MULTICOLOR PHOTOELECTRIC $WBVR$ OBSERVATIONS OF THE CLOSE BINARY SYSTEM HZ HER = HER X-1 IN 1986–1988.

I. METHOD AND OBSERVATIONS

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Abstract

We present results of four-color ($WBVR$) photoelectric observations of the close binary HZ Her = HER X-1 in 1986–1988. As a rule, the duration of the observations exceeded two 35-day X-ray orbital periods in the 1986–1988 observing seasons. The accuracy and length of the photoelectric observations facilitated multi-faceted studies, which enabled us to define several fine photometric effects in the light curves of the binary more precisely and attempt to interpret them in a model for the matter flow from the optical component to the accretion disk around the neutron star. This model provides a satisfactory explanation for the inhomogeneity of the gas flow and “hot spot”, as well as the existence of distinct “splashes” moving in their own Keplerian orbits around the outer parts of the Keplerian disk. We present series of light curves for all the observing seasons, as well as color–color diagrams that reflect the physics of various photometric effects. The transformation coefficients for each of the instrumental systems for the three observatories at which the observations were carried out are given. Atmospheric extinction was taken into account during multi-color observations of the object, with subsequent correction for atmospheric effects with accuracies ranging from $0.003^m$ to $0.005^m$ for air masses up to $M(z) = 2$. 


1 INTRODUCTION

The X-ray source Her X-1 and the physically related optical star HZ Her (GSC 2598-01298; \(16^h57^m49.83^s, +35\degree 20'32.6''\) (J2000)), which is an A7 sub-giant, form a close binary system, which exhibits a wide range of unique and physically distinct optical and X-ray variability [1].

The X-ray period of the pulsar \(P_1 \approx 1.24\) s, which is associated with the rotation of the neutron star [2], which is in a disk-accretion regime, the orbital period \(P_2 \approx 1.7\) d responsible for the X-ray eclipses and strong optical variability \((\sim 2'' - 3''\)\), and the precession period \(P_3 \approx 34.875\) d due to the precession of the neutron-star accretion disk, characterize the uniqueness of the HZ Her close binary [3–6]. The X-ray flux and the shape of the optical light-curve of the close binary vary with the period \(P_3 \approx 34.875\) d [8, 9].

The optical component periodically eclipses the X-ray source associated with the neutron star. The main cause of the optical variability of the X-ray binary is the reflection effect or, more precisely, the heating of the atmosphere of the optical component (with luminosity \(L_v \approx 10^{35}\) erg/s) via reprocessing of the powerful, hard X-ray emission \((L = 10^{37}\) erg/s at 2–10 keV) in the photosphere of the optical star.

An appreciable asynchronism between the orbital motion and the rotation of the optical star is observed [10–12]. Early studies suggested that the optical star overflows its Roche lobe and loses matter on the thermal time scale. More recent studies suggest that the dominant effect in the system is accretion onto the neutron star.

At the same time, this X-ray binary is a classical prototype of an entire class of X-ray sources with low-mass optical components: the masses of the X-ray and optical components are \(M_x = 1.3 \pm 0.14 M_\odot\) and \(M_v = 2.2 \pm 0.1 M_\odot\) [13], respectively.

The reflection effect in the close binary does not disappear at any time during the 35-day precession cycle. This is related to accretion onto the neu-
tron star and the subsequent formation of an accretion disk in the system [14].

Table 1: Distribution of the observations

| Observatory (telescope)* | Observing season | 1986 | 1987 | 1988 |
|--------------------------|------------------|------|------|------|
| | Number of nights / Number of individual points in the WBVR bands |
| Crimean Observatory of the SAI (Zeiss-600 reflector) | 14 / 56 | 19 / 149 | 12 / 150 |
| Maidanak High-Altitude Observatory of the SAI (Zeiss-600 reflector) | 24 / 99 | 10 / 132 | 25 / 183 |
| Tien Shan High-Altitude Observatory of the SAI (AZT-14 reflector) | 43 / 88 | 2 / 24 | 6 / 67 |

* An FEY-79 single-channel photometer and standard WBVR filters were used on all telescopes.

2 OBSERVATIONS

We present here the results of observations of the close binary HZ Her from 1986 [15] to 1988 in the WBVR bands. The W filter ($\lambda_{\text{eff}} \approx 3500$ Å, $\Delta \lambda_{1/2} \approx 520$ Å) is a revised version of the standard ultraviolet filter of the UBVR system [16]. Since the effective wavelength of the W filter is $\sim 100$ Å shorter than the wavelength of the U filter, color variations in the close-binary system are expressed more strongly in our observations than in UBV data. The total number of individual WBVR observations carried out at three observatories over 155 nights in 1986–1988 is 948 (Table 1).

We used C3 = GSC 2598-01270 ($16^{h}57^{m}17.84^{s}$, $+35^{\circ}21\prime45.0^{\prime\prime}$, J2000) as a comparison star in these observations. We obtained the WBVR magnitudes and color indices of this star by matching to the standards HD 152380,
HD 147924, HD 148253 [14]:

\[ W = 12.920^m \pm 0.050^m, \quad B = 13.172^m \pm 0.032^m, \]
\[ V = 12.596^m \pm 0.014^m, \quad R = 12.127^m \pm 0.020^m. \]

These values agree with the \( B \) and \( V \) magnitudes of C3 found in [17] within the errors.

The stars C2 = GSC 2598-01267 (16\(^{\text{h}}\)57\(^{\text{m}}\)34.41\(^{\text{s}}\), +35\(^{\circ}\)21′57.0″, J2000) and C4 = GSC 2598-01274 (16\(^{\text{h}}\)58\(^{\text{m}}\)06.21\(^{\text{s}}\), +35\(^{\circ}\)21′32.9″, J2000) were also used as a comparison star and check star, respectively. To reduce the errors of the photoelectric observations, a comparison star was observed in the same filter before and after every observation of HZ Her. The check star was observed two to four times during each observing session. The background in the vicinity of HZ Her was also periodically measured.

To obtain a denser set of observations, the comparison star C3 and background were measured every 30–40 min with subsequent extrapolation to the time of the observations of HZ Her. As in [18], the transformation coefficients were also measured each season. Because the instrumental system we used differs only slightly from the standard \( UBVR \) system, the relation between the transformation coefficients can be expressed by the first-order linear equations

\[ V = v_0 + \eta_v + \xi_v (B - V), \]
\[ U - B = \eta_{U-B} + \xi_{U-B} (u - b)_0, \]
\[ B - V = \eta_{B-V} + \xi_{B-V} (b - v)_0, \]
\[ V - R = \eta_{V-R} + \xi_{V-R} (v - r)_0, \]

where the unknowns are the transformation coefficients \( \eta \) and \( \xi \). The best photometric nights were used to determine these coefficients. The transformation coefficients \( \xi \) were then averaged during each observing season, and the values of the zero-points \( \eta \) for each night of the given season were computed using these average \( \xi \).
Table 2: Transformation coefficients $\xi$

| Observatory                        | $\xi_V$          | $\xi_{W-B}$        | $\xi_{B-V}$        | $\xi_{V-R}$        | $n$  |
|-----------------------------------|------------------|--------------------|--------------------|--------------------|------|
| Crimean Observatory of the SAI    | 0.013 ± 0.003    | 0.962 ± 0.005      | 1.102 ± 0.003      | 1.088 ± 0.004      | 38   |
| Maidanak High-Altitude Observatory SAI | 0.012 ± 0.003    | 0.958 ± 0.004      | 0.937 ± 0.007      | 1.065 ± 0.007      | 41   |
| Tien Shan High-Altitude Observatory SAI | 0.054 ± 0.002    | 0.997 ± 0.009      | 0.929 ± 0.005      | 1.068 ± 0.008      | 27   |

The calculated average values of $\xi$ and their errors are listed in Table 2. In Table 2, $n$ is the number of nights used to derive $\xi$. We always used the same detectors on the Zeiss-600 and AZT-14 reflectors. Our detector was a FEU-79 (multi-alkali photo-cathode S-20) photomultiplier. If the photomultiplier was changed, the transformation coefficients $\eta$ and $\xi$ were recalculated.

Atmospheric extinction was taken into account during broad-band (multi-color) observations of HZ Her (including the $WBVR$ observations). Moreover, the color characteristics of HZ Her change substantially during the orbital and precession periods. During differential observations of variable stars using standard and check stars that were similar in color and located close in the sky, the problem of atmospheric extinction essentially does not arise. Account for atmospheric extinction is also necessary to reduce the systematic measurement errors to values of the order of $0.001^m - 0.002^m$.

Assigning a standard spectral energy distribution is still a problem for peculiar stars such as HZ Her; in this case, iteratively correcting for atmospheric extinction in fundamental multi-color astrophotometry, as is proposed in [19], enables correction for atmospheric effects for our broad-band $WBVR$ measurements with accuracies no worse than $0.005^m$ in $W$ and $0.003^m$ in $B$, $V$, and $R$, if the air mass $M(z)$ does not exceed two at the high-altitude observatories ($h \geq 3000$ m). These errors must be approximately doubled for the lower-altitude observatories [19]. We are speaking here of systematic errors. The random errors (atmospheric flickering, rapid variations of the transparency, photon noise in the detectors etc.) can be larger, but they can
be suppressed by increasing the number of independent measurements.

During observations made together with T.R. Isrambetova at the Maid-
anak High-Altitude Observatory (Uzbekistan) in 1987–1988, we used the
reduction coefficients of the Zeiss-600 telescope (a single-channel WBVR
electrophotometer with an automatized control system, using a FEY-79 pho-
tomultiplier as a detector). The relative spectral sensitivity of the system
was fairly stable, and was checked twice per season (Spring-Summer and
Summer–Autumn). The reduction coefficients to the standard photometric
system were obtained using multiple measurements of the standard stars in
the fields SA 107, 108, and 111-113 [20]. This yielded the relations

\[
\begin{align*}
B - V &= 1.071(\pm 0.021)(b - v) - 0.068^m(\pm 0.018^m), \\
V - R &= 0.803(\pm 0.033)(v - r) + 0.173^m(\pm 0.014^m),
\end{align*}
\]

where \(b\), \(v\), and \(r\) are the instrumental magnitudes and \(B\), \(V\), and \(R\) are
the magnitudes in the Johnson photometric system.

We calculated the corrections to the magnitudes using the known instru-
mental color indices using the expressions

\[
\begin{align*}
B - b &= 0.094(b - v) - 0.099^m, \\
V - v &= 0.014(b - v) - 0.015^m, \\
R - r &= 0.234(v - r) - 0.208^m.
\end{align*}
\]

Table 3: Results of the observations

| JD 2400000+ | \(\varphi\) | \(\psi\) | \(W\) | \(B\) | \(V\) | \(R\) | \(n\) |
|------------|----|----|----|----|----|----|----|
| 1          | 46615.3830 | 0.873 | 0.756 | 15.075 | 15.125 | 14.667 | 14.328 | 6 |
| 2          | 46616.4574 | 0.983 | 0.757 | 15.144 | 15.314 | 14.946 | 14.660 | 8 |
| 3          | 46618.4099 | 0.181 | 0.758 | 14.855 | 15.306 | 14.779 | 14.585 | 6 |

In the later observations in 1989–1998 (and in all observatories at which
observations were carried out by the author), the reduction coefficients to the
standard Johnson photometric system were obtained from measurements of standard stars in the field of h and χ Per (12 standard stars were measured each time) and of NGC 884 (13 standard stars were measured each time).

The scatter of the individual points on the light curves is substantially larger than the observational errors. This probably reflects physical variability of the system [21, 22].

The observations were processed using a differential method. The orbital phases ϕ were calculated according to the elements [23]

\[ \text{Min Hel} = JD2441329.57519 + 1.70016773^d E. \]

The observational data are summarized in Table 3. We present part of the table as an illustration; the entire table is located at [http://lnfm1.sai.msu.ru/~sazonov/](http://lnfm1.sai.msu.ru/~sazonov/). The columns of Table 3 give (1) the consecutive number of each observation, (2) the Julian dates of the observations, (3) the phases ϕ of the orbital period, (4) the precession phases ψ, (5)–(8) the magnitudes in the W, B, V, and R bands, and (9) the number of individual observations n.

The observational data for HZ Her for all years were analyzed according to the phase of the 35-day cycle, taking into account the fact that precession times correspond to the ephemeris [24]

\[ T_{35} = JD(2441781.0±0.5) + (34.875^d±0.003^d) E. \]

The phases ψ of the 35-day cycle were calculated assuming that ψ = 0 when the X-ray source turns on [14, 24–27].

### 3 OBSERVATIONS IN 1986

WBVR observations of the HZ Her = Her X-1 close binary were carried out in July–October 1986 using the 600-mm reflector of the Crimean Station of the Sternberg Astronomical Institute (SAI), the 480-mm (AZT-14) reflector
HZ Her (1986)
of the Tien Shan High-Altitude Observatory, and the 600-mm reflector of the Maidanak High-Altitude observatory, using a single-channel electrophotometer in a photon-counting regime (Fig. (1.1-1.4)). In 1986, the reflection effect in the system remained at the classical (average) level, as can be seen from the light curves (Figs. 1-4; this and all other figures can be found in electronic form at http://lnfm1.sai.msu.ru/~sazonov/HZ Her=Her X-1). The main origin of this optical variability of HZ Her is the reprocessing of X-rays in the photosphere of the optical component of the system [11].

The spatial position of the X-ray source Her X-1 relative to the optical component HZ Her is always known with high precision. Therefore, we always have comprehensive information about the shape of the hot spot in the photosphere of the optical star, and, hence, about the spatial distribution of the X-ray emission of the neutron star.

In models with an anisotropic X-ray source with a complex accretion disk around the neutron star [28, 29], a certain asymmetry of the hot spot forms, which is reflected as “shoulders” with different heights in the optical light curves (in our chosen theoretical formalism, “shoulders” are those parts of the light curve at orbital phases from $\varphi = 0.40$ to $\varphi = 0.57$).

In the 1986 season, short flares (10 to 20 minutes long) were detected during individual nights in $W$, $B$, $V$, and $R$ close to orbital phases 0.015–0.025, with amplitudes of 0.03"m, 0.02"m, 0.02"m, and 0.01"m, respectively (Fig. (2.1-2.4).

We are interested in analyzing the observed manifestations of accretion-related structures in the system (most importantly, the accretion disk around the neutron star, gas condensations and other perturbing components) relative to the minimum brightness in the $W$, $B$, $V$, $R$ bands (Fig. (1.1-1.4) and the minimum $W-B$ color index (Fig. (3.1-3.4), close to the main minimum (orbital phases $\varphi = 0.96–0.04$). The brightness and $W-B$ variations (Fig. 3.1) are most probably due to precession and the physical parameters of the neutron-star accretion disk.
HZ Her (1986)

orb. phase

V

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

13.2
13.4
13.6
13.8
14
14.2
14.4
14.6
14.8
HZ Her (1986)
Characteristic kinks in light curves are observed at these same orbital phases [30]. There is a temporal correlation of these kinks in the optical light curve with the formation of dips in the X-ray curve. The latter are probably related to a certain regime for the mass flow from the optical component of HZ Her onto the neutron star [27]. These typical kinks and inflection points in the vicinity of the primary minimum (Min I) are essentially present in the 1986 light curves at all precession phases of the 35-day cycle.

All these effects lead to complex evolution of the optical light curves between observing seasons. The light curves in all spectral bands have a sharp bell-like shape, with a wide Min I and well-defined secondary minimum (Min II), but somewhat higher-amplitude right branch of the light curve (close to orbital phase $\varphi = 0.63$). This photometric peculiarity provides evidence for a displacement of the hot spot with orbital phase (with its area constant in the 1986 season), relative to the central meridian of the optical component of the system.

At the Min I ingress in the 1986 season, the light curve is steeper and more ordered and “classical” during the decline, and flatter during the rise, displaying a small dispersion of the brightnesses at the same orbital phases measured on different nights. This observational data indicate some asymmetry of the light curve close to the primary minimum. This suggests a variation of the colorimetric parameters of the accretion disk when it is eclipsed by the optical star. The difference in the brightness of the accretion disk at the ingress and egress of the X-ray eclipse is $0.20^m$ (Fig. 1.1), consistent with results of similar computations made in [31].

The color indices of the outer regions of the accretion disk differ quite significantly at the ingress and egress of the X-ray eclipse (Fig. 3.1-3.4). The same is true of the $(W-B)-(B-V)$ and $(V-R)-(B-V)$ color–color diagrams (Fig. 4.1-4.2).

Based on these observational data, we conclude that there was an increase in the size of the accretion structures in HZ Her in 1986 [27, 31],
Figure 6: Light curve of HZ Her in 1986 in $B$ for Min I.
Figure 7: Light curve of HZ Her in 1986 in $V$ for Min I.
Figure 8: Light curve of HZ Her in 1986 in $R$ for Min I.
which is reflected in the shape of the light curve (the right shoulder of the
light curve is somewhat higher than the left one).

Moreover, close to Min I (orbital phases \( \varphi = 0.96 - 0.04 \)), the variations
of the minimum brightness and \( W - B \) were of the order of 0.25\(^m\), which
happens in this system extremely rarely [31–33].

These variations in the brightness (Fig. (1.1-1.4)) and color index (Fig. 3)
with phase \( \varphi \) are probably most plausibly explained by variations in the size
of the accretion structures in the system, which re-radiate the X-ray flux in
the optical [14, 31, 34].

In addition, the system probably loses mass through the second Lagrange
point \( L_2 \). All this facilitates the formation of extended accretion structures in
the system and their manifestation in the optical at all phases of the 35-day
precessional cycle.

Also in 1986, significant changes in the physical conditions in the
HZ Her = Her X-1 close binary caused some observed effects that were cor-
related in the X-ray and optical.

According to EXOSAT data [35–37], nonuniform X-ray irradiation of
the outer regions of the accretion disk is observed at certain phases of the
precessional cycle, and asymmetry of the reprocessed disk X-ray emission is
observed in the optical. This corresponds to the model proposed in [38, 39]
and elaborated in [31, 32].

Thus, there are reasons to suggest that there is an increase in the accre-
tion rate onto the neutron star in this case. The first reason for this could
be a strong increase (decrease) in the mass influx into the neutron-star ac-
cretion disk, related to different mass-flow regimes and conditions for the
outflow from the Lagrange point \( L_1 \) at different epochs [32, 40]. Second, the
viscosity of the accretion disk could suddenly increase, causing it to become
turbulent rather than laminar [41], or this may be a manifestation of a tur-
bulent accumulating disk [42]. All these effects are reflected in the 1986 light
curve. Third, note also that, at the orbital phases of elongations of the X-ray
source ($\varphi = 0.25$ and $\varphi = 0.75$), the light curve of the system is practically the same as light curves obtained at other epochs in the same season; this indicates that the area of the hot spot was approximately constant during the 1986 season.

The main principles we have used in our analysis of the light curve to determine the geometry and spatial location of the hot spot, as well as the physical parameters of the accretion structures in the system, are presented in [39]. When applied to the observational data, these mathematical methods enable us to fit the data and to find the reflection of various effects in the light curves obtained in 1986.

Fitting of the data obtained close to the X-ray eclipses suggests that the brightness of the system was somewhat higher than in 1987–1988 and 1989–1998 (for which there are still unpublished photoelectric observations).

The $W-B$ color index was also higher in 1986 than in the following years. Analysis of the $(W-B)-(B-V)$, $(V-R)-(B-V)$ color–color diagrams (Fig. 3.1, 3.2) leads to the logical conclusion that the hot spot was located on the trajectory of the motion of the accretion structures along the limb of the optical component of the close binary.

4 OBSERVATIONS IN 1987

The results of the 1987 observations are presented in Fig. (5.1-5.4). As is more common, the left shoulder of the secondary minimum on the light curve is higher than the right one. Moreover, a photometric anomaly is observed close to orbital phase $\varphi = 0.50$, with an amplitude of $0.4^m$ in $B$ and $V$ and $0.3^m$ in $R$. This anomaly is less pronounced, or “smeared” in $W$.

This photometric peculiarity was not observed in other seasons for which we have data, and this anomaly in the secondary minimum is also absent from other published data. The total amplitude of the brightness variations in the 1987 secondary minimum exceeded $0.3^m$ in $V$, with the $V$ brightness level
HZ Her (1986)
close to Min II reaching minimum values close to 13.5\textsuperscript{m}. Such brightness levels were not found in subsequent observations.

Of special interest are observations of the system in the primary minimum, close to orbital phases from \(\varphi = 0.97\) to \(\varphi = 0.03\) (we consider here a Roche-lobe configuration with the libration point \(L_2\) located at the outer edge of the neutron-star accretion disk). The gas flows from the system through \(L_2\).

Analysis of these photometric peculiarities gives a detailed light curve of the system in the vicinity of Min I. In particular, we observed a “sharp” minimum in the orbital light curve twice in 1987. This minimum is most likely due to the eclipse of a gaseous structure heated by the X-ray flux at \(L_2\) \cite{34, 43–46}.

Taking into account model constraints on the mass of the variable HZ Her and the neutron star, the radius of the binary orbit, the distance of the \(L_2\) from the neutron star, and the area of condensations, and assuming that the surface brightness of gas condensations heated by X-rays close to \(L_2\) can in a first approximation be taken to be the surface brightness of HZ Her, it is possible that eclipses of gas condensations are observed in the primary minimum (Min I).

This occurs because, at a certain degree of Roche lobe filling by the optical star, some gas leaves the system via \(L_2\), which is located at the outer edge of the neutron-star accretion disk. Therefore, gas condensations can form, probably close to \(L_2\). A blob could also form at the outer edge of the accretion disk, with physical characteristics and optical manifestations more or less identical to those of such a gas condensation.

If the spatial configuration of the optical component has triangular libration points \(L_4\) and \(L_5\), X-ray heated gas condensations could be located at orbital phases \(\varphi = 0.166\) and \(\varphi = 0.833\), respectively.

A photometric peculiarity was found in the 1987 light curve close to orbital phases \(\varphi = 0.847 - 0.853\); this peculiarity was similar to a blob \cite{27,
that de-excitates over some time.

Deep flickering of the X-ray source on time scales of several minutes is also observed at orbital phases close to $\varphi = -0.15$, at the epochs of dips in the X-ray light curve [47]. This flickering could be due to the de-excitation of some structures, such as gas condensations in the system.

The detailed light curve close to Min I and Min II shows oscillations of the minimum brightness, $W-B$, and $B-V$ with $\varphi$, at the level of $0.1^m$. Such oscillations were not observed in 1986 or 1987. The variations of the brightness and of the $W-B$, $B-V$, $V-R$, and $B-R$ color indices with $\varphi$, as well as the nature of the $(W-B)-(B-V)$, $(V-R)-(B-V)$ diagrams (Figs. 6.1-6.4 and 7.1-7.2), can be explained by variations of the areas of accretion structures re-emitting X-ray flux in the optical and the regimes for the gas flow from the optical component to the neutron star.

During X-ray eclipses, $W-B$ and the $W$ brightness correlate with the accretion rate; i.e., the $W$ brightness of the system increases if there is less gas around the neutron star. A prominent photoelectric effect in the $W$ band and variations of this effect on time scales close to $\sim 30-35$ days requires a sufficiently hot gas with temperature $T \approx 2.5 \times 10^6$ K and a number density of electrons $n_e = 7 \times 10^{11}$ cm$^{-3}$ flowing from the inner Lagrange point $L_1$ [48]. This may form a gaseous corona surrounding the outer regions of the accretion disk [45].

It is interesting to compare the light curves presented in this paper and those obtained in other studies [21, 32, 34, 49]. Close to elongations of the X-ray source ($\varphi = 0.25$ and $\varphi = 0.75$), our observations are in qualitative agreement with the data of other authors. This provides confirmation that geometry of the hot spot was constant in 1987. The highly chaotic state of the brightness in Min I and Min II is striking.

At orbital phases from $\varphi = 0.30$ to $\varphi = 0.40$, there is a seasonal increase in the brightnesses in $W$ (by $0.30^m$) and $B$ (by $0.20^m$); the $V$ and $R$ brightnesses are at their 1986 levels. There is a flat plateau in Min I in all the
Figure 15: Light curve of HZ Her in 1986 in $W$. 

HZ Her (1987)
Figure 16: Light curve of HZ Her in 1986 in $B$
Figure 17: Light curve of HZ Her in 1986 in V
Figure 18: Light curve of HZ Her in 1986 in $R$
bands. Thus, in this observing season, the left shoulder of the light curve in the vicinity of Min II has somewhat higher brightness than the right shoulder. Long flares are observed in Min I (from 20–30 to 60–80 min), with amplitudes up to \(0.07m - 0.08m\). The behavior in the \(WBVR\) bands is correlated.

Similar flares are also observed close to orbital phases 0.15–0.25 and 0.75–0.85. There are also short flares close to the phase 0.015, with amplitudes of \(0.01m, 0.02m, 0.02m\), and \(0.03m\) in \(R, V, B, \) and \(W\), respectively. These are probably related to hot condensations of matter in the accretion structures (and in the accretion flow in general) that are projected onto the limb of the optical component of the close binary.

5 OBSERVATIONS IN 1988

The results of our photoelectric observations in 1988 (Fig. (8.1-8.4)) differ substantially from the results for 1986 and 1987, in the presence of many components of the orbital light curve (most of the observations were made close to the brightness maximum and in the “on” state) and many fine photometric details in the light curves at different phases of the 35-day precessional cycle.

This is true first and foremost of certain peculiarities of the orbital light curve close to the primary minimum Min I, where a smooth (classical), flat bottom, without any deviations, is observed in most cases. In the 1988 season, some variations of the curve and a slight increase of the brightness were observed close to orbital phases \(\varphi = 0.97 - 0.04\).

Such periodic variations in the light curve were also noted in [31, 34]. This suggests an increase in the accretion disk in the 1988 season (the usual average size of the accretion disk is \(\approx 0.5\) of the radius of the optical component of HZ Her, an A7 star). The inclination and degree of warping of the accretion disk change [31]. In our opinion, these variations are related to different mass-flow regimes and occur in strictly defined precessional phases.
Figure 19: \((W - B)\), vs. orbital phase \(\varphi\) for the 1987 season
Figure 20: \((B-V), \) vs. orbital phase \(\varphi\) for the 1987 season
Figure 23: Color–color diagrams $(W-B) - (B-V)$ for the 1987 season.
of the 35-day cycle.

These photometric structures in the light curve close to orbital phase $\varphi = 0.02$ form extremely infrequently. As a rule, these optical flares are preceded by dips in the X-ray light curve, which are probably related to variations in the rate of mass flow from the optical star HZ Her onto the neutron-star companion [27, 31].

As a consequence, the lengths of the secondary minimum also increased. This contradicts the conclusions drawn in [34], and can be explained by the small number of observational points presented in [34] compared to our study, as well as the absence of data in the $W$ (or $U$) and $R$ bands in [34]. Our analysis here is based on $WBVR$ observations and a larger number of points, especially close to Min II. The duration of Min II in 1988 was about 0.41 to 0.62 in orbital phase, providing evidence for a periodic migration of the hot spot along the meridian and the latitude of the optical component, and for some increase in the accretion disk around the neutron star in 1988.

Also in the 1988 season, the minimum values of $W-B \approx 0$ were detected (at precession phase $\psi = 0.86$; Fig. (9.1-9.4)), which correspond to the spectral class of the optical component in Min I and a deficit of UV emission. Note that all photometric effects related to the 35-day cycle are manifest most strongly in the UV, as is clearly visible in the plots for $W$ and $B$ for all the observing seasons.

A joint and qualitative analysis of our observational data, X-ray observations [50–52], and observations in other spectral bands (both in the same seasons and later) enables refinement of the geometry and places limits on variations of the hot spot and accretion structures. In the studies cited above, the 35$^d$ period was analyzed at precessional phases $\psi = 0.76–0.80$ with the aim of looking for manifestations of blobs close to the gas flow projected onto the orbital plane of the system. A similar analysis was carried out in [34]. HZ Her = Her X-1 was observed in the anomalous low state at phase $\psi = 0.76–0.88$ [53].
HZ Her (1988)
Figure 33: Color–color diagrams \((W-B) - (B-V)\) for the 1988 season.
Figure 34: Color–color diagrams \((V - R) - (B - V)\) for the 1988 season.
The total brightness amplitude close to Min II in the 1988 season was up to $\sim0.55^m$ in $V$. The brightness level close to Min II (orbital phase $0.475-0.485$) reached its minimum values: $12.6^m$ in $W$, $13.5^m$ in $B$, $13.4^m$ in $V$, $13.4^m$ in $R$.

$W - B$ was small compared to the previous observing seasons. Analysis of the $(W - B) - (B - V)$, $(V - R) - (B - V)$ color–color diagrams (Fig. 10.1-10.2) suggests that the hot spot was located along the trajectory of the motion of the accretion structures over the limb of the optical component of the close binary, but the relation with the trajectory was less pronounced than in 1986 and 1987.

Thus, some chaos of the brightness close to Min II was observed in the 1988 season at various phases of the 35-day cycle, especially in the UV. This may indicate spatial evolution of the optically thick and warped accretion disk around the neutron star. The disk creates shadows on the surface of the optical component, which can give rise to physical variability of the accretion structures and manifestations of gas flows in the system; in turn, these shadows come about due to differences in the rate of mass flow from the optical component onto the neutron star.

6 CONCLUSIONS

Our study leads to the following conclusions.

– We have presented data on eight full precessional cycles of the close binary, enabling us to identify certain fine photometric effects that both confirm the conclusions of other authors and provide new information on the system.

– The homogeneity of our set of data containing electrophotometric observations in four optical bands ($W$, $B$, $V$, $R$) makes them of special value, and provides additional information on fine effects in the HZ Her = Her X-1 system.
– In the 1986–1988 observing seasons (and subsequent 1989–1998 seasons), there is a clear correlation between the light curves in all four bands ($W, B, V, R$).

– The light curves of HZ Her we have presented here are in qualitative agreement with light curves obtained by other authors from photometric observations taken in the same periods, and the data correlate well at all phases of the precessional cycle. This correlation [31] is also confirmed by the location of the outer regions of the accretion disk during the ingress and egress of the X-ray eclipse, as follows from the $(W - B) - (B - V)$ color–color diagrams.

– The $W - B, B - V, V - R,$ and $B - R$ color indices differ substantially at phases of the X-ray eclipse, $0.930 - 0.078$. This can probably be explained by season-to-season changes in the physical state of the neutron-star accretion disk and the conditions for mass flow in the close binary.

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