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Discrete flow of matter in the X-ray binary Her X-1

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It is shown that the "clock mechanism" of the discrete flow of matter in the X-ray binary Her X-1/HZ Her, explained in the model proposed by Crosa and Boynton and developed by us in the late 1980s, continues to work. This model successfully explains many phenomena in this X-ray system, including occasionally observed peaks on optical light curves, formed by interaction of discretely incident matter with the outer parts of the accretion disk, as a result of which plasma clots ("blobs") are formed. Based on the published light curves constructed on the basis of the richest photometric data obtained in 1972–1998 and 2010–2018, a phase diagram (Φ, Ψ) of the identified peaks is constructed. We conclude that the appearance of peaks on the orbital light curves at certain orbital phases, depending on the phase of the 35-day cycle, continues, and the mechanism of blob formation still works at the present time. Observations on eROSITA provide new evidence for the existence of a corona around the accretion disk, predicted by us in the frame of this model in the late 1980s.

Keywords: X-Ray binary, Her X-1, light curves, accretion, accretion disk

1 Introduction

HZ Her/Her X-1 is an intermediate-mass X-ray binary, IMXB (orbital period $P_{orb} = 1.7^d$), consisting of an evolved A7 subgiant star and a neutron (n) star, which is an X-ray pulsar (period 1.24^s). The optical star fills its Roche lobe, and matter flowing from the star creates an accretion disk around the n star. The optical orbital light curve is formed mainly by rotation of the tidally distorted X-ray-heated star. The donor star is affected by a strong irradiation effect. There are also other factors influencing this light curve: eclipses of the tilted accretion disk and by it, as well as the X-ray shadow cast on the star's photosphere (e.g., see Howarth & Wilson, 1983). The X-ray orbital light curve is formed mainly by the eclipse of the X-ray component.

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In Her X-1, there is also a quasi-period $P_{pr} = 35^d$, the so-called "precessional" period. It is associated with retrograde precession of the tilted accretion disk, related to free precession of the n star. This cycle consists of a 7-orbit "main-on" state and a 5-orbit "short-on" state of low intensity, separated by two intervals during which the X-ray flux is lacking ("turn-off" states). The X-ray turn-on, the beginning of the "main-on" state (in this paper, the 35-day cycle phase $\Psi = 0$) occurs at the orbital phases $\Phi \approx 0.2 - 0.3$ or $\Phi \approx 0.7$. The time of $\Phi = 0$ corresponds to the middle of the X-ray eclipse coinciding with the main minimum of the optical light curve.

The X-ray orbital light curves are also superimposed with pre-eclipse and anomalous dips. A pre-eclipse dip appears after the X-ray turn-on at $\Phi \approx 0.85$ and then occurs at earlier orbital phases in successive orbits. The anomalous dips are observed during only two orbital periods after the X-ray turn-on at $\Phi \approx 0.55$. It was the result of the study of these dips that led Crosa & Boynton (1980) to the assumption about discrete flow of matter in the X-ray binary Her X-1.

Recently, there has been renewed interest in different manifestations of this "precession" cycle, $P_{pr} = 35^d$. For example, Kolesnikov et al. (2020) constructed a detailed model describing variations of the shape of the orbital light curve in the optical range in relation to the phase of this cycle. This model takes into account many factors, including the forced precession of the warped tilted accretion disk and the free precession of the X-ray pulsar illuminating and heating the optical star. In general, it describes the overall shapes of the light curves well, but without explaining the observed details: spikes (peaks) on the optical light curves, steps in the minima.

In the model by Shakura et al. (1999), an X-ray dip occurs when the accretion stream crosses the observer's line of sight before entering the disk. To explain the X-ray anomalous dips, Klochkov, Shakura, Postnov et al. (2007) had to assume that the accretion disk changed its inclination to the orbital plane (the wobbling disk). This may be due both to tidal forces and to dynamic interaction of the accretion stream with the outer parts of disk.

Besides the above-mentioned peaks and steps on the optical light curves, the physical model proposed by the cited authors, despite its complexity, has not yet explained many observed factors, for example, flickering of the X-ray flux in pre-eclipse and anomalous X-ray dips, bursts of linear polarization, etc. The phenomenological model for periodical mass transfer by Crosa & Boynton (1980), subsequently developed and supplemented by us, explains these details. The observational facts confirm this model to which this contribution is dedicated.

2 Periodical mass transfer in Her X-1

2.1 The model

An empirical model of the periodic mass transfer in the system of Her X-1 was first described by Crosa & Boynton (1980). This is the so-called "clock" mechanism of matter transfer to the second component, based on long-term observations of X-ray dips. Subsequently it was developed by us (Karitskaya et al., 1986; Bochkarev & Karitskaya, 1986; Bochkarev et al.. 1988; Bochkarev & Karitskaia, 1989; Bochkarev & Karitskaya, 1992). Every 0.81^d, matter flows from the star because the X-ray pressure

disappears near the internal Lagrangian point when the star enters the shadow of the tilted precessing accretion disk. According to our estimates, the external radiation pressure p_x is ~ 1.5 times higher than the internal p (the sum of the gas and radiation pressure) at the level of the photosphere (heating by X-ray radiation was taken into account) (Bochkarev & Karitskaia, 1989). The previously accumulated matter quickly flows out from the optical star. At the exit from the eclipse, this pressure again locks the matter. After about 4^h, the matter collides with the outer part of the disk. The gas heats up, spreads out, and a blob (a hot thickening) is created on the rim of the disk. A spike is formed on the orbital light curve. Theoretical estimations of heights of these peaks ($\sim 0.3^m$ in B, V, $\sim 0.7^m$ in U) agree with previous observations (Karitskaya et al., 1986). A blob is carried away by the circular motion in the rotation direction of the binary system with a period of $P_c = 15^h$ and gradually relaxes. When it hits the line of sight, pre-eclipse and abnormal dips are formed in the X-ray range. According to Crosa & Boynton (1980) and Karitskaya et al. (1986), the appearance of blobs on the line-of-sight explains why the X-ray turn-on occurs during different orbital phases, $\Phi \approx 0.2$–0.3 or $\Phi \approx 0.7$. This model turned out to be extremely productive and allowed us to explain a lot of observational facts, which in turn stimulated us to continue its development.

2.2 Photometric, polarimetric, and spectroscopic manifestations

During the eclipse of the accretion structure by the optical star, almost exactly at the phase $\Phi = 0$, steps up to $\sim 0.1^m$ (Kilyachkov & Shevchenko, 1980, in U, B, V) and steps down to $\sim 0.05^m$ (Kippenhahn et al., 1980, in B) are sometimes observed. They are well explained, in the first case, by the exit of the blob from the eclipse by the star, and in the second case, by its entry into the eclipse (Karitskaya et al., 1986, Bochkarev & Karitskaia, 1989). The sizes of the star, disk, and blob are just such that these events occur exactly in these times, at $\Phi = 0$, and correspond well to the above-mentioned appearance of blobs in the outer part of the disk. It turns out that, in these cases, the blob makes a second revolution around the disk.

During the observations of 1972–1975, Shakhovskoi & Efimov (1978) observed a burst of linear polarization just at the phase $\Phi = 0$. The amplitude was $\approx$0.5%, and FWHM, $\Delta\Phi \approx 0.01$. This phenomenon was explained in Karitskaya et al. (1986) with a partial eclipse of the blob by the optical component. The obtained estimates are consistent with observations. This event also corresponds well to the mentioned appearance of the blob at the outer part of the disk.

Our, not numerous, spectroscopic observations of HZ Her, performed using a 1000-channel TV spectral scanner of the 6-m telescope BTA, showed variable emission details in the profiles of Balmer lines, apparently belonging to the blob (Bochkarev & Karitskaia, 1989). Similar variable profiles of lines with emission manifestations were observed in Bopp et al. (1972). During the eclipse of the accretion structure, hot gas lines CIV, NV, OIV were observed in the UV spectra, which are most likely associated with a hot blob (Anderson et al., 1993).

2.3 The phase diagram (Φ, Ψ) for the times of blob appearance

Based on the mechanism of blob formation described previously, we should expect blob formation, and therefore the appearance of peaks on the light curves, at certain orbital phases Φ_D, depending on the phase Ψ of the 35-day cycle, counted from the time of the X-ray radiation turn-on (Ψ=0):

$$\Phi_D = \Phi_{D0} - \Psi, \Phi_D = \Phi_{D0} - \Psi + 0.5, \quad (1)$$

where Φ_{D0} is the orbital phase of the appearance of the first blob immediately after the turn-on of Her X-1. Crosa & Boynton (1980) found $\Phi_{D0} = 0.78$ from long-term observations of X-ray dips. This corresponds to the first entrance of the star to the shadow from the tilted accretion disk at $\Phi_R = 0.68$.

This is well confirmed by the phase diagram, Ψ versus Φ_D, in Fig. 1 in Karitskaya et al. (1986). The theoretical straight lines described by (1) are drawn in the (Φ_D, Ψ) plane. Points corresponding to the peaks observed on the light curves fit these lines well. These peaks were taken from the light curves published by that time, mainly from Howarth & Wilson (1983), where the theoretical calculated orbital light curves, depending on the phase of the 35-day cycle, had been compared with photometric data. Unfortunately, in most cases, the turn-on times were not known. To determine the phases of the 35-day cycle, Howarth & Wilson (1983) performed polynomial fits to the known times of the X-ray turn-on. In other cases, we used for these purposes an empirical model developed in Staubert, Bezler, & Kendziorra (1983) for the turn-on times of Her X-1 (a random-walk noise model).

The blob appearance orbital phases Φ calculated according to the model from the times of the appearance of the steps up and down and the observed burst of linear polarization (see above) also fit these lines perfectly.

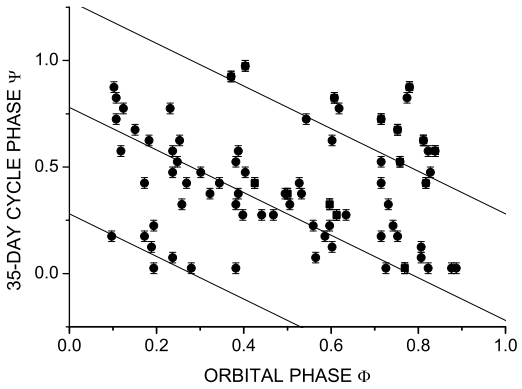


Figure 1 The phase diagram (Φ, Ψ) of the times of blob occurrences at the disk rim, coinciding with the times of appearance of peaks on optical orbital light curves (see text). Φ is the orbital phase, Ψ is the 35-day cycle phase, $\Psi = 0$ corresponds to the X-ray source turn-on. Regardless of the fact that some of the events could have been accidental (erroneous for some reason), the diagram clearly shows three sequences of points located along the theoretical lines, the middle of which is described by the left equation of (1), and the extreme ones, by the right equation.

In the recent work by Kolesnikov et al. (2020), a huge amount of photometric material was used to construct optical light curves for different phases of the 35-day cycle. This photometrical material includes the results of B, V observations of 1972–1998 and 2010–2018. The authors constructed the orbital B, V light curves for 20 phase intervals of the 35-day cycle and, for comparison, calculated theoretical light curves for these intervals. Individual measurements obtained during 35-day cycles with unknown turn-on times were ignored. The main features of the model include a tilted, warped and precessing accretion disk and a freely precessing X-ray pulsar illuminating and heating the optical star. Looking through these 20 light curves and comparing the observation points with theoretical curves, we found 77 events (possible peaks, deviations of points upwards). Single points were not taken into account. Figure 1 shows the (Φ, Ψ) phase diagram where points correspond to these peaks. Theoretical straight lines described with (1) are drawn. The diagram clearly shows three sequences of points located along the theoretical lines, the middle of which is described by the left equation of (1), and the extreme ones, by the right equation. Regardless of the fact that some of the events could have been accidental (erroneous for some reason), the sequences are clearly visible and traceable. The extreme sequences of points can be merged with the middle sequence by raising the lower one and lowering the upper one by a half-period of the 35-day cycle (see Fig. 2). Using least squares, the resulting sequence of points was fitted with an inclined line $\Psi = a - b \times \Phi$, where $a = 0.770$, $\sigma_a = 0.027$, $b = -0.866$, $\sigma_b = 0.050$. The value of a surprisingly coincides with Φ_{D0} and b coincides, within $3\sigma_b$, with 1.0. Thus, it can be concluded that the mechanism of blob formation continues to work at the present time.

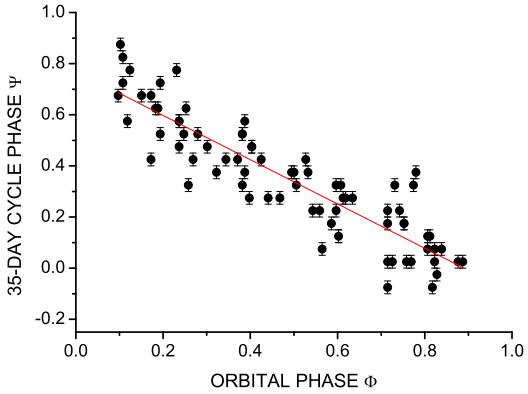


Figure 2 The phase diagram (Φ, Ψ) (see caption of Fig. 1), where the middle sequence of points from Fig. 1 is shown. The extreme sequences of points have been merged with it (see text). A straight line fitting these points is drawn.

3 A model of fragmented blobs and a hot corona around the disk. Observational evidences of the corona existence

The discovery of flickering of X-ray flux during X-ray dips with EINSTEIN (Vrtilek & Halpern, 1985) and EXOSAT (Voges et al., 1985) led to a significant development of the blob model (see Bochkarev & Karitskaya, 1986; Bochkarev & Karitskaia, 1989; Bochkarev & Karitskaya, 1992). To explain X-ray flickering during the X-ray source eclipse by a blob, as well as the long lifetime of the cold blob, we had to assume the existence of a hot corona around the disk. When interacting with this corona, a Rayleigh–Taylor instability develops, and after a few hours, the blob breaks up into separate drops. Small drops quickly evaporate, and large ones are held by the pressure of the corona. Each drop rotates around the disk in its Keplerian orbit. If the orbits intersect with the disk, drops fall on it. The rest of them move on and can exist for one and a half to two revolutions around the disk. The size of the drops is $\sim 3 \times 10^{10}$ cm, the density is $\sim 4 \times 10^{13}$ cm^{-3}, the temperature is $\sim$30 000 K.

During the eclipse of the X-ray source by this fragmented blob, we may expect flickering with a characteristic time of $\tau \sim 150 - 500$ s, which is observed in dips. To explain the stability of drops, an assumption is made about the existence of a hot corona around the disk, the corresponding model was created (Bochkarev & Karitskaia, 1989; Bochkarev & Karitskaya, 1992; Bochkarev, 1989). The following parameters of the corona were obtained: density $\sim 5 \times 10^{11}$ cm^{-3}, temperature $\sim 3 \times 10^6$ K. The coronal gas rotates with the disk. A detailed calculation of the heating and ionization balance in the radiation field of a neutron star is presented in Bochkarev (1989), Bochkarev (1991). Observational evidence for the existence of this corona was presented and discussed in detail: the existence of an X-ray flux during the 35-day "off" state, smooth entry and exit from the X-ray eclipse, the presence of the Fe (6–7) keV emission line during the "off" states, etc. The existence of a corona with similar parameters was confirmed by observations of the shape of an X-ray eclipse with the Rossi X-ray Timing Explorer (Leahy, 2015).

SRG/eROSITA all-sky survey observed Her X-1 during the low states of the X-ray source (Shakura et al., 2021) when the outer part of the accretion disk eclipsed the neutron star. The X-ray orbital light curves were received. The authors concluded that there were three distinct regions scattering X-ray radiation: the optically thin hot corona above the irradiated hemisphere of the optical star; the optically cold atmosphere of the star; and the optically thin hot halo above the accretion disk. The latter is exactly the corona discussed above.

4 Discussion and conclusion

Truemper et al. (1986) made an assumption about the free precession of the neutron star, occurring in the opposite direction with respect to the rotation of the binary system Her X-1 (retrograde precession). It was a result of studying variability of the profiles of X-ray pulses from this X-ray pulsar with $P_n = 1.24^s$ changing with a phase of $P_{pr} = 35^d$. Further research confirmed this result (see, for example, Postnov et al., 2013). The retrograde precession of the accretion disk with the same period also

exists. This follows at least from sequential changes in the shape of the orbital light curve with $P_{pr} = 35^d$. It has been suggested that it is the pulsar that affects the accretion, causing the precession of the disk. It follows from here that the orbital phase of the entry of the star into the shadow of the disk has remained the same. Thus, over the years, there has been no failure in the "clockwork mechanism" and the model. The changing radiation pressure on different parts of the star's surface due to the changing geometry of the incidence of the X-ray flux can regulate the flow of matter.

The appearance of peaks on the orbital light curves at certain orbital phases, depending on the phase of the 35-day cycle, continues. This is confirmed by the (Φ, Ψ) phase diagram. Thus, it can be concluded that the mechanism of blob formation continues to work at the present time. It is surprising that the orbital phase of the appearance of the first blob immediately after the time of Her X-1 turn-on coinciding with $\Psi = 0$ remains the same, $\Phi_{D0} \approx 0.78$, during about 40 years. It follows from this that the orbital phase of the first entrance of the star to the shadow from the tilted accretion disk has remained the same, $\Phi_R = 0.68$. For many years, there has been no failure in the "clock mechanism" of discrete flow of matter in the X-ray binary Her X-1. This confirms the evidence in favor of the considered model.

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