A precessing warped accretion disk around the X-ray pulsar Her X-1

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Abstract. We have performed an analysis and interpretation of the X-ray light curve of the accreting neutron star Her X-1 obtained with the ASM RXTE over the period 1996 February to 2004 September. The averaged X-ray light curves are constructed by means of adding up light curves corresponding to different 35 day cycles. A numerical model is introduced to explain the properties of the averaged light curves. We argue that a change of the tilt of the accretion disk over the 35 d period is necessary to account for the observed features and show that our numerical model can explain such a behavior of the disk and reproduce the details of the light curve.

1. Introduction

Her X-1/HZ Her is a close binary system with a 1.7 d orbital period containing an accretion powered 1.24s X-ray pulsar (Giacconi et al. 1973, Tananbaum et al. 1972). The X-ray flux of the source shows a \(\sim 35\) d periodicity which is thought to be due to a counter-orbitally precessing tilted accretion disk around the neutron star which most likely has a twisted form (Gerend & Boyron 1976).

The 35 d cycle contains two on states (high X-ray flux) – the main-on and the short-on – separated by \(\sim 7-8\) d interval of low X-ray flux – off state.

According to the generally accepted model the main-on state starts when the outer disk rim opens the line of sight to the source. Subsequently, at the end of the main-on state the inner part of the disk covers the source from the observer.

An interesting feature of the X-ray light curve are the X-ray dips (Shakura et al. 1999 and references therein), which can be separated into three groups: pre-eclipse dips, which are observed in the first several orbits after X-ray turn-on, and march from a position close to the eclipse toward earlier orbital phase in successive orbits; anomalous dips, which are observed at \(\phi_{\text{orb}} = 0.45-0.65\) and post-eclipse recoveries, which are occasionally observed as a short delay (up to a few hours) of the egress from the X-ray eclipse in the first orbit after turn-on. A general model explaining all types of X-ray dips has been suggested by Shakura et al. 1999 where dips are produced by the accretion stream and wobbling outer parts of the accretion disk.

The analysis of Her X-1 observations obtained with the All Sky Monitor (ASM) on board of the Rossi X-ray Timing Explorer (RXTE) satellite (see Bradt et al. 1993) which cover more than 90 35 d cycles allowed to improve the statistics of the averaged X-ray light curve of Her X-1 with respect to previous analysis (Shakura et al. 1998a, Scott & Leahy 1999, Still & Boyd 2004). In addition to well-known features (pre-eclipse dips and anomalous dips during the first orbit after X-ray turn-on) the averaged X-ray light curve shows that anomalous dips and post-eclipse recoveries are present for two successive orbits after the turn-on in the short-on state. These details have already been reported by Shakura et al. 1998a but statistics was poor and the authors have not reproduced them with their model.

In this work we substantially improve the numerical model presented by Shakura et al. 1999. Now it accounts for the dynamical time scale of the disk and includes explicit calculations of the precession rate at each phase of the 35 d period. The inclination of the disk is allowed to change during the 35 d cycle.

With the improved model we reproduce all details of the averaged light curves including those which were left unexplained previously.

2. Observations

For the analysis of the X-ray light curve of Her X-1 we use data from the ASM (Levine et al. 1996). The archive contains X-ray flux measurements in the 2-12 keV band, averaged over \(\sim 90\) s. The monitoring began in February 1996 and continues up to date. The archive is public and accessible on the Internet [1].

Preliminary processing of the X-ray light curve was carried out by the method described by Shakura et al. 1998a. The goals of this processing are the reduction of the dispersion of the flux through

\(^{1}\) http://xte.mit.edu/asm1c/srcs/herx1.html
rebinning, resulting in a smoothed light curve, and the determination of the turn-on time of each individual 35 day cycle, with the aim to classify the cycles into two classes: turn-on around orbital phase $\sim 0.2$, and turn-on around orbital phase $\sim 0.7$ (they appear with about equal probability).

Using the RXTE/ASM (with $\sim 5$ cts/s from Her X-1 in the main-on) details cannot be explored in individual 35 day cycles. However, if we construct averaged light curves through superposition of many 35 d light curves common details (e.g. X-ray dips, post-eclipse recoveries) become recognizable. This has been done e.g. by Shakura et al. 1998a, Scott & Leahy 1999, Still & Boyd 2004. The ASM archive has grown considerably, allowing to construct averaged light curves with smaller dispersion than in previous works.

As mentioned above, in most cases turn-ons occur near orbital phases 0.2 and 0.7. Thus all 35 d cycles have been divided into two groups – with the turn-on near $\phi_{\text{orb}} = 0.2$ and near $\phi_{\text{orb}} = 0.7$. Inside each group the light curves were superposed and averaged, after shifting them in such a way that the eclipses coincided. The superposed light curves are shown in Fig. 1.

In the short-on state complicated dip patterns can be observed. Anomalous dips near orbital phase $\phi_{\text{orb}} = 0.5$ and post-eclipse recoveries are present on two successive orbits after the beginning of the short-on state. This can also be seen in one individual short-on observed by RXTE/PCA shown in Fig. 2 (see also Leahy et al. 2000, Oosterbroek et al. 2000, Inam & Baykal 2005).

3. The model

As mentioned in the Introduction, it is believed that the alternation of the On and Off states is caused through shadowing by a counter-orbitally precessing tilted twisted accretion disk. In our model Shakura et al. 1999, pre-eclipse dips occur when the accretion stream crosses the observer’s line of sight before entering the disk. This can happen only if the stream is non-coplanar to the systems orbital plane. The reason for the stream to move out of the orbital plane is non-uniform X-ray heating of the optical stars atmosphere by the X-ray source, which produces a temperature gradient near the inner Lagrange point. The non-uniformity of the heating comes from the partial shadowing of the optical star surface by the accretion disk. Furthermore, such a stream forces the outer parts of the accretion disk to be tilted with respect to the orbital plane. The tidal torques cause the disk to precess in the direction opposite to the orbital motion. Due to tidal torques and the dynamical action of the accretion stream the outer parts of the disk develop a notable wobbling (nutational) motion twice the synodal period. For an observer, the X-ray source can be screened by the outer parts of the disk for some time during the first orbit after the X-ray turn-on. This causes anomalous dips and post-eclipse recoveries.

3.1. Numerical calculations of the disk motion

The method of calculation of the disk motion under the action of tidal forces and the accretion stream is described by Shakura et al. 1999. The disk was approximated by a solid ring with the radius equal to the outer radius of the disk. The inclination of the disk with respect to the orbital plane was assumed to be constant. Under these assumptions the dynamical time scale of the disk $t_d = M_d/M$ (where $M_d$ and $M$ are the mass of the disk and the ac-
cretion rate correspondingly) which characterizes the dynamical action of the stream turned out to be significantly shorter than the viscous time scale which leads to inconsistency. Also this model failed to explain some details of the averaged light curve, namely, anomalous dips and post-eclipse recoveries on two orbits after the secondary turn-on.

In this work the model is substantially improved. In order to reconcile the dynamical and viscous time scales of the disk we introduce two characteristic radii: the outer radius of the disk \( r_{\text{out}} \sim 0.3a \) which determines the tidal wobbling amplitude, and the effective radius \( r_{\text{eff}} \sim 0.18a \) which determines the mean precession motion of the disk. The value of this effective radius is found from the requirement that the net precession period of the entire disk be equal to the observed value \( 20.5P_{\text{orb}} \) and the dynamical time scale \( t_d = M_d/\dot{M} \) (which characterizes the dynamical action of the stream) be 10 days. This value for the dynamical time is chosen to be of order of the viscous time from the impact radius \( \sim 0.1a \) which is around 10 days and scales as \( r^{-3/2} \).

The inclination of the disk is allowed to change with the precessional phase. It requires that the rate of precession was calculated for each precessional phase separately since it depends on the disk inclination.

It is important to note that the region of the disk beyond \( r_{\text{imp}} \), where is no matter supply (called the “the stagnation zone”) and which mediates the angular momentum transfer outwards for accretion to proceed, can react to perturbations induced by the stream impact much faster than on the viscous time scale. Indeed, in a binary system, tidal-induced standing structures can appear in the outer zone of the accretion disk (see e.g. Blöndin 2000 and references therein) and perturbations of angular momentum can propagate through this region with a velocity close to the sound speed (while the matter will accrete on the much slower viscous time scale). Recent analysis of broad-band variability of SS 433 (Revnivtsev et al. 2005) suggests that such a picture is realized in the accretion disk in that source. So the entire disk (inside and beyond \( r_{\text{imp}} \)) reacts to changes in the mass transfer rate through the accretion stream on a time scale not longer than the viscous time scale of the disk from the impact point (i.e. \( \sim 10 \) days).

3.2. Evidence for a change in the tilt of the disk

The fact that during the short-on state of Her X-1 more absorption dips appear on the averaged X-ray light curve (the anomalous dips and post-eclipse recoveries during two successive orbits of the averaged short-on) as well as in an individual short-on observed by PCA (Fig. 2 and Inam & Baykal 2005) suggests that the angle \( \epsilon \) between the disk and the line of sight remains close to zero during the first two orbits after the turn-on in the short-on state. This is in contrast to the main-on state, where such features are observed only during one orbit after turn-on.

We failed to reproduce the observed behavior assuming constant inclination of the disk. The observations imply a generic asymmetry between the beginning of the main-on and short-on states. This asymmetry can take place only if the disk tilt \( \theta \) changes with precessional phase.

The physical reason for this could be the periodic change of the mass transfer rate from the inner Lagrange point into the disk. If free precession of the neutron star is ultimately responsible for the 35-day cycle in Her X-1 (Brecher 1972, Trümper et al. 1986, Shakura 1999, Shakura et al. 1998b), the conditions of X-ray illumination of the optical stars atmosphere will periodically change with precession phase. This in turn will lead to changes in the velocity components of the gas stream in the vicinity of the inner Lagrangian point and hence in the matter supply rate to the accretion disk. Recently, X-ray pulse profiles evolution with the 35 d phase was successfully reproduced both in the main-on and short-on states in the model of freely precessing neutron star with complex surface magnetic field structure (Ketsaris et al. 2000, Wilms et al. 2003).

4. Results

The physical picture of the change of the disks tilt adopted here is as follows. The rate of mass transfer \( \dot{M} \) supplied by HZ Her (which for a given moment can be different from the accretion rate of the neutron star because the viscous time scale for mass transport through the disk both delays and smoothes the mass flow) changes periodically over the precession cycle in response to changing illumination of the optical star atmosphere due to free precession of the neutron star. The streams action causes the outer disk to precess slower than it would do if only tidal torque was acting, and it also changes the outer disk’s tilt on the dynamical time scale of about 10 days (see above), which is sufficient to explain periodic disk tilt variations over the precession cycle. The wobbling of the outer disk is mainly due to tidal forces (the dynamical action of the stream provides minor contribution). The viscous time scale in the “stagnation zone” is much longer, so the viscous torques cannot smooth out the external disk variations.

Figure 4 shows the result of modeling of the disk motion. The angle \( \epsilon \) (vertical axis) is the angle between the direction from the center of the neutron star to the observer and to the outer parts of the accretion disk with non-zero thickness. The complex shape of the disks wobbling is clearly seen. The sine-like dashed curve shows schematically the same angle for the inner accretion disk regions which eclipse the X-ray source at the end of on-states. The horizontal line is the observer’s plane and the vertical dashed lines mark centers of the binary eclipses. The main-on and short-on states are indicated. The source is screened by the disk when the observer is in the dark area or between this area and the inner disk line. It is seen that
the wobbling effects can be responsible for the observed (several) anomalous dips (marked with "A") and post-eclipse recoveries at the beginning of the short-on state (marked with "PE").

5. Conclusions

The following main results have been obtained from analyzing and modeling RXTE/ASM X-ray light curves of Her X-1.

1. The shape of the averaged X-ray light curves is determined more accurately than was possible previously (e.g. by Shakura et al. 1998a).

2. We have significantly improved the model developed in Shakura et al. 1999 by including the calculation of the dynamical time scale of the disk, more accurate calculation of its precessional motion and allowing the disk to change its inclination with respect to the orbital plane during the 35 d cycle.

3. With the improved model we successively reproduced observed details of the X-ray light curve including the anomalous dips in two successive orbits after the beginning of the short-on state and the post-eclipse recovery after the first eclipse which were left unexplained previously.

4. We argue that the changing of the tilt of the accretion disk with 35d phase is necessary to account for the appearance of these features and the observed duration of the main-on and short-on states.

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