Evolution of asymmetries in the circumstellar disc of the Be/X-ray binary X Persei

R. Zamanov¹,⋆, K. A. Stoyanov¹, U. Wolter², N. A. Tomov¹, D. Marchev³, and L. Iliev¹

¹ Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, Tsarigradsko Shose 72, BG-1784 Sofia, Bulgaria
² Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany
³ Department of Physics and Astronomy, Shumen University, 115 Universitetska Str., 9700 Shumen, Bulgaria

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ABSTRACT

We present spectroscopic observations of the Be/X-ray binary X Per obtained during the period December 2017 - March 2019 (MJD 58095 - MJD 58568). In December 2017 the Hα, Hβ, and HeI 6678 emission lines were symmetric with violet-to-red peak ratio V/R ≈ 1. During the first half of the period (MJD 58095 - MJD 58360) the V/R-ratio decreased to 0.5 and the asymmetry developed simultaneously in all three lines. During the second half of the period (MJD 58360 - MJD 58570) the V/R-ratio increased, however with the HeI 6678 line showing a markedly different behaviour than the Balmer lines. A third component with velocity $≥ 250$ km s⁻¹ appeared in the red side of HeI line profile. Possibly, during the first half of the period the entire disc become asymmetric and/or elliptical. The third component in HeI can be an indication for inner elliptical disc with eccentricity $≈ 0.4$.

Key words. Stars: emission-line, Be – stars: winds, outflows – circumstellar matter – X-rays: binaries – stars: individual: X Per

1. Introduction

The relatively bright variable star X Persei (HD 24534) is the optical counterpart of the X-ray source 4U 0352+309 (van den Bergh 1972, Braes & Miley 1972), and is classified in the Be/X-ray subclass of massive X-ray binary stars (e.g. Reid 2011). It consists of an early type Be star and a slowly spinning neutron star. Delgado-Martí et al. (2001) determined the orbital period $≈ 250$ d, orbital eccentricity $e = 0.11$, semi-major axis $a = 2.2$ a.u and orbital inclination $i = 26^\circ - 33^\circ$. The X-ray data revealed a neutron star with spin period $≈ 836$ s, which does not display transient X-ray outbursts. Maitra et al. (2017) detected changes in the accretion geometry of X Per based on changes in the pulse profile and energy spectrum. The pulse period shows episodic spin-ups and spin-downs which indicates that the pulsar is close to a torque equilibrium and the long pulse period suggests a strong magnetic field (Yatabe et al. 2018).

The primary is very rapidly rotating main sequence Be star which forms an outwardly diffusing gaseous disc. During the last century, the visual brightness of X Per varies in the range $V = 6.8$ to 6.2 mag. The spectrograms of X Per from 1913 to 1972 show X Per to have bright hydrogen lines that are variable in structure, velocity, and intensity. At times the spectrum is veiled and very few features can be distinguished (Cowley et al. 1972). In the last decades, X Per exhibited two discless phases (around 1976-1977 and 1989-1990) when the emission lines disappeared and the circumstellar disc around the donor star is disrupted (Norton et al. 1991, Roche et al. 1997). The long-term variability of the emission lines and optical brightness indicate for mass ejections from the donor star into the circumstellar disc (Li et al. 2014).

We present optical spectroscopic observations obtained in the last two years and discuss the asymmetries in the circumstellar disc.

2. Observations

The optical spectra of X Per were secured with the ESpeRo Echelle spectrograph (Boney et al. 2017) on the 2.0 m RCC telescope of the Rozhen National Astronomical Observatory, Bulgaria. Usually, we have one 2 minutes exposure (because Hα could be saturated on longer exposure) and one 10 or 15 minutes exposure, where Hβ and HeI line can be investigated. Additionally, we have observations with the HEROS spectrograph (Schmitt et al. 2014) on the 1.2 m TIGRE telescope in the astronomical observatory La Luz in Mexico.

The variability of Hα, Hβ, and HeI 6678 emission lines of X Per is presented in Fig. 1. The spectra are normalized to the local continuum and a constant is added to each spectrum. In this figure is visible that the blue peak gradually decreased in the period July - September 2018 and after that increased again.

3. Results

During the period December 2017 - March 2019, the equivalent width of the Hα emission line ($W_\alpha$) varies in the range $-26$ Å $≤ W_\alpha ≤ -15$ Å, the equivalent width of Hβ emission line ($W_\beta$) varies in the range $-4.3$ Å $≤ W_\beta ≤ -2.6$ Å, and the equivalent width of HeI 6678 emission line varies in the range $-2.0$ Å $≤ W(HeI 6678) ≤ -0.85$ Å. The variability of the equivalent widths is presented in Fig. 2. There is a correlation between equivalent widths of these three lines. The correlation analysis between $W_\alpha$ and $W_\beta$ gives Pearson correlation coefficient 0.81, significance $p-value = 2 × 10^{-12}$, for $W_\alpha - W(HeI 6678)$ it gives Pearson...
Fig. 1. Variability of \( H\alpha \), \( H\beta \) and \( 6678 \) emission line profiles of X Per. The date of observations is in format YYYYMMDD.

correlation coefficient 0.68, \( p = 1.3 \times 10^{-8} \), and for \( W\beta - W(6678) \) Pearson correlation coefficient 0.49 and \( p = 6.7 \times 10^{-4} \). The correlation is very strong between the strong lines \( H\alpha \) and \( H\beta \).

3.1. Disc size

The variability of the distance between the peaks is presented in Fig[3] There is moderate relationship between \( \Delta V\alpha \) and \( \Delta V\beta \) with Pearson correlation coefficient 0.50 and significance \( p = 7 \times 10^{-7} \). The correlation analysis gives moderate anti-correlation between \( \Delta V\alpha \) and \( \Delta V(6678) \) with Pearson correlation coefficient -0.42 (n.b. negative values) and \( p = 2 \times 10^{-4} \). No correlation exists between \( \Delta V\beta \) and \( \Delta V(6678) \) – the Pearson coefficient is only 0.04. This is connected with the behaviour visible in Fig[3] that after MJD 56450 a decrease of \( \Delta V(6678) \) is visible – it changes from 220 km s\(^{-1}\) to 150 km s\(^{-1}\) for less than 150 days. No similar tendency is visible in \( \Delta V\alpha \) and \( \Delta V\beta \).

The emission lines form in the disc surrounding the Be star. The discs of the Be stars are Keplerian supported by the rotation \[e.g. Porter & Rivinius (2003) and references therein\]. For a Keplerian circumstellar disc the peak separation can be regarded as a measure of the outer radius \( R_{disc} \) of the emitting disc \[Huang 1972\]:

\[
R_{disc} = R_1 \frac{(2 \, v \, \sin \, i)^2}{\Delta V^2},
\]

where \( R_1 \) is the radius of the primary and \( v \, \sin \, i \) is its projected rotational velocity. For the primary we adopt \( R_1 = 10.5 \ R_\odot \) and mass \( M_1 = 13.5 \ M_\odot \) \[Zamanov et al. 2019\]. During the period of our observations, the two peaks are visible in the emission lines profiles and we can estimate the disc radius using Eq[1] The disc size for different emission lines are in the ranges:

- \( R_{disc}(H\alpha) = 115 \sim 190 \ R_\odot \)
- \( R_{disc}(H\beta) = 75 \sim 120 \ R_\odot \)
- \( R_{disc}(6678) = 40 \sim 80 \ R_\odot \)

The average ratios between disc sizes (which is equivalent to the ratio of the peak separations) are:

- \( R_{disc}(H\alpha)/R_{disc}(H\beta) = 1.8 \pm 0.2 \)
- \( R_{disc}(H\alpha)/R_{disc}(6678) = 3.0 \pm 0.9 \)
- \( R_{disc}(H\beta)/R_{disc}(6678) = 1.8 \pm 0.4 \)

We note in passing that these ratios do not depend on the adopted values of \( v \, \sin \, i \) and \( R_1 \) (see Eq[1]).
Fig. 2. Variability of equivalent widths of \( H\alpha \) (black squares), \( H\beta \) (red pluses), and HeI6678 (blue circles).

Fig. 3. The distance between the peaks of the emission lines – \( H\alpha \) (black squares), \( H\beta \) (red pluses), and HeI6678 (blue circles).

Fig. 4. \( V/R \) ratio for \( H\alpha \) (black squares), \( H\beta \) (red pluses), and HeI6678 (blue circles). It is calculated as \( V/R = (I_B - 1)/(I_R - 1) \).

Fig. 5. Three component structure of HeI 6678 and HeI7065 lines in March 2019. The upper spectra are obtained with TIGRE, the lower with the Rozhen telescope.

3.2. \( V/R \) ratio

On Fig. 1 it is visible that the \( H\alpha \) emission line, in December 2017 is symmetric with \( V/R \approx 1 \). The same is for \( H\beta \) and HeI6678 emission lines. After that all three lines become asymmetric. On Fig. 4 is presented the \( V/R \) ratio, calculated as \( V/R = (I_B - 1)/(I_R - 1) \), where \( I_B \) and \( I_R \) are the intensity of the blue and red peak, respectively. The spectra are normalized before the measurements and the continuum level is \( \equiv 1 \).

1. In the beginning of the present data set the \( V/R \)-ratio for all three lines is \( \approx 1 \).

2. During the first half of the period (MJD 58095 - MJD 58365) in all three lines \( V/R \)-ratio varies in practically the same manner – it decreased from \( V/R \approx 1 \) to \( V/R \approx 0.5 \), with speed \( \Delta(V/R) / \Delta t \approx 2 \times 10^{-3} \, d^{-1} \).

3. During the second half of the period (MJD58365 - MJD58570) the \( V/R \)-ratio of \( H\alpha \) and \( H\beta \) goes up from 0.5 to \( \sim 1.0 \). However the behaviour of \( V/R \)-ratio of HeI6678 deviates from the behaviour of \( H\alpha \) and \( H\beta \) lines (see Fig. 4). \( V/R \) (HeI) changes from 0.5 to 1.5, having speed of change \( \Delta(V/R) / \Delta t \approx 4 \times 10^{-3} \, d^{-1} \). For comparison, the \( H\alpha \) emission peaks have speed of change \( \Delta(V/R) / \Delta t \approx 1.7 \times 10^{-3} \, d^{-1} \) and the \( H\beta \) peaks – \( \Delta(V/R) / \Delta t \approx 2.3 \times 10^{-3} \, d^{-1} \). Additionally to that a third component appeared in the red side of HeI profile (Fig. 5). This third component emerged in November 2018 and is visible on all spectra obtained after that.

4. the last spectrum of the present data set is obtained on 25 March 2019. On this spectrum \( H\beta \) is symmetric, and \( V/R(H\alpha) < 1, \, V/R(H\beta) \approx 1, \, V/R(HeI6678) > 1 \) (see Fig. 1). HeI6678 has a peculiar three peak profile (Fig. 5).

3.3. Asymmetries in the disc

The observed behavior of the \( V/R \)-ratio is an observational evidence of development of asymmetries in the outer and inner parts of the circumstellar disc around the primary of the Be/X-ray binary X Per.

1. At MJD 58095 the circumstellar disc was symmetric with \( H\alpha, \, H\beta \) and HeI having two equal peaks (\( V/R \approx 1.0 \)).
(2) During the first half of the period (MJD 58080 - MJD 58300) the asymmetry development is similar in Ha, Hβ, and HeI. The fact that the changes in V/R-ratio are practically identical in all three lines (Ha, Hβ and HeI, see Fig 4) means that the asymmetry develops in the entire disc simultaneously. Probably it is transformation of the circular disc into elliptical one.

(3) During the period MJD 58450 - 58600 the asymmetry of the inner disc (visible in HeI) deviates from the behaviour of Ha and Hβ emission lines. The V/R ratio changes considerably faster in HeI in comparison with Ha and Hβ (Fig 3), which is an indication that the structural changes are faster in the innermost region of the disc (i.e. those located at distances ≤ 50 R⊙).

3.4. Third component in He I

After November 2018 a third component appears in the red side of HeI line. This component displays velocity 250-350 km s⁻¹. The three component structure of HeI 6678 line is very well visible on both Rozhen and TIGRE spectra obtained in March 2019. The Keplerian velocity around the primary is \( V_{\text{Kepl}} = \sqrt{GM/M_\odot} \), where \( G \) is the gravitational constant and \( r \) is the distance. We estimate that the observed velocity of the third component corresponds to a distance from the center of the primary 40 - 20 R⊙. Bearing in mind that \( R_1 \approx 10.5 \) R⊙, it means that this component originates somewhere about 1-3 stellar radii above the stellar surface. The velocity of this component is similar to the velocities observed during the double disc formation in 1994 (Tarasov & Roché 1995), when the blue and red peaks of the inner disc were at -308 km s⁻¹ and +258 km s⁻¹, respectively.

4. Discussion

Projected rotational velocity of the primary is estimated \( v \sin i = 200 \) km s⁻¹ (Slettebak 1982), \( v \sin i = 215 \pm 10 \) km s⁻¹ using HeI λ4026 Å absorption line (Lyubimkov et al. 1997), and \( v \sin i = 191 \pm 12 \) km s⁻¹ from the width of the Ha emission (Zamanov et al. 2019). This gives on the surface of the star Keplerian velocity \( V_{\text{Kepl}} = 247 \) km s⁻¹. Adopting inclination \( i = 30^\circ \) (Delgado-Martí et al. 2001), and that the star rotates with 0.8 of the critical velocity (e.g. Porter & Rivinius 2003), we estimate \( v \sin i = 198 \) km s⁻¹, which is in agreement with the above values. This agreement also is a clue that there is no considerable deviation between the orbital plane of the binary and the equatorial plane of the Be star.

The recent radiative transfer calculations on the structure of Be discs in coplanar circular binary systems suggest V/R cycle every half orbital period (Panoglu et al., 2018). We do not see signs of such modulation in X Per in our data, which covers 473 days, i.e. almost two orbital periods.

Hirata & Kogure (1977) were first to argue about existence of two component structure of the circumstellar envelope Be stars on the example of well known star Pleione. They proposed a model for the envelope of this star consisting of two layers and also considered a separate fast rotating layer closer to the stellar equator. The formation of a new envelope, coexisting with the previous one is also detected by Nemravová et al. (2010).

In the spectrum of X Per four peaks were observed in HeI6678 emission line in 1994-1995. This is interpreted as due to a double disc structure (Kunjaya & Hirata 1993, Tarasov & Roché 1995). Probably, we have similar situation in March 2019, however the blue peak of the inner disc coincides with the blue peak of the outer disc (on Fig 5) is visible that the blue peak is wider and stronger). If this is the case, the inner disc is likely to be elliptical. For the instantaneous orbital speed of a body at any given point in its trajectory (the vis-viva equation):

\[ v = \sqrt{\frac{GM_1}{r} \left(\frac{2}{r} - \frac{1}{r^2}\right)} \]

\( r \) is the distance at which the speed is to be calculated, and \( a \) is the length of the semi-major axis of the elliptical orbit. Assuming radial velocities of the inner disc peaks ~120 km s⁻¹ and +260 km s⁻¹, we calculate that the inner disc probably has eccentricity \( e \approx 0.40 \), and size (semi-major axis) ~ 20 R⊙. For the outer disc visible in HeI, we measure radial velocities of the peaks ~120 km s⁻¹ and +60 km s⁻¹, and estimate radius ~ 60 R⊙.

There are different theories about the origin of the long-term V/R variability in Be stars [e.g. Hanuschik et al. (1993), Section 4.2]. The most accepted is the global oscillation scenario, which proposes that Keplerian disc around a Be stars is subject to global distortion - a one armed density wave, which is an updated version of the old elliptical disc model (Struve 1931).

The deviation of V/R ratio of HeI6678 from that of Ha and Hβ (Fig 3) as well as the third component in HeI lines (Fig 5), might be signs of a new density wave starting from the innermost parts of the disc.

5. Conclusions

We have observed asymmetries in the outer and inner parts of the circumstellar disc in the Be/X-ray binary X Per. We encourage high-resolution spectroscopic observations (e.g. Echelle spectrographs on 2.0m class telescopes) to monitor the evolution of the circumstellar disc. This can help to understand the formation of large scale perturbations in the circumstellar environment and their connection with accretion onto neutron star.

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Article number, page 4 of 5
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