Optical Observations of the CBS HZ Her=Her X-1

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Introduction

The high accuracy and long time span of photoelectric observations allow them to be used for multifactor analyses and refining some of the "fine" photometric effects in the light curves of close binary systems. The results obtained can be subsequently interpreted in terms of the model of mass flow from the optical component of the close binary systems onto the accretion disk of the neutron star, which can explain satisfactorily the irregularities of the gaseous flow, the "hot spot", and the presence of splashes moving in individual Keplerian trajectories about the outer parts of the accretion disk of the neutron star Her X-1.

Photometric peculiarities of the accretion formation of the neutron star Her X-1 and its geometry in 1986-1990

When analyzing the photometric data in during the 1986 season (fig01(a-d)), one must bear in mind that the scatter of individual measurements in the B, and especially, in the W filter at times exceeds, on the average, the corresponding standard errors (up to $0^m.30^m.5$), most likely, due to the physical variability of the optical star, as we pointed out in our earlier papers [1], [2], [3].

During the 1988 season the accretion formation in the system increased in size, resulting in an increase of the duration of the secondary minimum Min , contrary to the conclusion made by Kiliachkov [4]. This discrepancy can be explained by the small number of observational data points used by the above authors compared to the data set that we use in this paper, and the lack of W- (or U-) and R-band in the former analysis.

The system exhibits certain light variations at various precession phases, which can be linked to the observed x-ray variations of the Her X-1 source and which appear to depend on the spatial orientation of the tilted and geometrically warped disk of the neutron star (NS) precessing with a period of $P_3 \cong 34^d.875$. The optical light variations considered may also be due to the increase or decrease of the pulsar beam size as suggested by Bisnovatyi-Kogan [5] and periodic variation of the accretion rate onto the NS. These light variations may explain the 35-day activity cycle of Her X-1. The lack of synchronization between orbital rotation and the axial rotation of the optical component in the CBS can also explain the precession of the accretion disk (AD) of the NS.

Many models are known to explain the main property of the 35-day cyclic variations of the system - the periodic disappearance of the x-ray flux for a terrestrial observer combined with the almost constant x-ray luminosity of the NS [6]. This conclusion follows from the fact that the reflection effect continues to be observed even during the periods when no x-ray flux from the system is recorded on the Earth.

The observations made in 1986-1988 exhibit certain light variations in the precession phase interval (0.90-0.10), which can be linked to the observed x-ray variations of the Her X-1 source and which appear to depend on the spatial orientation of the tilted and geometrically warped disk of the NS precessing with a period of $P_3 \cong 34^d.875$.

I favor the model of mass flow from the optical component of the CBS onto the AD of the NS, which satisfactorily explains the irregularities in the gaseous flow [3], [4], [7], [8], [9], the "hot line", and individual splashes [10] moving in individual Keplerian trajectories about the outer parts of the AD of the Her X-1 neutron star [11], [12].

This model explains the variety of my observational data. Note also that the numerical results obtained in earlier papers [7] complement the proposed mechanism. The comments made in the above paper unambiguously indicate that the intersection of the family of the nearest ballistic orbits of the gaseous flow produce concentrations of flow particles, which move along certain spiral trajectories toward the accretor of the CBS with ever increasing velocities due to the gravitational acceleration caused by the primary component and which we can interpret as a complex structure — a shock — interacting with the ambient matter — i.e., with the accretion disk of the compact object. As a result, if a star, like HZ Her, fills completely its inner critical Roche lobe (ICRL), most of the mass flows through the L_1 point, falls onto the NS, and feeds the AD.

However, gas may partly scatter beyond the ICRL of the 7-type star and the pulsar, mostly in the vicinity of the orbital plane of the CBS and at small heights in the $\pm z$ plane [7], [8], [13], [14]; it can also escape from the system via the L_2 point, crossing the neighboring ballistic trajectories of the particles of the gaseous flow emerging from the optical component of the system at small distances from the inner Lagrange point L_1, i.e., before the jet encounters the outer edge of the AD of the neutron star.

The location of the region where trajectories intersect depends significantly on the initial velocities of flow particles. With increasing absolute value of initial velocities of flow particles the crossing region shifts downstream so that the jet matter should collide with the accretion disk of the neutron star before the trajectories intersect with each other.

The intersection of ballistic trajectories of flow particles in HZ Her= Her X-1 may explain, among other factors, the formation of irregularities in the gaseous jet of the CBS, which result in the flicker of the "hot line" in the HZ Her= Her X-1 CBS, which appears in the region where the gaseous jet collides with the disk-like envelope as observed at optical wavelengths.

We thus conclude that:

- The 1986 observations exhibit a certain increase of the accretion rate onto the neutron star (fig02(a-d));

- During the 1987 season optical outbursts were observed in the 0.15-0.25 and 0.75-0.85 orbital phase intervals. Short flux outbursts in the phase interval near 0.015 were recorded in the R,V,B, and W filters with the amplitudes of $0^m.10$, $0^m.15$, $0^m.25$, and $0^m.35$, respectively;

- During the 1988 observing season the system behaved somewhat chaotically near Min , especially at UV wavelengths, and this behavior should be interpreted as a spatial manifestation of an optically thick warped accretion disk;

- The WBVR light curves of 1989 reflect the dynamics of the behavior of the system. Most of the observations were made during the "off" phase, however, some observations were made during the high state. The accretion formation exhibits a somewhat asymmetric behavior with the sign reversed compared to the previous season. A "sharp" minimum, like in the 1987 season, appeared once near Min. Near Min II the light curve has a "classic" flat form.

- During the same observing season the light curve exhibited a photometric peculiarity in the orbital phase interval $\varphi = 0.815 - 0.875$ resembling a cooling gaseous condensation or a "blob" (a blob of high-temperarture plasma circulating at the outer edge of the AD of the neutron star) [15], [16].

- The WBRI light curves of the 1990 season are indicative of a certain decrease and equalization of the luminosities of both halves of the accretion formations, and of a certain change of the asymmetry of the light curve (especially in the B and V filters). The size of the emitting region of the accretion formation appears to have remained unchanged compared to its appearance during the 1988-1989 seasons.

Dynamics of the Flux Variations in Min I and Min II and Mass Flow from the Optical Component

Crosal [15] performed the most detailed analysis of a phenomenological model for the CBS HZ Her=Her X-1 assuming constant mass flow from the primary star onto the NS. This model explains the observational manifestations of the system that were associated with the physical state of its x-ray flux and that of its accretion disk (AD).

A change in the mode of mass flow from the optical component of the CBS to the accretion disk of the neutron star results in a change of the geometry, degree of disk warp and, consequently, of the disk temperature (from 18000 to 25000 [3], [4],), resulting in the variations of different duration (from 30-40 minutes to 2-3 hours) and amplitude (from $0^m.2 \pm 0^m.3$ in the R and V filters and up to $0^m.4 \pm 0^m.5$ in the B and W filters) appearing in the light curve. This behavior shows up in an appreciable scatter of the (W-B) color index compared to that of (B-V) and (V-R).

The variation of (W-B) (the cause) by up to $0^m.6$ (e.g., during the 1987 and 1992 seasons according to my observations) at the same phases of the light curve results in (the consequence) changes in the geometric size and temperature of the "hot spot" and accretion formations (fig03(a-b)).

Near Min I of the orbital period changes are observed in the asymmetry of the accretion formation, which are associated with different phases of the 35-day cycle. The "hot spot" exhibits a certain evolution with respect to the central meridian of the system even during the first cycle of the 35-day period. The luminosity of the "hot spot" and its geometric size remained more or less the same as in 1988. We see variations of the (W-B), (B-V), (V-R), and (B-R) color indices as a function of the orbital phase and for various precession phases.

During that observing year strong variations of the (W-B) color index were observed, which are indicative of a certain decrease of the temperature of the accretion formation in the "off" state of the x-ray source, whereas the temperature and size of the accretion formation remained within the traditional intervals of the previous observing seasons. In 1990 the "hot spot" exhibited appreciable evolution in the "on" state relative to the central meridian of the system.

We also observe in 1986-1998 a certain UV flux deficit during the optical minima of HZ Her.

Gaseous formations and the corona scatter the radiation of the optical component of the CBS, which is also observed during the phases of optical eclipse ($\varphi_{orb.} = 0.97 - 0.03$), and this fact should be taken into accounts in precision observations and subsequent interpretation of the data obtained at these phases.

The fact that W-band flux shows very strong variability (amounting to $0^m.20 - 0^m.35$ over a single observing night ($\sim$ 3 $-$ 4 hours)) leads us naturally to conclude that we are observing hot gas located in a rather close vicinity of the optical component of the CBS and flowing away from it with velocities of about several hundred km/s [7], [17], namely, more than 210-260 km/s [7] before encountering the accretor — the fact that was convincingly confirmed in later papers [18].

Here we observe gaseous jets in the CBS, which undoubtedly expand when reaching the AD of the neutron star, and these processes must depend on the ambient properties in the vicinity of the CBS (and, in particular, in the vicinity of the accretion disk of the neutron star) through which the jets move. This medium is far from uniform.

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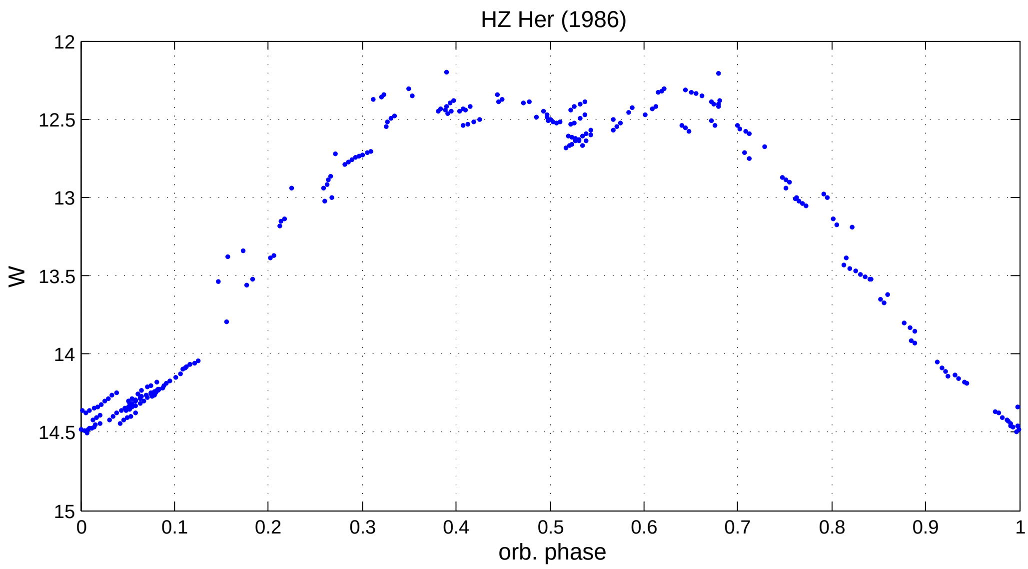

Figure 1: The 1986 W-band light curve folded with the period $P = 1^d.70016773$

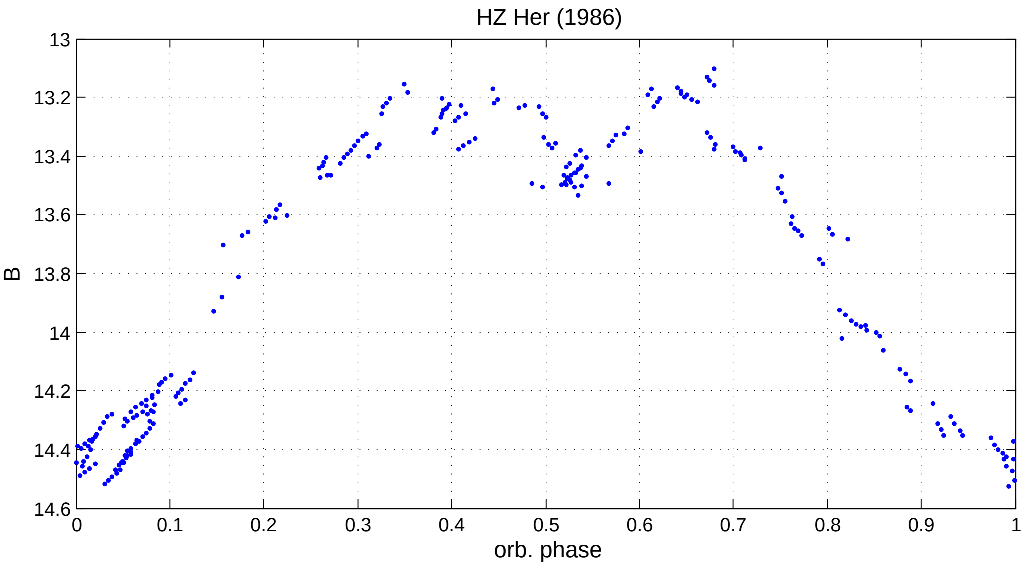

Figure 2: The 1986 B-band light curve folded with the period $P = 1^d, 70016773$

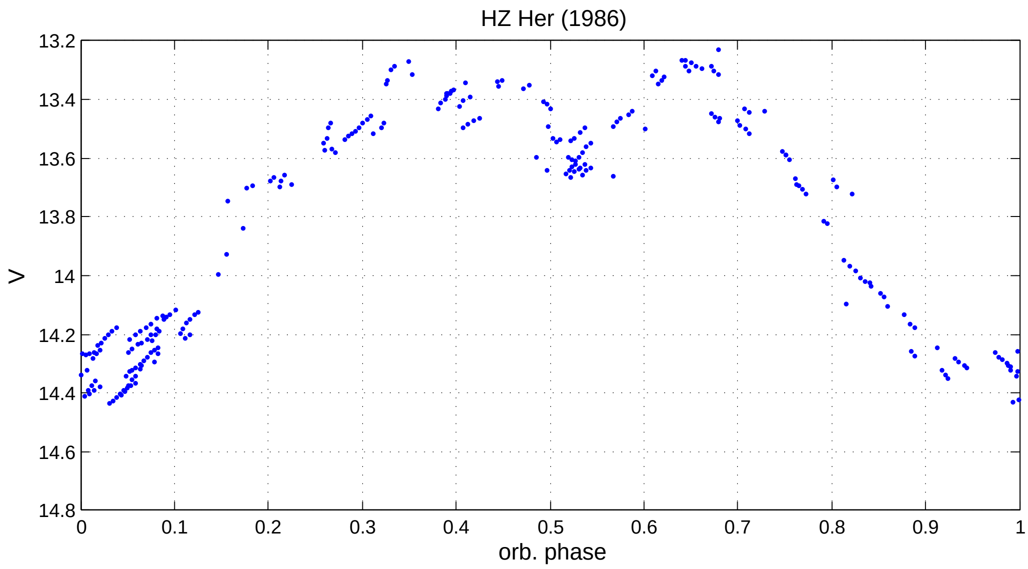

Figure 3: The 1986 V-band light curve folded with the period $P = 1^d, 70016773$

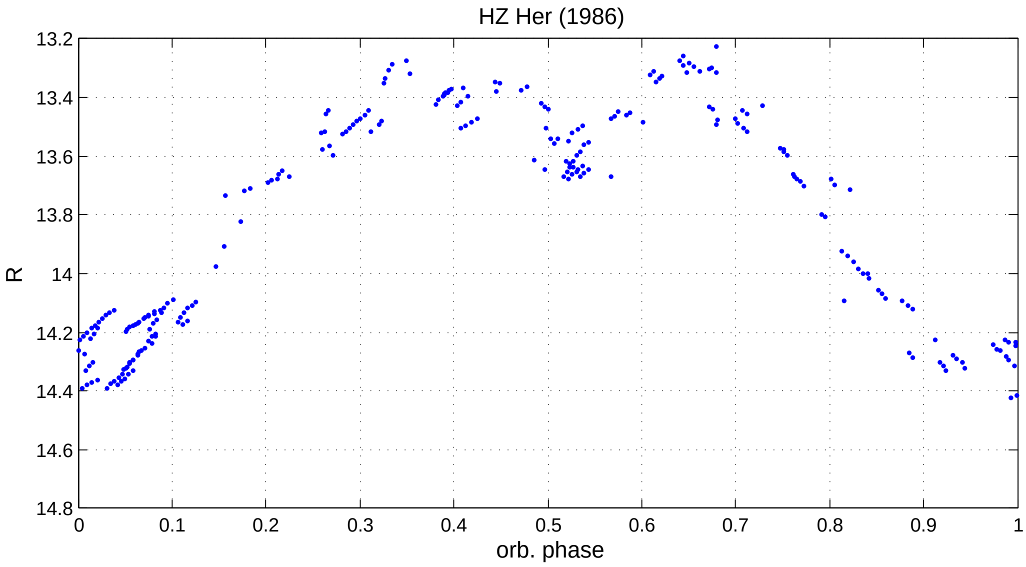

Figure 4: The 1986 R-band light curve folded with the period $P = 1^d, 70016773$

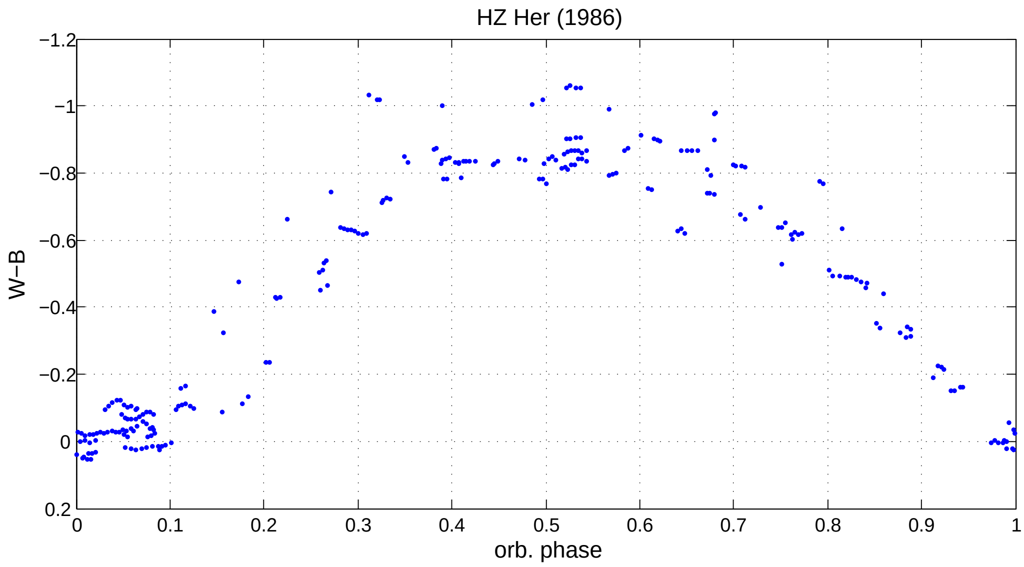

Figure 5: W-B color of HZ Her as a function of orbital phase φ for the 1986 data

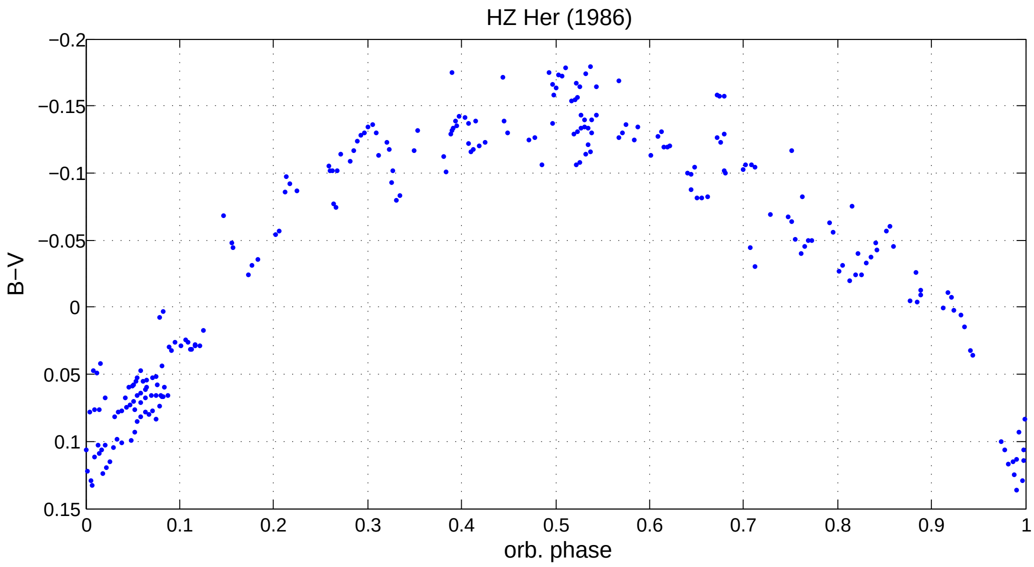

Figure 6: (B-V) color of HZ Her as a function of orbital phase φ for the 1986 data

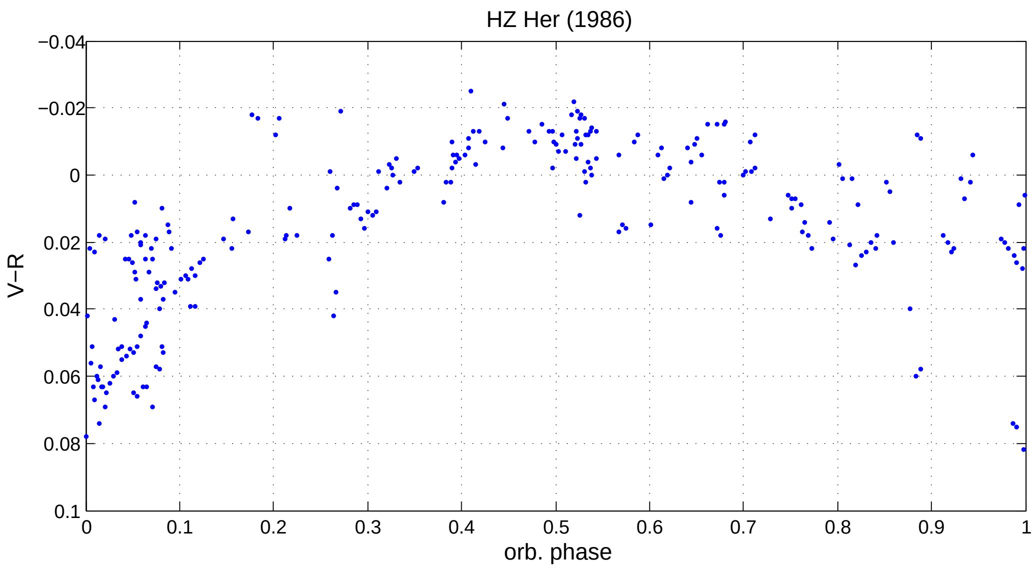

Figure 7: (V-R) color of HZ Her as a function of orbital phase φ for the 1986 data

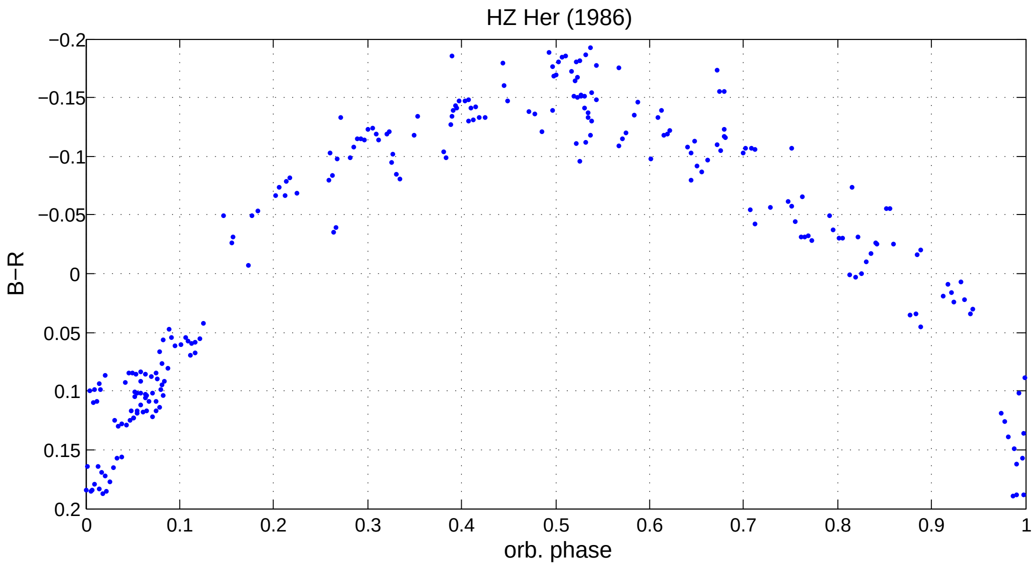

Figure 8: (B-R) color of HZ Her as a function of orbital phase φ for the 1986 data

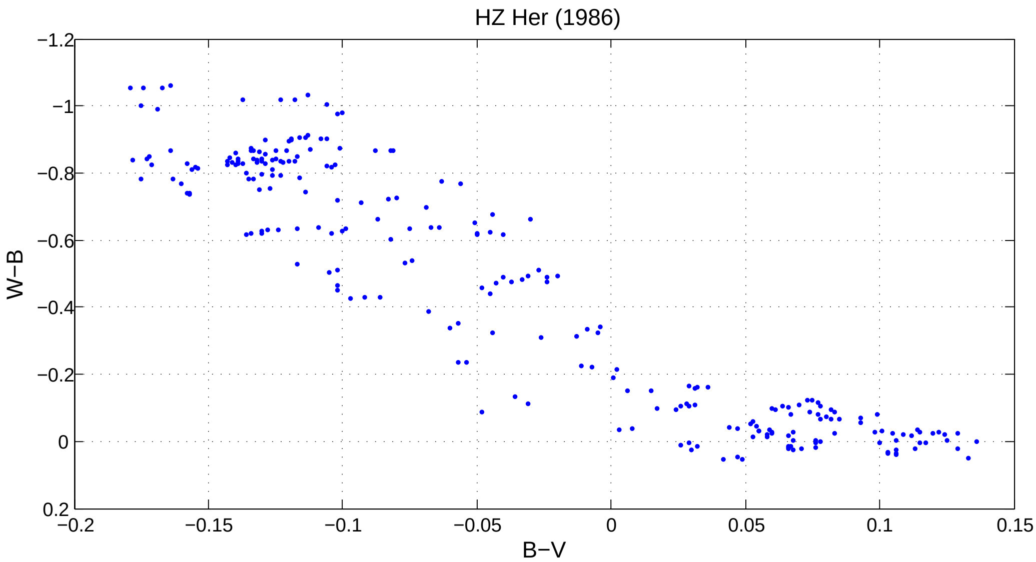

Figure 9: The 1986 (B-V)-(W-B) two-color diagram of HZ Her

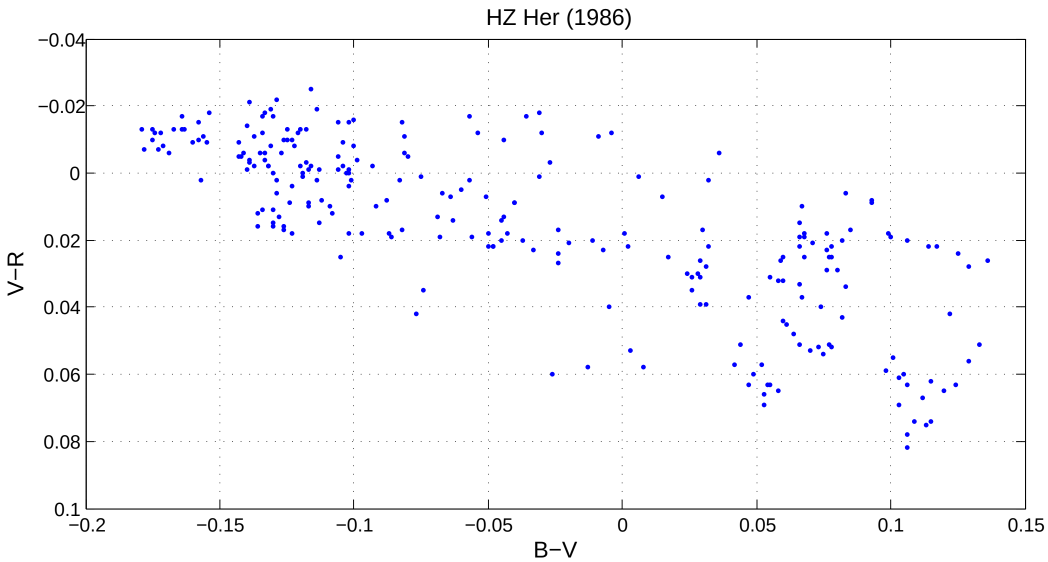

Figure 10: The 1986 (B-V)-(V-R) two-color diagram of HZ Her