High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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On the nature of the 35-day cycle in the X-ray binary Her X-1/HZ Her

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Abstract. The X-ray binary Her X-1 consists of an accreting neutron star and the optical companion HZ Her. The 35-day X-ray variability of this system is known since its discovery in 1972 by the UHURU satellite and is believed to be caused by forced precession of the warped accretion disk tilted to the orbital plane. We argue that the observed features of the optical variability of HZ Her can be explained by free precession of the neutron star with a period close to that of the forced disk precession. The model parameters include a) the intensity (power) of the stream of matter flowing out of the optical star; b) the X-ray luminosity of the neutron star; c) the optical flux of the accretion disk; d) the X-ray irradiation pattern on the donor star; e) the tilt of the inner and outer edge of the accretion disk. A possible synchronization mechanism based on the coupling between the neutron star free precession and the dynamical action of non-stationary gas streams is discussed shortly.

Keywords. X-rays: binaries, stars: neutron, stars: binaries: close

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 (Tananbaum *et al.* 1972). The orbital period is 1.7 days, the X-ray pulsar spin period is 1.24 seconds. The optical 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, as was first found by the inspection of archive photoplates (Cherepashchuk *et al.* 1972). Note that before X-ray observations, HZ Her was classified as an irregular variable.

The X-ray light curve of Her X-1 is modulated with a 35 day period. Most of the 35-day cycles last 20.0, 20.5 or 21.0 orbital periods (see, e.g. Shakura *et al.* (1998), Klochkov *et al.* (2006)). The 35-day X-ray cycle consists of a 7-day “main-on” state and a 5-day

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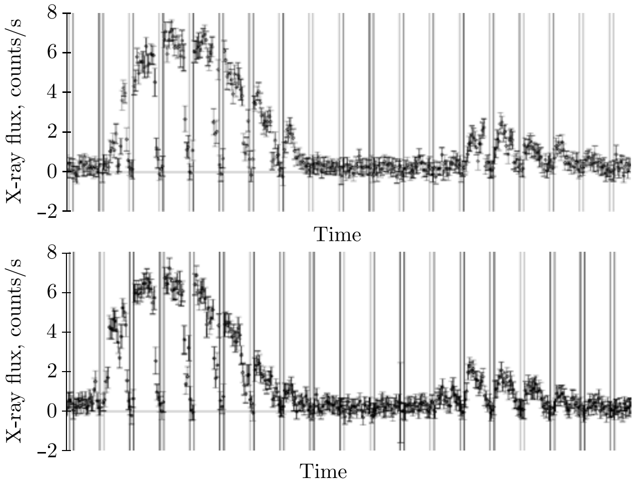

Figure 1. RXTE/ASM light curves of the 35-day X-ray cycle (Shakura *et al.* (1998), Klochkov *et al.* (2006)). Vertical lines show eclipses of the X-ray source by the donor star. Top: the "turn on" near the orbital phase 0.7. Bottom: the "turn on" near the orbital phase 0.2.

"short-on" state of lower intensity, separated by two 4-day "off" states during which X-ray radiation switches off completely (Fig. 1). The X-ray observations of the flux are well explained by the precession of the accretion disk.

2. 35-day cycle

The 35-day cycle turn-ons most frequently occur at the orbital phases ~ 0.2 or ~ 0.7, which is due to the tidal nutation of the outer parts of the disk with the double orbital frequency when the angle between the line of sight and the outer parts of the disk changes most rapidly (Katz (1973), Levine & Jernigan (1982), Boynton (1987)). The 35-day cycle of Her X-1 is explained by the accretion disk precession in the direction opposite to the orbital motion (Gerend & Boynton (1976), Shakura *et al.* (1999)). Soon after the discovery of the X-ray pulsar, the NS free precession was suggested to explain the observed 35-day modulation (Brecher 1972). Later on, the EXOSAT observations of the evolution of X-ray pulse profiles of Her X-1 were also interpreted by the NS free precession (Truemper *et al.* 1986). Extensive studies of Her X-1 suggested a warped and tilted accretion disk around the NS. Its retrograde precession results in consecutive opening and eclipses of the central X-ray source (Boynton 1987).The X-ray light curve is asymmetrical between the eclipses due to the scattering of the 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. There is no essential spectral change during the X-ray flux decreases, suggesting the photon scattering on free electrons of the hot corona near the disk inner edge (Becker *et al.* (1977), Davison & Fabian (1977), Parmar *et al.* (1980), Kuster *et al.* (2005)). The X-ray pulse profiles are observed to vary with the 35-day phase (Truemper *et al.* (1986), Deeter *et al.* (1998), Scott *et al.* (2000), Staubert *et al.* (2013)) differing significantly at the main turn-on and at the short-on. Such changes of the pulses are difficult to explain using the precessing disk only.

The X-ray RXTE/PCA pulse evolution with 35-day phase can be explained (Postnov *et al.* 2013) 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

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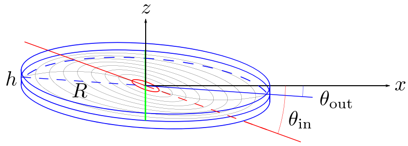

Figure 2. Model of the disk. Inner edge colored in red, outer edge colored in blue. Width h of the outer edge and radius R also showed. Twist angle on the picture equals 0 (nodal lines are coloured in green). Tilt angle of the inner edge is $\theta_{\rm in}$, tilt angle of the outer edge is $\theta_{\rm out}$. y-axis directed along the nodal lines off the reader.

magnetic regions around the magnetic poles are included, which is a consequence of a likely non-dipole magnetic field (Shakura *et al.* (1991), Panchenko & Postnov (1994)).

3. Modeling of the optical light curves of HZ Her

Here we perform a modellng of long-term B-light curves. The photometrical light curve was constructed using the following observations: 1972 – 1998 data compiled from Petro & Hiltner (1973), Davidson *et al.* (1972), Davidson *et al.* (1972), Boynton *et al.* (1973), Lyutyj (1973), Grandi *et al.* (1974), Lyutyj (1973), Cherepashhuk *et al.* (1974), Voloshina *et al.* (1990), Lyutyj & Voloshina (1989), Kilyachkov & Shevchenko (1978), Kilyachkov & Shevchenko (1980), Kilyachkov & Shevchenko (1988), Kilyachkov (1994), Kippenhahn *et al.* (1980), Gladyshev (1985), Mironov *et al.* (1986), and Goransky & Karitskaya (1986) ($\approx$ 5800 points); 2010 – 2018 data were obtained by the present authors ($\approx$ 7600 points).

The model includes two basic components:

a) an inclined, warped, forced precessing accretion disk;

b) a freely precessing neutron star.

The shape of the model optical light curve strongly depends on the X-ray shadow on the optical star produced by the warped accretion disk and on the X-ray irradiation pattern. The shadow is calculated as follows. The disk is splitted along the radius in a finite number of rings and the solid angle between each i-th and $i+1$-th ring is calculated, giving the i-th element of the shadow. As the disk is warped, the i-th and $i+1$-th rings lie in different planes. The full shadow is produced by all elements.

Geometrical parameters of the disk are given by the tilt to the orbital plane and the phase disk angle which are different for the outer and inner disk edges (See Fig. 2). The disk phase is counted opposite to the orbital motion. It is set to $0.00-0.05$ at the moment of the X-ray "turn on". The tilt and phase angles of the i-th ring change linearly from the outer edge to the inner edge. The difference between the inner and outer edge is called the twist angle. The twist angle and the difference between the tilt angle of the outer and inner disk edge determine the shadow size. If the twist angle is zero and the tilt of the outer and inner edge is the same, the disk shadow is determined only by the width of the outer disk.

To calculate the X-ray irradiation of the optical star we have used the model by (Postnov *et al.* 2013). This model has been modified to limit the precessional motion of the North magnetic pole to $\beta_{cr} = \arccos(\sqrt{3}/3) \approx 54^\circ\, 44'$. If the magnetic dipole axis is inclined by β_{cr} to the NS rotation axis, the magnetic torque on the inner edge of the disk vanishes (Lipunov & Shakura (1976), Lipunov *et al.* (1981), Lipunov (1987)).

To the north and to the south of this angle, the magnetic torque is non-zero; the sign of the twist angle is expected to change when crossing this critical angle. However, we found that the model with the twist angle changing sign gives a less good fit to the observation than the model with a constant sign. Therefore, we set the angle between the NS precession and axes to 80°, and the angle between the magnetic dipole and precession

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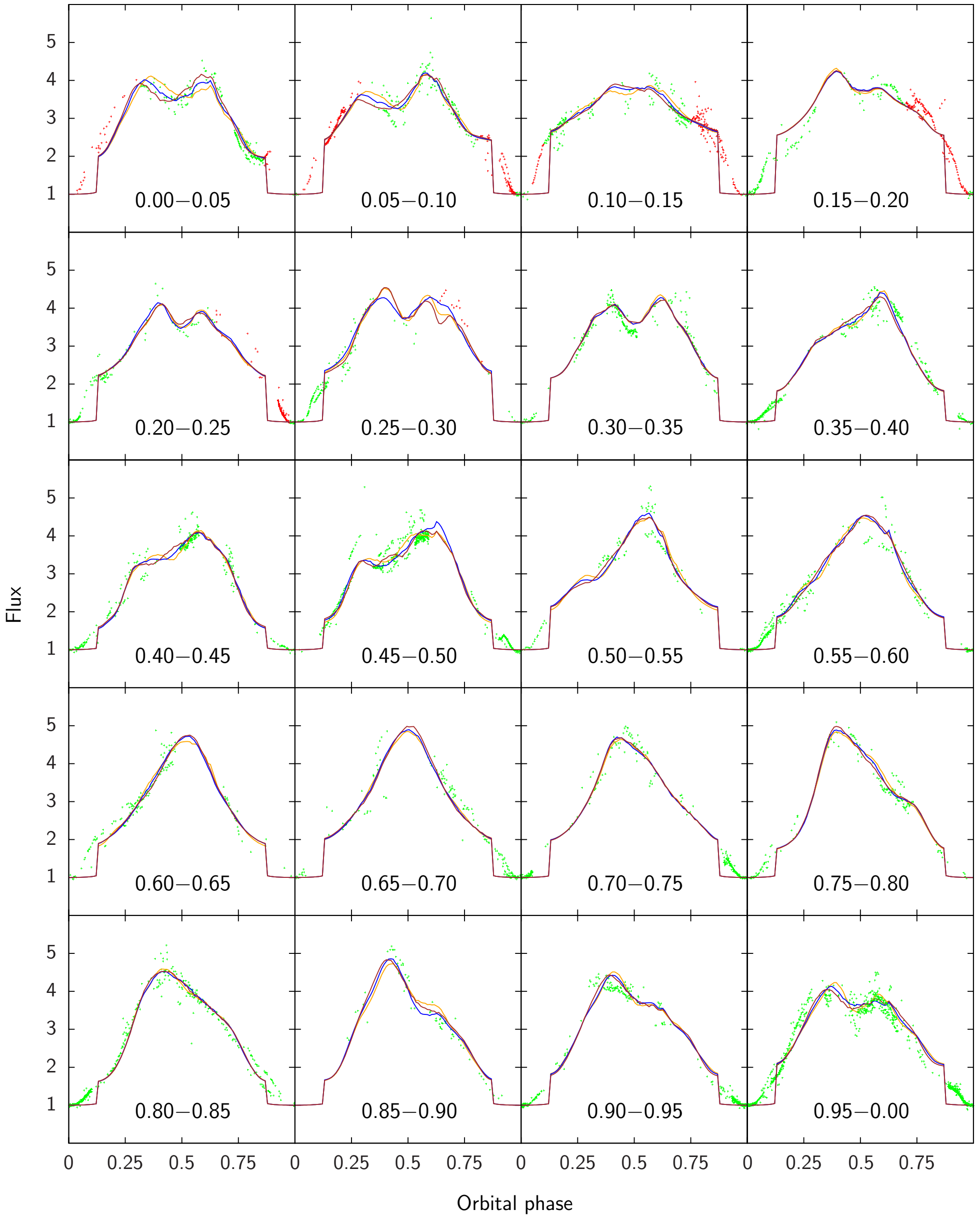

Figure 3. Synthetic light curves and observed data (points). The 35-day period is divided in 20 phase bins each. Phase $0.00-0.05$ correspond to the X-ray "turn on". The data are colored: in green — the most robust points; in grey — less robust points; in red — points correspond to the gas stream acting on the disk (bright spot). At each phase three synthetic light curves are shown: in orange, blue and brown corresponding to a twist angle of -50, -60 and -70, respectively.

axes to 20°. In this case the angle between the dipole and NS spin axes varies within the range $60° - 100°$ and the magnetic torque does not change sign during the free precession period.

At the 35-day phase $0.25-0.30$ from the "turn on", the magnetic dipole reaches a maximal angle of $80+20=100°$ to the rotation axis (this is the phase 0 of the NS free

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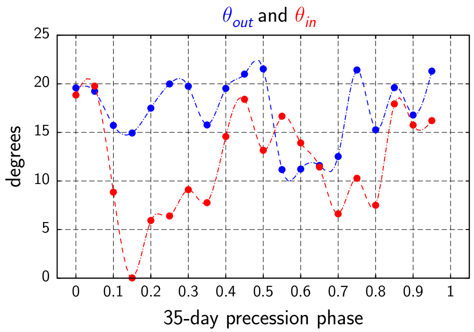
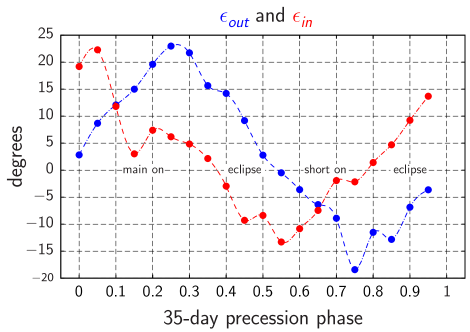
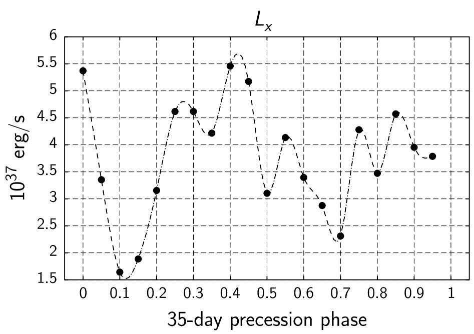


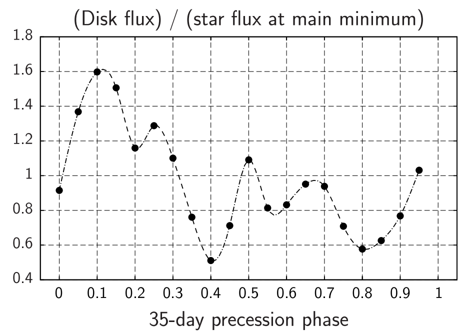
Tilt of the outer $\theta_{\rm out}$ and inner $\theta_{\rm in}$ edge of the disk as a function of the disk precession phase.



The angle between the direction to the observer and the outer $\epsilon_{\rm out}$ and the inner $\epsilon_{\rm in}$ disk planes as a function of the disk precession phase.



X-ray luminosity as a function of the disk precession phase.



The disk contribution to the optical flux normalized to the flux from the non-irradiated side of the optical star as a function of the disk precession phase.

Figure 4. Figure 4: Best-fit parameters of the model

precession). At the phase $0.75-0.80$, this angle is $80-20=60°$ (this is phase 0.5 of the NS free precession). This difference $(0.25-0=0.75-0.5=0.25)$ between NS free precession phase and phase counted from X-ray "turn on" is the best-fit value.

Orientation of the NS in the picture plane does not affect the shape of the X-ray pulses, but has a strong effect on the optical light curve. This makes it is possible to determine the orientation of the NS spin axis with respect to orbital plane. The angle between the NS spin axis and the projection of the normal to the orbital plane on the sky is called κ.

The best-fit over all precession phases is obtained for $\kappa=5°$. The tilt and phase of the outer and inner disk, the X-ray luminosity and contribution to the optical flux from the disk have been optimized at each precessional phase (see Fig. 3). The best-fit twist angle of the disk is $-60°$. The minus sign means that during the precession motion, the outer disk lags behind the inner disk. Figure 4 shows the best-fit parameters of the model. Figure 3 shows the synthetic light curves with three different twist angles: -50, -60, -70, and observed B light curves of HZ Her.

The modeling was not performed for the orbital phase intervals $0.0-0.13$ and $0.87-1.0$. At these phases, the disk is eclipsed by the optical star. The brightness distribution over the disk is complex, and we leave its study for future work.

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Several peak-like features at the first five precessional phase intervals shown in Fig. 3 should be noted (red dots). These features were observed for the first time by Kippenhahn *et al.* (1980). This is the result of non-stationary streams striking the accretion disk. These streams form an important part of the general nonlinear dynamics of the system. The streams synchronize the forced accretion disk precession and the NS free precession. Importantly, such a situation is realized only if the NS rotation axis is misaligned with the angular orbital momentum (the non-zero angle κ in our notation).

Period of the NS's free preceession is stable on timescales of several dozens precession cycles (Postnov *et al.* 2013). The disk precession period is not so stable. There are two reasons for forced disk precession: the main reason is the tidal-driven precession (opposite to the orbital motion) and second reason is dynamical action of the streams (along to the orbital motion). There is an equilibrium state of the system in which period of the free precession and forced precession is the same. If disk deviates from this equilibrium state to shorter period then X-irradiation becomes larger and power of the streams also becomes larger and vice versa. It makes disk to return to the equilibrium period.

The optical light curves demonstrate the secondary minimum near the precession phase 0.25 because of the passing of the disk and of the widest part of the shadow above the irradiated part of the optical star at the orbital phase about 0.5. The secondary minimum is absent at the precession phase near 0.75 because the disk is projected onto its own shadow on the optical star surface.

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