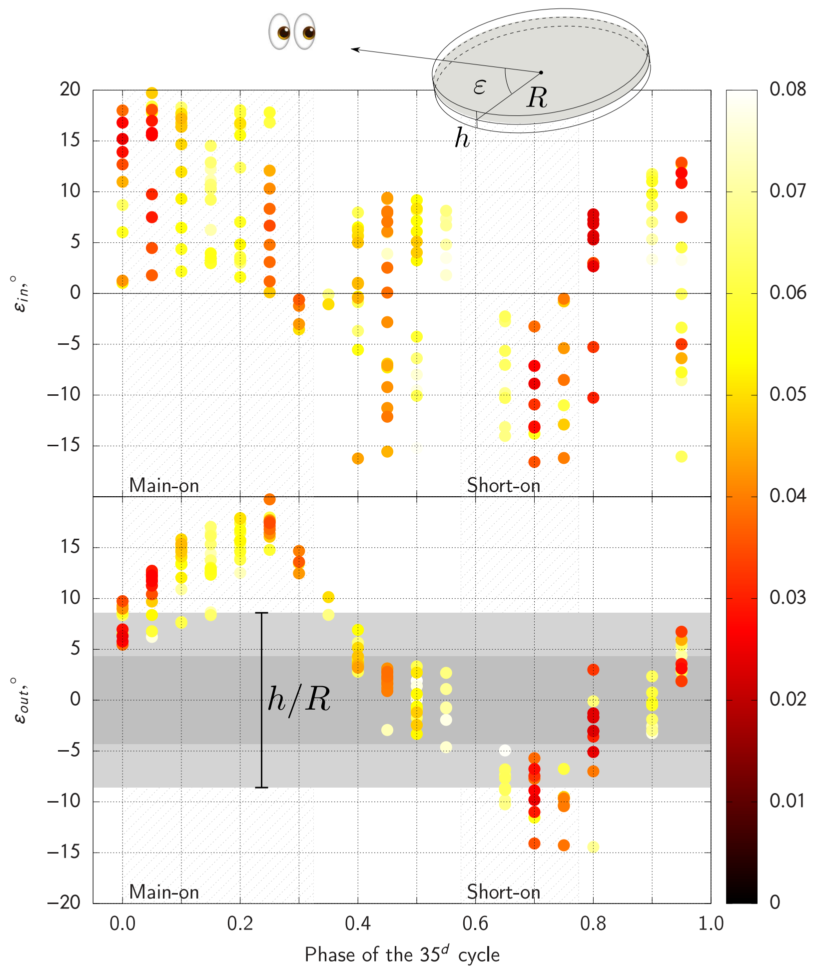

Figure 5: ε_{out} is the angle between the observer's line of sight and the disk's outer plane, see picture above graph. ε_{in} is the angle between the observer's line of sight and the disk's inner plane. The vertical shaded regions indicate an interval of 35^d cycle where X-ray flux is visible ("Main-on" and "short-on"). The horizontal shaded area on the second graph is the width of the outer edge of the disk.

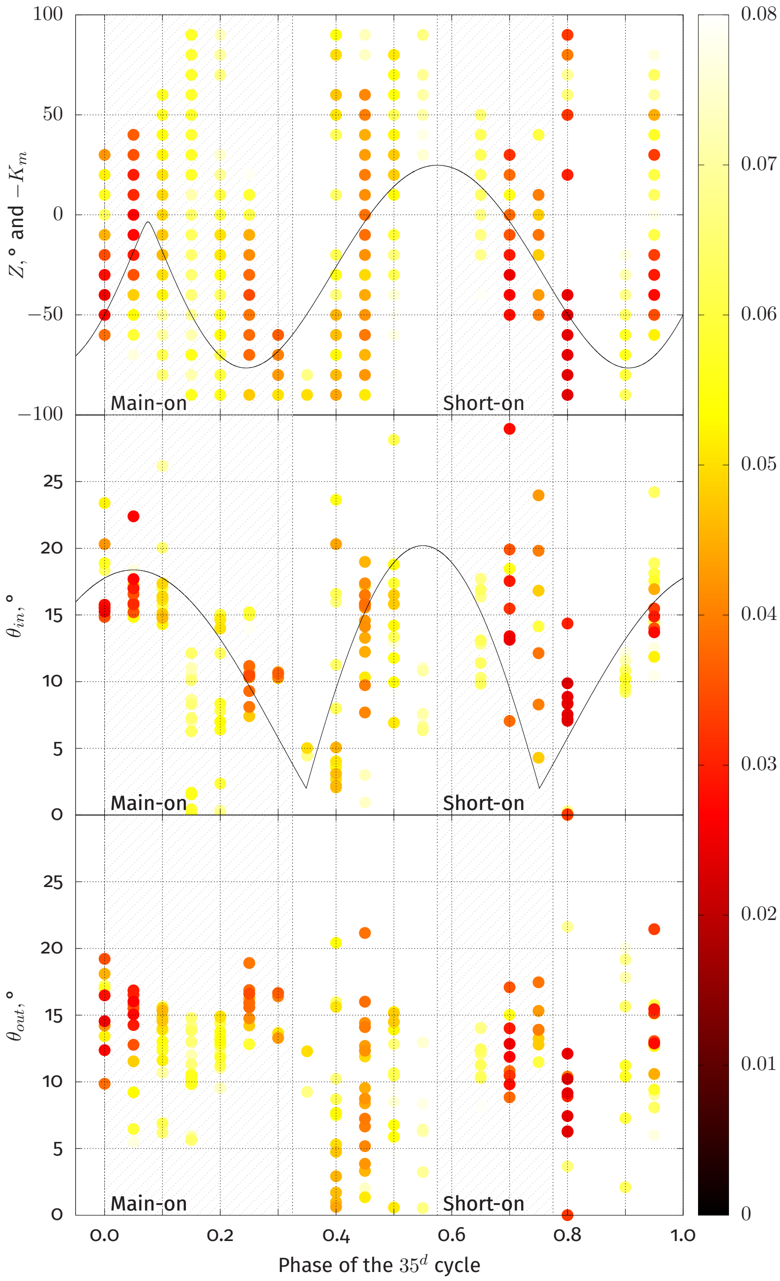

Figure 6: Z is the angle between the nodal lines of the inner and outer edges of the disk. θ_{in} and θ_{out} are the angles between the disk's plane and the orbital plane (see Fig.3). The solid line on the first graph is the theoretical magnetic torque K_m acting on the disk's inner edge [27]. Notice strong corellation of the θ_{in} with Z. When the magnetic torque K_m is maximal, inner edge of the disk becomes closer to the equatorial plane of the neutron star. Change of Z and θ_{in} with 35^d cycle favors to the presence of the free precession of the neuthon star.