On the Nature of the 35-day Cycle in X-ray Binary Her-X-1 = HZ Her

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The X-ray binary Her X-1 consists of an accreting neutron star and the optical component 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 precession of the warped accretion disk tilted to the orbital plane. We assume that the neutron star undergoes free precession and argue that the optical variability of HZ Her can be explained by forced precession of the accretion disk with a similar period as that of the neutron star. 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.

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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 a $1.0 - 1.5\ M_\odot$ neutron star observed as X-ray pulsar [1]. The binary 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, being first found by the inspection of archive photo-plates [2]. (Note that before X-ray observations, HZ Her was classified as irregular variable).

The X-ray flux curve of Her X-1 is modulated by a 35 day period. Most of the 35-day cycles lasts 20.0, 20.5 or 21.0 orbital periods (see, e.g., [3],[4],[5]). The 35-day X-ray cycle consists of a "main-on" of seven orbital periods and a "short-on" of five orbital periods, separated by two "off-states" of four orbital cycles each, during which the X-ray flux switches off almost completely. The X-ray observations are well explained by the precessing accretion disk.
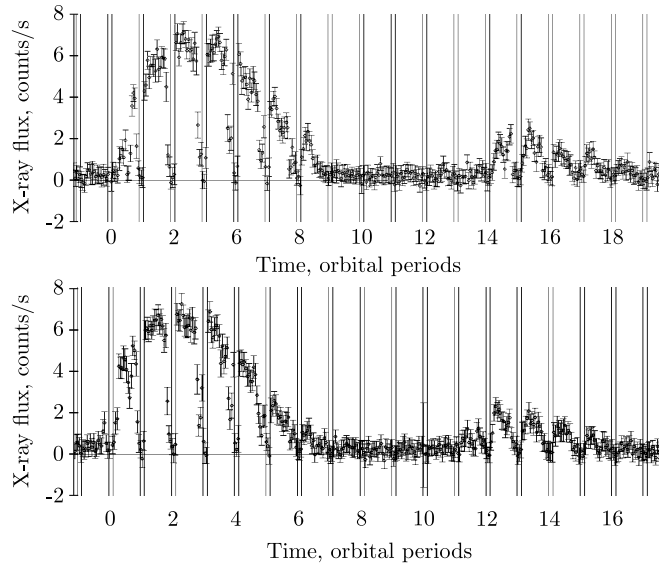

Figure 1: RXTE/ASM light curves of the 35-day X-ray cycle [4]. The vertical lines show eclipses of the X-ray source by the donor star. Top: the "main opening" (also called "turn-on") near orbital phase 0.7. Bottom: the "main opening" near orbital phase 0.2.

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 [6], [7], [8]. The 35-day cycle of Her X-1 is explained by the precession of the accretion disk, precessing in the opposite direction of the orbital motion [9], [10]. Soon after the discovery of the X-ray pulsar, NS free precession was suggested to explain the observed 35-day modulation [11]. Later on, EXOSAT observations of the evolution of the X-ray pulse profiles of Her X-1 were also interpreted by free

precession of the NS [12]. Extensive studies of Her X-1 suggested a warped tilted accretion disk around the NS. Its retrograde precession results in consecutive openings and eclipses of the central X-ray source [8]. 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 lack of the soft X-ray flux because of strong absorption. There is no essential spectral change during the X-ray flux increase, suggesting photon scattering on free electrons of the hot corona near the disk inner edge [13], [14], [15], [16]. The X-ray pulse profiles are observed to vary with 35-day phase [12]], [17], [18], [19] changing significantly during the main-on and the short-on. Such changes are difficult to explain using the precessing disk only. The X-ray RXTE/PCA pulse evolution with 35-day phase can be explained [20] by NS free precession with a complex magnetic field structure on the NS surface. In this model, in addition to the canonical field (a magnetic dipole field), arc-like magnetic regions around the magnetic poles are included, which is a consequence of a likely non-dipole magnetic field [21], [22]. Another explanation of the changes of the X-ray flux and X-ray pulses rely on the partial blocking of the NS surface by the inner part of the accretion disk [18],[23]. Such suggestions require fine-tuning of the angle of the inner part of the disk. For reasonable assumptions for the inner radius $R_{in} \approx 100 R_{NS}$, the accuracy of the angle of the inner disk should be $\theta_{in} \sim R_{NS}/R_{in} \approx 0.5°$. Our model requires only $\theta_{in} > 0$ at the short-on. Moreover, the hot corona above the inner edge of the disk has a finite opacity and it blurs the X-ray pulses, but in model [23] the inner edge should be sharp in order to partially cover the NS surface.

3. Modeling of optical light curves of HZ Her

Here we performed a modeling of long-term B-light curves. The photometrical light curve was constructed using the following observations: 1972 – 1998 data compiled from [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40] ($\approx$ 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 the X-ray irradiation pattern. The shadow is calculated as follows. The disk is split 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.

The geometrical parameters of the disk are given by the tilt to the orbital plane and the phase disk angle (changing smoothly from the outer to the inner disk edges). The disk phase is counted along the orbital motion. It is set to zero at the moment of the maximal opening of the outer disk with respect to the observer. 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 [20]. In this model despite of usual rotation of the NS with $P_{rot} = 1.24^s$ period there is rotation along one of the three main inertia axes with $P_{pr} \approx 35^d$ period due to the free precession (Fig. 2). The angle between the
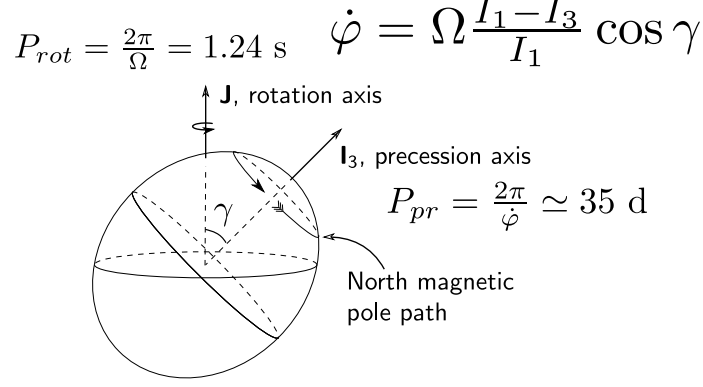
$$P_{rot} = \tfrac{2\pi}{\Omega} = 1.24 \text{ s} \qquad \dot{\varphi} = \Omega \frac{I_1 - I_3}{I_1} \cos\gamma$$

$$P_{pr} = \frac{2\pi}{\dot{\varphi}} \simeq 35 \text{ d}$$

Figure 2: Scheme of the free precession of the NS.

rotation axis and the inertia axes $\gamma = 50°$. The angle between the magnetic dipole axis and the inertia axis is $30°$. During the free precession the magnetic dipole axis covers a small circle on the sky with radius $30°$.

At the 35-day phase 0.1 from the "main opening", the angle between the magnetic dipole axis and rotational axis becomes maximal ($\beta = 50° + 30° = 80°$). This is the phase zero of the NS free precession. At phase 0.6, this angle is minimal ($\beta = 50° - 30° = 20°$). This is phase 0.5 of the NS free precession.

If the magnetic dipole axis is inclined at $\beta_0 = \arccos(\sqrt{3}/3) \approx 54.7°$ to the NS rotation axis, the magnetic torque $\mathbf{K_m}$ on the inner edge of the disk vanishes (Fig. 3) [41], [42], [43].

$$\mathbf{K_m} = \frac{4\mu^2}{3\pi R_d^3} \cos\alpha (3\cos\beta - 1)[\mathbf{n}_\omega, \mathbf{n}_d] \tag{3.1}$$

Here μ is the magnetic moment of the NS, R_d is the inner radius of the disk, α is the angle between NS's rotational axis and the inner disk axis, β is the angle between the rotational axis of the NS and the NS's magnetic axis. $\mathbf{n}_\omega$ is the unity vector along NS's rotational axis, $\mathbf{n}_d$ is the unity vector along the disk's axis.

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. Non-zero magnetic torque causes the twist of the inner edge of the disk with respect to the outer edge. In other words, node lines of the inner and outer edges of the disk do not match, there is an angle between them that we call Z, which can be both greater or lower than zero depending on the sign of the magnetic torque. The negative sign means that during the precessional motion, the outer disk drags behind the inner disk and vice versa. The value of the angle β (the angle between magnetic dipole axis and the rotational axis) becomes equal to β_0 twice during the free precession period. At this moments we should expect
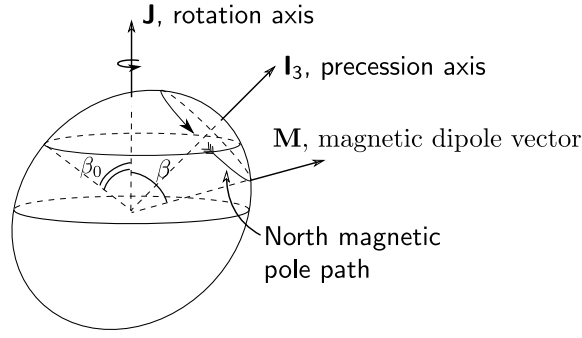
Figure 3: Path of the magnetic dipole due to free precession. Here β is the angle between the magnetic dipole axis and the rotational axis. If $\beta = \beta_0$, then $K_m = 0$.

$Z = 0$. So, we should expect the opposite sign of Z in the North and in the South. Orientation of the NS rotation axis 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 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 overall precession phase is obtained for $\kappa = 8°$ with the 35-day precession phase 0.1 and 0.6 corresponding to the NS precession phase 0 and 0.5, respectively.

During the 35-day cycle the disk has a variable angular velocity with a mean value of $18°$ per orbit (Fig. 4). The angular velocity of the inclined disk is defined by the tidal forces of the binary system and the dynamic action of the accretion streams. The accretion streams reduce the disk's angular velocity. The disk has the lowest velocity at phases near 0.1 where irradiation by the NS is maximal. Previously, we had suggested a simpler model with a constant angular velocity of the disk and constant Z [44]. The present refined model with a variable angular velocity of the disk provides better fits than the model with constant angular velocity.

When the irradiation is maximal, the accretion flow is also maximal and the dynamic action of the accretion streams on the disk becomes maximal too. On the other hand, at the maximal angular velocity of the disk (at phases near 0.6 where NS's north magnetic pole is most distant from the equator of the NS) the irradiation effect is minimal. We suggest the following formula for the angular velocity of the disk: $\dot{\phi}[°/1.7^d] = 18° - A\cos[2\pi(x - 0.05)]$, where A is the semi-amplitude of the angular velocity of the disk, x is the phase of the 35-day cycle ($x = 0.0$ corresponds to main opening), ϕ is the phase angle of the disk. The best estimate for A is $9°$.

The tilt of the outer θ_{out} and inner θ_{in} disk, the X-ray luminosity L_x and the contribution to the optical flux from the disk have been optimized at each precession phase (see Table 1). At each precession phase Z takes fixed values from $-100°$ to $100°$ with $10°$ step. We used five disk h/R ratios: 0.05, 0.1, 0.2, 0.3, 0.4; five inclinations: 90, 89, 88, 87, 86; several angular velocity amplitudes A. θ_{out} and θ_{in} as well as accociated parameters shown in the table 1 are satisfying the X-ray visibility in the main-on and the short-on, θ_{in} does not exceed θ_{out} by more than $2°$. Finally, parameters shown in the Table 1 represent the 30% top best χ^2 models.

Table 1 shows the best-fit parameters of the model. Best Z values are shown in Fig. 5. Fig. 6 shows the synthetic light curves with best-fit parameters and observed B light curves of HZ Her.
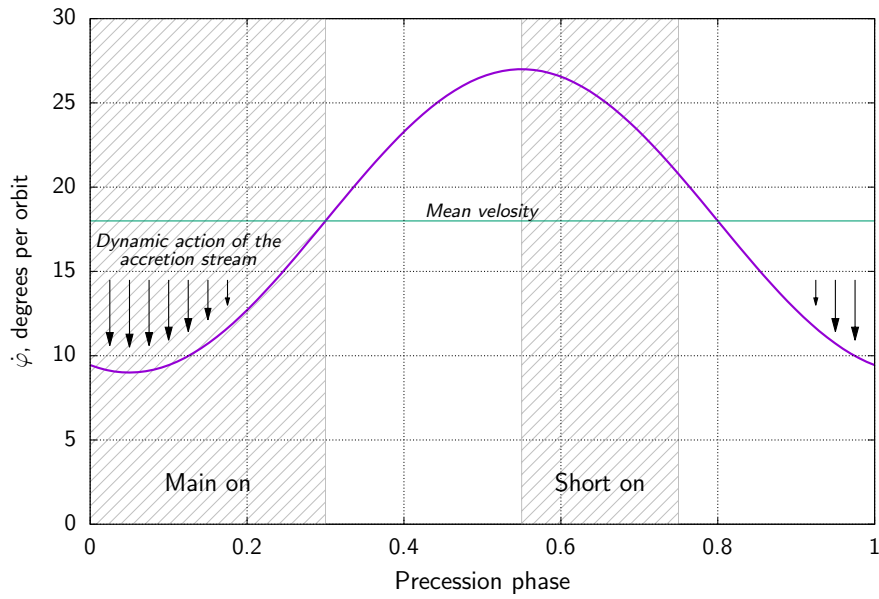
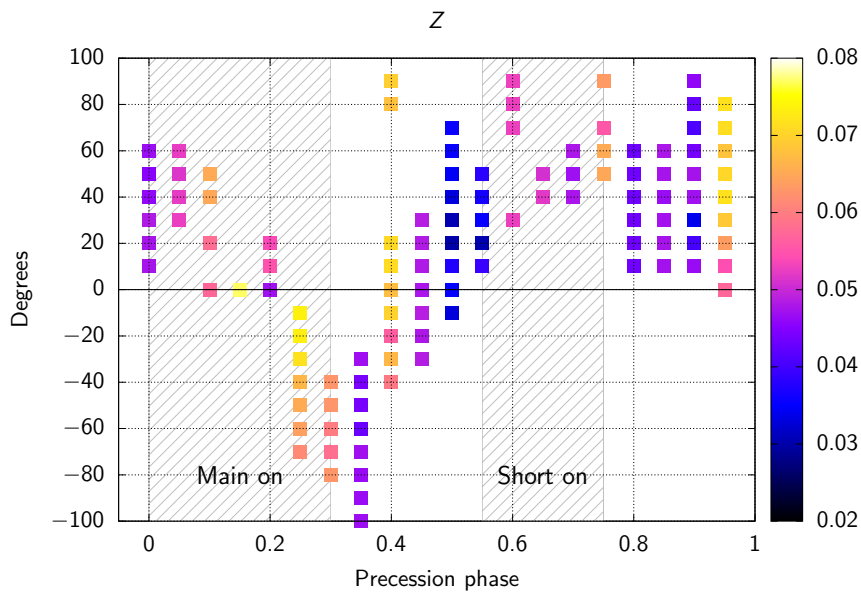**Figure 4:** Disk precession variable velosity.

Figure 5: The angle between the inner and outer edges of the disk as a function of the disk precession phase

The modeling was not performed for the optical phase intervals $0.0 - 0.13$ and $0.87 - 1.0$. At these phases, the disk is obscured by the optical star. The brightness distribution over the disk is complex, and we leave its study for future work.
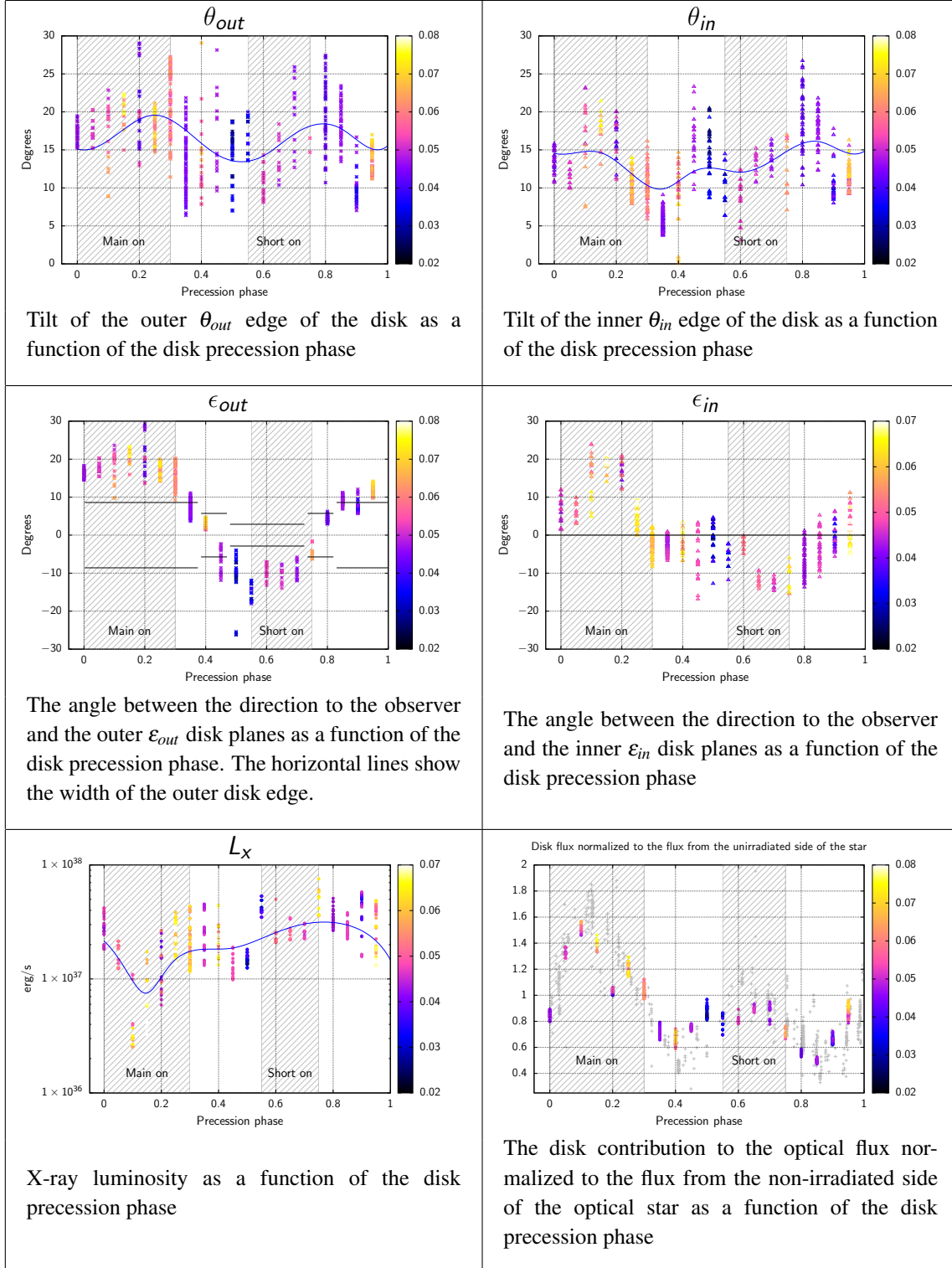
Several peak-like features around the first five precession phases should be noted (red dots in Figure 6). These features were observed for the first time by [37], [45], [39] and were investigated

for the first time by [46]. 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. An original modeling of these streams was done by [47]. The streams synchronize the precession of the accretion disk to the precession of the NS. We note that 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).

The optical light curves demonstrate the secondary minimum near 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 precession phases near 0.75 because the disk is projected onto its own shadow on the optical star surface.

4. Acknowledgements

Table 1: Best χ^2 models. Inclination is $89°$, $\kappa = 8°$, $A = 9°$.

θ_{out}

Tilt of the outer θ_{out} edge of the disk as a function of the disk precession phase

θ_{in}

Tilt of the inner θ_{in} edge of the disk as a function of the disk precession phase

ϵ_{out}

The angle between the direction to the observer and the outer ε_{out} disk planes as a function of the disk precession phase. The horizontal lines show the width of the outer disk edge.

ϵ_{in}

The angle between the direction to the observer and the inner ε_{in} disk planes as a function of the disk precession phase

L_x

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

Disk flux normalized to the flux from the unirradiated side of the star

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
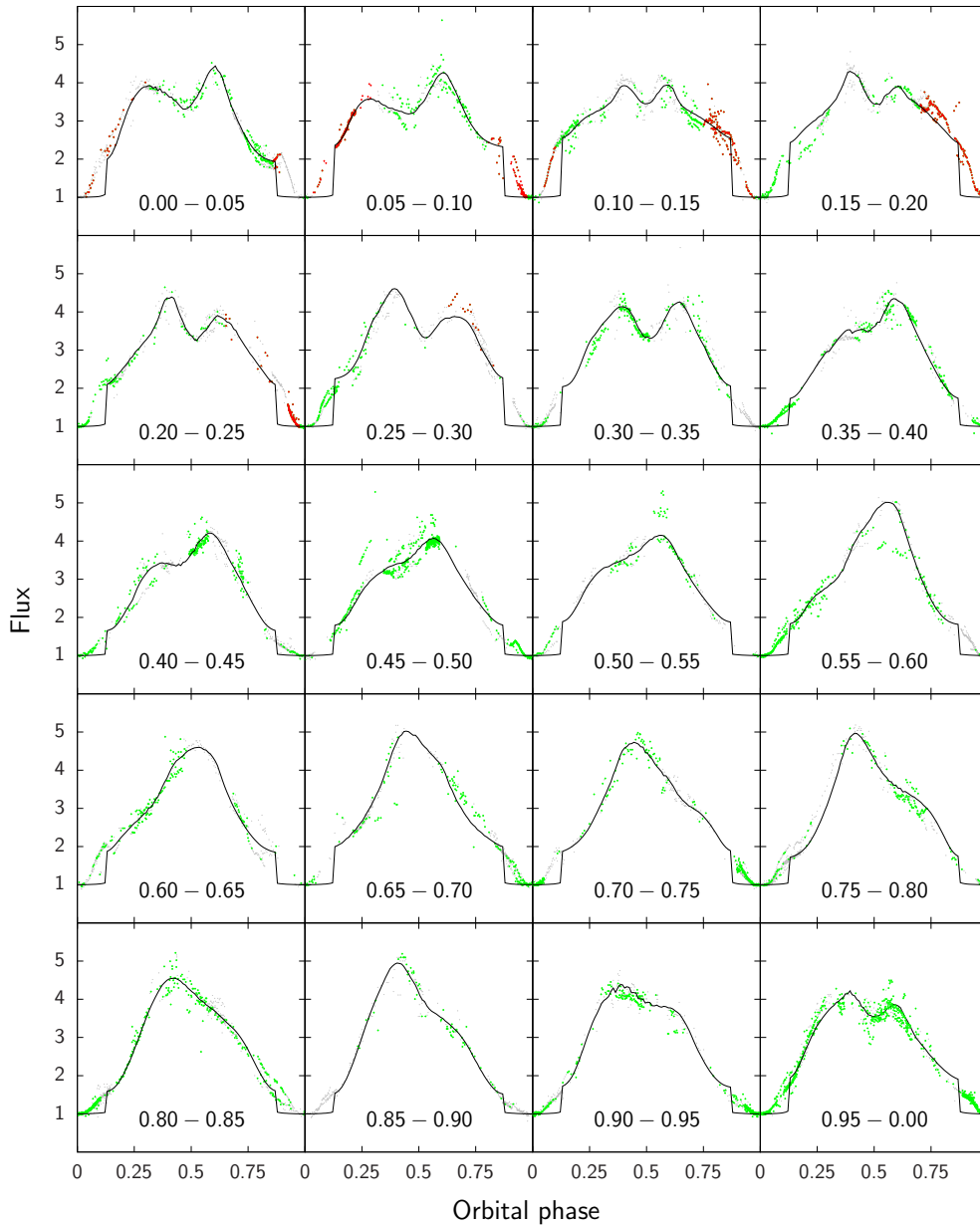
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Figure 6: Best-fit synthetic light curves and observed data (points). The 35-day period is divided into 20 phase bins each. The data are colored: in green — the most robust points; in grey — less robust points; in red — points correspondng to the gas stream acting on the disk (bright spot).

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