Spectral observations of X Persei: Connection between Hα and X-ray emission

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Received 21 November 2018 / Accepted 10 January 2019

ABSTRACT

We present spectroscopic observations of the Be/X-ray binary X Per obtained during the period 1999–2018. Using new and published data, we found that during “disc-rise” the expansion velocity of the circumstellar disc is 0.4–0.7 km s⁻¹. Our results suggest that the disc radius in recent decades show evidence of resonant truncation of the disc by resonances 10:1, 3:1, and 2:1, while the maximum disc size is larger than the Roche lobe of the primary and smaller than the closest approach of the neutron star. We find correlation between equivalent width of Hα emission line (Wα) and the X-ray flux, which is visible when 15 Å < Wα ≤ 40 Å. The correlation is probably due to wind Roche lobe overflow.

Key words. stars: emission-line, Be – stars: winds, outflows – X-rays: binaries – accretion, accretion disks – stars: individual: X Per

1. Introduction

X Persei (HD 24534) is a relatively bright variable star, detected in X-rays with Uhuru satellite and identified as the optical counterpart of the pulsating X-ray source 4U 0352+309 (Braes & Miley 1972; van den Bergh 1972). This object belongs to the class of Be/X-ray binaries which contains about 100 confirmed and suspected members in our Galaxy, see e.g. Apparao (1994) and Reig (2011). The main component of X Per is a hot massive rapidly rotating Be star. The secondary is a slowly spinning neutron star, i.e. core-collapse or electron-capture supernova. Knigge et al. (2011) suggested that it may be the dynamical Comptonization in the accretion flow of photons emerging from the polar cap (Doroshenko et al. 2012).

In the last century, the visual magnitude of X Per varies in the range V = 6.8–6.2 mag. The brightness variations are accompanied by variations in the intensity of the emission lines. The optical spectrum of X Per shows strong emission in the Balmer lines, when it is brighter than 6.5 mag (Dorren et al. 1979; Telting et al. 1990). Absence of emission lines in 1977 was noted by de Loore et al. (1979). Roche et al. (1993) identified that the low state was during 1974–1977. Dramatic changes were observed in 1990, when X Per lost the Hα emission line, infrared excess, and circumstellar disc (Norton et al. 1991). The emission lines disappeared and the optical spectrum was dominated by absorption lines, which is typical for normal early-type star.

We present optical spectroscopic observations obtained in recent decades and discuss the radius of the circumstellar disc, outflowing velocity in the disc, disc truncation, and connection with X-ray emission.

2. Observations

The optical spectra of X Per were secured with the 2.0 m telescope of the Rozhen National Astronomical Observatory, Bulgaria and with the robotic 1.2 m TIGRE telescope located is the astronomical observatory La Luz in Mexico. The Rozhen spectra were obtained with the Coude spectrograph and with the Echelle spectrograph ESpRo (Bonev et al. 2017). The Coude spectra have dispersion 0.1 Å px⁻¹ or 0.2 Å px⁻¹, while the Echelle spectra have 0.06 Å px⁻¹ at 6560 Å and 0.04 Å px⁻¹ at 4800 Å. The
TIGRE spectra were obtained with the HEROS spectrograph, which provides a spectral resolution of 20,000 over the visual spectral range from 3800 Å to 8800 Å (Schmitt et al. 2014). A few more spectra were downloaded from the ELODIE archive (Moultaka et al. 2004). These were obtained with the 1.93 m telescope of Observatoire de Haute-Provence.

The measured parameters are given in Table A.1. The variability of Hα emission line of X Per is presented in Fig. 1 (emission line profile), Fig. 2 (distance between the peaks), Fig. 3 (comparison between two high resolution profiles), Fig. 4 (histogram of the Hα disc size), and Fig. 5 (long term behaviour). During the period 1992–2018, the equivalent of Hα emission line (Wα) varies from 2 Å up to 40 Å. From Fig. 1, it is visible that the Hα emission line, which exhibits various profile shapes, in some cases is symmetric with two peaks that are well separated, single-peak, double-peak and asymmetric profiles indicating density inhomogeneities.

3. Primary component

3.1. Radius and mass of the primary

From IR observations, Taranova & Shenavrin (2017) obtained temperature \( T = 26000 \pm 1000 \text{K} \) and radius \( R_1 = 17.1 \pm 0.6 R_\odot \) for the donor star, adopting distance to the system \( d = 1300 \text{pc} \). Gaia Data Release 2 (Gaia Collaboration 2016, 2018) gives parallax 1.234 mas, which corresponds to a distance 810 pc. With the Gaia distance the results of Taranova & Shenavrin (2017) should give \( R_1 = 10.7 R_\odot \).

The \( B - V \) and \( U - B \) colours of X Per in low state should represent the colours of the primary component. During the period JD 2448545 (1991 October 15) - JD 2449046 (1993 February 27), the brightness of X Per was low \( V \approx 6.77 \), and the circumstellar disc was very small. At that time the average colours \( (B - V) = 0.09 \pm 0.03 \) and \( (U - B) = -0.68 \pm 0.03 \) (Zamanov & Zamanova 1995). Adopting interstellar extinction towards X Per \( E_{B-V} = 0.356 \) (Viotti et al. 1982; Nikolov et al. 2017), we calculate dereddened colours \( (B - V)_0 = -0.26 \pm 0.03 \) and \( (U - B)_0 = -0.95 \pm 0.03 \). Following Schmidt-Kaler (1982), these colours correspond to B1 III–V spectral type, which is about one spectral type later than B0 derived by Roche et al. (1997) and Lyubimkov et al. (1997), and O9.5III by Fabregat et al. (1992).

Using the well-known formula for the absolute V magnitude, we obtain \( M_V = -3.86 \). The bolometric magnitude is \( M_{\text{bol}} = M_V + BC \), where the bolometric correction is \( BC = -2.70 \) (Schmidt-Kaler 1982; Nieva 2013). Using the solar values \( T_\odot = 5780 \text{K} \) and \( M_{\odot}^{\text{bol}} = 4\text{M}_\odot \), we calculate \( R_1 = 9.2 R_\odot \), which is similar to the above value from Taranova & Shenavrin (2017).

Hohle et al. (2010) give average masses for B0V and B1V stars \( 15.0 M_\odot \) and \( 12.0 M_\odot \), respectively. Hereafter for the primary of X Per, we adopt radius \( 9.2 R_\odot < R_1 < 10.7 R_\odot \) \( (R_1 = 10.5 \pm 1.2 R_\odot) \) and mass \( 12.0 M_\odot \leq M_1 \leq 15.0 M_\odot \) \( (M_1 = 13.5 \pm 1.5 M_\odot) \).

3.2. Rotation of the primary

Dachs et al. (1986) and Hanuschik (1989) established a relation between \( v \sin i \), full width at half maximum (FWHM), and \( \lambda \) of the Hα emission line. To calculate \( v \sin i \), we use this relation in the form

\[
\nu \sin i = 0.813 (\text{FWHM} 10^{0.08 \log W_\alpha - 0.14} - 70 \text{ km s}^{-1})
\]

(1)

where FWHM and \( v \sin i \) are measured in km s\(^{-1}\), \( W_\alpha \) is in [Å]. We measure FWHM and \( W_\alpha \) on our spectra and obtain projected rotational velocity in the range \( 179 \leq v \sin i \leq 217 \text{ km s}^{-1} \) with average \( v \sin i = 191 \pm 12 \text{ km s}^{-1} \). This value is close to that of Lyubimkov et al. (1997), who estimated projected rotational velocity \( v \sin i = 215 \pm 10 \text{ km s}^{-1} \) using HeI λ4026 Å absorption line.
expresses the fact that $R_0$ where $\epsilon$ is also connected with $W_t$.

When the two peaks are visible in the emission $R_\text{disc}$, $\Delta V_\alpha$ lines have two peaks (see Table A.1). We calculate median value $X$ Per we have 15 spectra on which both $H\alpha$ is larger, it follows the average behaviour of other Be stars. For $(1988)$, this probably indicates that the disc of $X$ Per was denser the disc was small. Because these points are above the populations are two points obtained on 19920903 and 19920905, when $R_\text{disc}$ is used in Coe et al. (2006) and Monageng et al. (2017).

4. Be disc

In Fig. 2, we plot $\log \Delta V_\alpha/2v \sin i$ versus $\log W_\alpha$. The black open circles are data for Be stars taken from Andri\l at (1983), Hanuschik (1986), Hanuschik et al. (1988), Dachs et al. (1992), Slettebak et al. (1992), and Catanzaro (2013). The blue plus signs are our measurements of $X$ Per. Most of the data points of $X$ Per are in the middle of the Be star populations. The exceptions are two points obtained on 19920903 and 19920905, when the disc was small. Because these points are above the population of other Be stars, following Sect. 5.2 of Hanuschik et al. (1988), this probably indicates that the disc of $X$ Per was denser during the early stages of its development. Later, when the disc is larger, it follows the average behaviour of other Be stars. For $X$ Per we have 15 spectra on which both $H\alpha$ and $H\beta$ emission lines have two peaks (see Table A.1). We calculate median value $\Delta V_\beta/\Delta V_\alpha = 1.24$ and average value $\Delta V_\beta/\Delta V_\alpha = 1.30 \pm 0.26$.

The Balmer emission lines form primarily in the disc surrounding the Be star, and the total flux of the feature (measured as the line equivalent width) is closely related to the size of the disc. 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 ($R_\text{disc}$) of the emitting disc,

$$R_\text{disc} = R_1 \left( \frac{2v \sin i}{\Delta V} \right)^2,$$

where $R_1$ is the radius of the primary, $v \sin i$ is its projected rotational velocity. When the two peaks are visible in the emission lines, we can estimate the disc radius using Eq. (2). The disc size is also connected with $W_\alpha$,

$$R_\text{disc} = \epsilon \ R_1 \ 0.467 \ W_\alpha^{1.184},$$

where $\epsilon$ is a dimensionless parameter, for which we adopt $\epsilon = 0.9 \pm 0.1$ (see Zamanov et al. 2016, Sect. 4.3). This equation expresses the fact that $R_\text{disc}$ grows as $W_\alpha$ becomes larger (e.g. Grundstrom & Gies 2006). A slightly different expression for the relation between $R_\text{disc}$ and $W_\alpha$ is used in Coe et al. (2006) and Monageng et al. (2017).

4.1. Radial outflow velocity

During the period JD 2448869 to JD 2450029 a steady increase of the $H\alpha$ emission is visible (Fig. 5). The equivalent width increased from $W_\alpha = -2.0 \text{\AA}$ to $-14.9 \text{\AA}$, and the distance between the peaks decreased from $\Delta V = 382 \text{\text{km s}^{-1}}$ to $\Delta V = 177 \text{\text{km s}^{-1}}$. Following Eq. (2) this corresponds to change of the disc radius from 13 $R_\odot$ to 62 $R_\odot$ and expansion velocity of disc $V_{\text{out}} = 0.35 \text{\text{km s}^{-1}}$. Using $W_\alpha$ and Eq. (3) this corresponds to change of the disc radius from 10 $R_\odot$ to 108 $R_\odot$ and expansion velocity of disc $V_{\text{out}} = 0.70 \text{\text{km s}^{-1}}$.

During the period JD 2452800 to JD 2455500 a steady increase of the $H\alpha$ emission is also visible (Fig. 5). The equivalent width increased from $W_\alpha = -12 \text{\AA}$ to $-37 \text{\AA}$. Using Eq. (3), this corresponds to $V_{\text{out}} = 0.67 \text{\text{km s}^{-1}}$.

We compared the high resolution emission line profiles obtained with the ESPERO spectrograph. An interesting result emerged when we compared the $H\alpha$ profiles obtained in December 2015 with that in March 2017 (see Fig. 3). It seems that during this period the material that was emitting in the wings of the $H\alpha$ emission moved to the outer parts of the disc and on the later spectrum this material emits in the central part of the line. Ring-like structures in Be discs are discussed for example by Struve (1931) and Rivinius et al. (2001). In $X$ Per, Tarasov & Roche (1995) detected the appearance and development of an inner ring-like structure in the period 1993–1995, when the disc was starting to rebuild after a disc-less phase.

Supposing that the variability seen on Fig. 3 represents a ring-like structure (a ring-like depth enhancement) in the disc, we calculate that the ring initially emits at $\Delta V = 220 \text{\text{km s}^{-1}}$, and later at $\Delta V = 78 \text{\text{km s}^{-1}}$. Applying Eq. (2) we obtain that the material moved from 40 $R_\odot$ to 325 $R_\odot$ for 447 days, having average outflow velocity 5.0 $\text{\text{km s}^{-1}}$. This velocity is about eight times faster than the velocity we estimated from disc build-up, and might be an indication that once the disc is developed the material can move faster inside the disc.

Fig. 2. Distance between the peaks normalized with stellar rotation vs. $W_\alpha$. 

Fig. 3. $H\alpha$ emission line profile of $X$ Per in December 2015 (black solid line) and March 2017 (red dotted line). The two are spectra obtained after one year apart. The difference between the spectra is also plotted and seems to indicates slow outward motion with velocity $=5.1 \text{\text{km s}^{-1}}$ (see Sect. 4.1).
The important resonances are not only those with disc gas rotational periods, and where $G$ is the gravitational constant, $n$ is the integer number of disc gas rotational periods, and $m$ is the integer number of orbital periods. The important resonances are not only those with $n:1$, but can as well be $n:m$ in general.

$$R_{\text{rim}}^{3/2} = \frac{m \ (G \ M_1)^{1/2}}{2 \pi} \ \frac{P_{\text{orb}}}{n},$$

where $G$ is the gravitational constant, $n$ is the integer number of disc gas rotational periods, and $m$ is the integer number of orbital periods. The important resonances are not only those with $n:1$, but can as well be $n:m$ in general.

The histograms of Hα disc size, $R_{\text{disc}}$, as calculated by Eq. (3), are plotted in Fig. 4. We use data for X-ray binaries (LSI+61 303, MWC 148, and MWC 656) distribution of $R_{\text{disc}}$ values has one very well-pronounced peak (Zamanov et al. 2016). In X Per we see a few peaks rather than a single peak. The most pronounced peaks correspond to 10:1, 3:1, and 2:1 resonances. In X Per it seems that in the beginning of the disc-rise the resonance 10:1 operates, after this more disc material appears, the disc grows, and the resonance 3:1 starts to operate, and later 2:1. A more or less similar situation is in the Be/X-ray binary V725 Tau / 1A 0535+262, where multiple resonances are discussed, i.e. 1:4, 1:5, and 1:7 (Coe et al. 2006). The orbital period of V725 Tau is 111.1 days (Finger et al. 1996). This similarity indicates that in such wide systems different resonances can operate probably depending on the mass loss of the primary and the development of its circumstellar disc.

Following Yatabe et al. (2018), we adopt $P_{\text{orb}} = 251.0 \pm 0.2$ d and mass of the neutron star $M_{\text{ns}} = 2.03 M_\odot$ For the primary we assume $M_1 = 13.5 M_\odot$ (see Sect. 3). With these values we calculate mass ratio $q = M_1/M_{\text{ns}} = 6.65$ and semi-major axis of the orbit $a = 418 R_\odot$. Using the formula by Eggleton (1983), we estimate the Roche lobe size of the primary $r_L = 228 R_\odot$. The orbital eccentricity of the system is low $e = 0.11$ (Delgado-Martí et al. 2001). The distance between components at periastron is $a (1 - e) = 372 R_\odot$ and at apastron is $a (1 + e) = 464 R_\odot$.

The maximum disc size observed in our data is $R_{\text{disc}} = 337 R_\odot$ which is smaller than the closest approach of the neutron star. However, it is larger than the size of the Roche lobe of the Be star, i.e. $r_L < R_{\text{disc}}(< \max) < a (1 - e)$.

The Be/X-ray binaries present different states of X-ray activity (Stella et al. 1986; Negueruela 1998). X Per does not show periodic Type I outbursts, which are common feature in the classical Be/X-ray binaries and occur when a neutron star moving along an eccentric orbit crosses the Be circumstellar disc during the periastron passage. The result that $R_{\text{disc}}(< \max) < a (1 - e)$ demonstrates that the neutron star does not pass through the disc of the donor star even at the maximum disc size observed during the last 30 years. Periodic Type I outbursts in X Per can be expected if $\sigma$ achieves the level of about 45 Å or above it.

### 4.3. Be disc → X-ray flux

The mass transfer rate onto the neutron star and subsequent accretion-driven X-ray flux should depend on the changes in the radius of the disc of the Be star that we can track through the variations in Hα emission line. The V-band magnitude,
Fig. 5. X Per – connection between Hα and X-ray variability. From top to bottom panels: V-band magnitude, equivalent width of Hα emission, circumstellar disc radius, and X-ray flux.

Wα, the calculated disc radius, and X-ray data are plotted in Fig. 5. The V-band data are from American Association of Variable Star Observers (AAVSO). The X-ray data are from RXTE/ASM (Jahoda et al. 1996; Levine et al. 1996) and MAXI (Matsuoka et al. 2009). The RXTE/ASM X-ray light curve is rebinned with a time of 30 days and scaled relatively to the MAXI counts (binning with 25 or 35 days provide very similar light curve). In the panel Wα, the red crosses are data from the literature (Reig et al. 2016; Grundstrom et al. 2007; Li et al. 2014). The blue plus signs represent Rozhen, TIGRE, and ELODIE data from our Tables A.1 and 2 of Zamanov et al. (2001).

Li et al. (2014) discussed the connection between Hα and X-ray flux during the period JD 2451000–2455000. They pointed out the time delay between the Wα maximum at about JD 2452000 and X-ray maximum, which is ~800 days later. They used this delay to estimate the viscosity in the outflowing disc (α parameter). We point that there is a similar time delay between a minimum in Wα at JD 2452600 and a minimum in RXTE/ASM X-ray flux at JD 2453500.

After JD 2454000 Wα increases and the X-ray flux also increases, which indicates that the neutron star accretes more material and probably truncates the outer parts of the disc. Two stronger peaks are visible in Wα at JD 2455000 and JD 2457500. Both of these peaks are also well detectable in the MAXI X-ray data. We performed correlation analysis and found moderate to strong correlation between Wα and X-ray flux with the Pearson correlation coefficient 0.61–0.66, Spearman’s (rho) correlation coefficient 0.61–0.68, and significance, p-value in the range 5 × 10^{-6}–1 × 10^{-8}. There is no time delay between Wα and X-ray flux after JD 2454000. If a time delay exists it is less than 40 days.

A comparison between the behaviour of V brightness and Wα shows that before JD 2453000 these parameters vary almost simultaneously – the maxima of Wα correspond to the maxima of the V-band brightness and have time delays ≤300 days. After it, the behaviour is different – the maxima of Wα and Rdisc correspond to minima of the V-band brightness.

5. Discussion

For Be stars, Hanuschik et al. (1988) found that the peak separations of Hα and Hβ emission lines follow the relation ΔVβ = 1.8AαVα. For X Per the ratio ΔVβ/ΔVα is considerably below the average value for Be stars (see Sect. 4). At this stage considerable deviation from the behaviour of the Be stars is also detected in LSI+61°303 (Zamanov et al. 2016). In both star the Hα-emitting disc is only 1.7 times larger than the Hβ-emitting disc, while in normal Be stars it is 3.2 times larger. This can be a result of truncation of the outer parts or different density structures in the inner parts of the Be disc.

The pulse period of neutron star in X Per shows episodic spin-ups and spin-downs. Between 1972 and 1978 the neutron star has been spinning up with a rate P/P ≃ −1.5 × 10^{-4} yr^{-1} (Henrichs 1983). Since 1978 till 2002 the neutron star has been spinning down with a rate P/P ≃ 1.3 × 10^{-4} yr^{-1}.

After 2002 (JD 2452000) a new episode of spin-up has begun (Blay & Reglero 2012; Acuner et al. 2014). This new spin-up began together with the increase of the X-ray brightness, and its start corresponds to the moment when Wα achieved 20 Å and Rdisc ≃ 150 R⊙

Yatabe et al. (2018) analysed X-ray data and estimated for the neutron star in X Per mass Mns = 2.03 ± 0.17 M⊙, and magnetic field B = (4–25) × 10^{11} G, adopting Gaia distance d = 810 pc. They also found that the X-ray luminosity varies in the range 2.5 × 10^{33}–1.2 × 10^{34} erg s^{-1}.

Postnov et al. (2017) proposed that in the enigmatic Be star γ Cassiopeia the elusive companion is a neutron star acting as a propeller. In this scenario, the subsequent evolutionary stage of γ Cas and its analogues should be X Per-type binaries comprising low-luminosity slowly rotating X-ray pulsars.

The corotation radius of the neutron star is

\[ R_{co} = \left( \frac{G M_{ns} R_{ns}^{2}}{4 \pi^{2}} \right)^{1/3}. \]  

(5)

The radius of its magnetosphere (the Alfvén radius) is

\[ R_{m} = \left( \frac{B R_{ns}^{4/7}}{M_{acc}^{7/7}(2GM_{ns})^{1/7}} \right)^{1/3}. \]  

(6)

In the standard theory of gravimagnetic rotators (Lipunov 1987; Campana et al. 2018) for a neutron star to be accretor (X-ray pulsar) the condition is that the magnetosphere radius should be smaller than the corotation radius, Rm ≤ Rco. Assuming Rns = 10 km and that X-ray flux is equal to the accretion luminosity,

\[ L_{acc} = G M_{ns} M_{acc} R_{ns}^{-1}. \]  

(7)
we estimate that the mass accretion rate is in the range $1.47 \times 10^{-12} - 7.07 \times 10^{-12} M_\odot\text{yr}^{-1}$ (from $9.28 \times 10^{13}$ to $4.45 \times 10^{14} \text{g s}^{-1}$). We calculate that at low accretion rate $R_{\alpha} \approx R_{\text{Ro}} \approx 0.24 R_\odot$, in other words at low X-ray flux the neutron star is close to the accretor-propeller transition boundary. The condition that the neutron star in X Per is an accretor (not propeller), $R_{\alpha} \leq R_\odot$, also puts a limit on the magnetic field strength, $B \leq 1.15 \times 10^{14} \text{G}$. This value is estimated taking into account the deviation of the magnetosphere radius from the Alfven radius (e.g. Bozzo et al. 2018). If the magnetic field is above this value, the neutron star would act as a propeller, the X-ray luminosity would decrease and the X-ray pulsations would disappear (which is not observed).

Roche et al. (1993) found a clear correlation between the optical, infrared, and X-ray behaviours during the 1974–1977 low state, followed by an extended period in which the X-ray behaviour appears to be unrelated to the optical. Li et al. (2014), analysing data obtained after the disc-less episode in 1990, found a time delay of about 800 days between $W_\alpha$ and X-ray flux. As the $W_\alpha$ increases, the X-ray flux also increases. This is indicating a direct linkage between the circumstellar disc around mass donor and accretion rate onto the neutron star. This linkage is visible when $W_\alpha > 20 \text{ Å}$ and $R_{\text{disc}} > 200 R_\odot$. When the circumstellar disc around the primary increases above 200 $R_\odot$, the quantity of the material that is captured in the accretion cylinder of the neutron star also increases. The Roche lobe size of the primary is $r_\alpha = 227 R_\odot$ (see Sect. 4.2). When $W_\alpha \approx 25 \text{ Å}$, $R_{\text{disc}} \approx r_\alpha$, the circumstellar disc fills the Roche lobe around the primary and the neutron star begins to accrete material from the Roche lobe overflow. In the past few years the existence of a relatively efficient mode of wind mass accretion in a binary system has been proposed, called the wind Roche lobe overflow (WRLOF; Mohamed & Podsidiowski 2007), which lies in between the canonical Bondi–Hoyle–Littleton accretion and Roche lobe overflow. In case of X Per, most probably before JD 2454000 the circumstellar disc is small, it is well inside the Roche lobe ($R_{\text{disc}} < r_\alpha$) and wind accretion (Bondi–Hoyle–Littleton accretion) is acting. After JD 2454000 when the circumstellar disc size achieves the Roche lobe, $R_{\text{disc}} \geq r_\alpha$, the accretion mode changes to WRLOF, and the neutron star is accreting material directly from the circumstellar disc (Roche lobe overflow from the circumstellar disc) without time delay.

Other possibilities include the development of spiral arms (Grundstrom et al. 2007) or other large-scale perturbations (Negueruela et al. 1998) in the circumstellar envelope excited by tidal interaction which may lift disc gas out to radii where the accretion by the neutron star becomes more effective.

6. Conclusions

We present optical spectroscopic observations of the Be/X-ray binary X Per, optical counterpart of the X-ray pulsar 4U 0352+309. In this work, we combine published data with our measurements. First, we estimate, that the expansion velocity of the circumstellar disc is in the range $0.4–0.7 \text{ km s}^{-1}$. Second, we find that the distribution of the disc radius from the average equivalent width suggests resonant truncation of the disc, while the maximum disc radius is smaller than the separation of the stars at periastron but larger than the Roche lobe of the primary. Third, we derive a correlation between the equivalent width of Hα emission line and X-ray flux, which is visible since JD 2454000, when 15 Å $< W_\alpha < 40 \text{ Å}$. We briefly discuss possible mechanisms of mass transfer.

Acknowledgements. This work is supported by the grant KI-06-H28/2 08.12.2018 (Bulgarian National Science Fund). It is based on observations from Rozhen National Astronomical Observatory, Bulgaria and the TIGRE telescope, located at La Luz, Mexico. TIGRE is a joint collaboration of the Hamburger Sternwarte, the University of Guanajuato and the University of Liège. This research has made use of data provided by RIKEN, JAXA, and the MAXI team; (2) results provided by the ASM/RXTE teams at MIT and at the RXTE SOF and GOF at NASA’s GSFC; and (3) observations from the AAVSO International Database contributed by observers worldwide. UW acknowledges funding by DLR, project 50OR17/01. DM acknowledges partial support by grants DN 08/2017 and RD-08-112/2018. We are very grateful to the referee whose comments helped to improve considerably the original manuscript.

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A173, page 6 of 9
Appendix A: Table

Table A.1. Spectral observations of X Per.

| File          | Telescope instrument | JD-start (min) | Exp-time (Å) | $W_\alpha$ (km s$^{-1}$) | $\Delta V_\alpha$ (km s$^{-1}$) | $\Delta V_\beta$ (km s$^{-1}$) |
|---------------|----------------------|----------------|--------------|---------------------------|----------------------------------|----------------------------------|
| 19920903*     | 2.0m Coude 2400000+  | 48869.5278     | 59           | -1.9                      | 382                              |                                  |
| 19920905*     | 2.0m Coude          | 48871.5042     | 54           | -2.2                      | 386                              |                                  |
| 19951107.0024 | Elodie              | 50029.4808     | 30           | -14.9                     | 177.8                            | 202.0                            |
| 19951107.0028 | Elodie              | 50029.5449     | 45           | -14.7                     | 176.9                            | 200.0                            |
| 19961217.0024 | Elodie              | 50435.3818     | 8            | -12.1                     |                                  |                                  |
| 19970817*     | 2.0m Coude 50029.4847 | 59           | -1.9                      | 382                              |                                  |
| 19980209a*    | 2.0m Coude 50029.5449 | 45           | -14.7                     | 176.9                            | 200.0                            |
| 19980209b*    | 2.0m Coude 50029.5449 | 45           | -14.7                     | 176.9                            | 200.0                            |
| 19981102a*    | 2.0m Coude 50029.5449 | 45           | -14.7                     | 176.9                            | 200.0                            |
| 19981102b*    | 2.0m Coude 50029.5449 | 45           | -14.7                     | 176.9                            | 200.0                            |
| 20000129.0005 | Elodie              | 51573.2545     | 30           | -9.3                      | 153.7                            | 190.3                            |
| 20000129.0006 | Elodie              | 51573.2767     | 30           | -10.0                     | 153.6                            | 193.5                            |
| 20010903.178  | 2.0m Coude 52156.5933 | 10           | -14.8                     | 122                              |                                  |
| 20010903.179  | 2.0m Coude 52156.6006 | 8            | -15.0                     | 120                              |                                  |
| 20011220.0011 | Elodie              | 52264.3216     | 30           | -11.4                     |                                  |                                  |
| 20011221.0008 | Elodie              | 52265.3375     | 60           | -11.7                     |                                  |                                  |
| 201211.010    | 2.0m Coude 53328.4980 | 33           | -16.2                     | 102.1                            | 168.3                            |
| 20120903.1    | 2.0m Coude 56173.5163 | 10           | -24.08                    |                                  |                                  |
| 20120903.2    | 2.0m Coude 56173.5235 | 10           | -24.4                     |                                  |                                  |
| 20130102.1    | 2.0m Coude 56295.3645 | 10           | -25.61                    | 81                               |                                  |
| 20130102.2    | 2.0m Coude 56295.3717 | 10           | -25.95                    | 88                               |                                  |
| 20130103.1    | 2.0m Coude 56296.3813 | 10           | -26.39                    | 85.9                             |                                  |
| 20130103.2    | 2.0m Coude 56296.3885 | 10           | -26.54                    | 85.8                             |                                  |
| 20141013.1    | 2.0m Coude 56944.4487 | 10           | -24.4                     | 105.5                            |                                  |
| 20141013.2    | 2.0m Coude 56944.4560 | 10           | -24.7                     | 101.8                            |                                  |
| 20141212.1    | 2.0m Coude 57004.4019 | 10           | -26.8                     | 87.2                             |                                  |
| 20141212.2    | 2.0m Coude 57004.4091 | 10           | -26.6                     | 108                              |                                  |
| 20151223.1    | 2.0m Echelle 57380.4701 | 30           | satur.                    |                                  | 144.0                            |
| 20151223.2    | 2.0m Echelle 57380.4916 | 10           | -36.4                     | 146.7                            |
| 20151224      | 2.0m Echelle 57381.3691 | 10           | -36.3                     | 145.3                            |
| 20151226      | 2.0m Echelle 57383.3341 | 10           | -36.1                     | 145.1                            |
| 20151227      | 2.0m Echelle 57384.3728 | 5            | -36.5                     | 145.2                            |
| 20160130      | 2.0m Echelle 57418.2988 | 5            | -33.9                     | 95.3                             | 124.9                            |
| 20160923      | 2.0m Echelle 57654.5749 | 10           | -30.8                     | 143.3                            |
| 20161211      | 2.0m Echelle 57734.3811 | 20           | -32.7                     | 63.0                             | 133.5                            |
| 20170317      | 2.0m Echelle 57830.2978 | 20           | -30.9                     | 126.1                            |
| 20171207.1    | 2.0m Echelle 58095.2062 | 2            | -23.5                     | 119.4                            |
| 20171207.2    | 2.0m Echelle 58095.2107 | 15           | -23.5                     | 120.3                            | 149.3                            |
| 20171207.3    | 2.0m Echelle 58095.2226 | 15           | -23.4                     | 119.6                            | 150.1                            |
| 20171208.1    | 2.0m Echelle 58096.203  | 2            | -22.7                     | 117.8                            |
| 20171208.2    | 2.0m Echelle 58096.207  | 10           | -23.5                     | 121.8                            | 148.0                            |
| 20171220.2134 | TIGRE 58108.6489     | 4            | -25.0                     | 125.3                            |
| 20171221.1853 | TIGRE 58109.5373     | 4            | -24.1                     | 122.4                            |

Notes. The spectra marked with (*) are partly published in Zamanov et al. (2001).
Table A.1. continued.

| File       | Telescope instrument | JD-start 2400000+ | Exp-time (min) | $W_α$ (Å) | $ΔV_α$ (km s$^{-1}$) | $ΔV_β$ (km s$^{-1}$) |
|------------|----------------------|------------------|----------------|-----------|---------------------|---------------------|
| 20171222.1854 | TIGRE               | 58110.5380       | 2              | –23.4     | 120.3               |                     |
| 20171223.1922 | TIGRE               | 58111.5571       | 4              | –23.8     | 120.8               |                     |
| 20171224.1926 | TIGRE               | 58112.5601       | 4              | –23.0     | 120.7               |                     |
| 20171230     | 2.0m Echelle         | 58118.2314       | 20             | –21.9     | 125.7               | 148.7               |
| 20180101     | 2.0m Echelle         | 58120.230        | 20             | –19.8     | 121.5               | 143.7               |
| 20180103.1928 | TIGRE               | 58122.5614       | 15             | –20.5     | 122.2               |                     |
| 20180103.2156 | TIGRE               | 58122.6638       | 15             | –21.2     | 123.9               |                     |
| 20180104.0017 | TIGRE               | 58122.7622       | 15             | –20.2     | 124.1               |                     |
| 20180104.1921 | TIGRE               | 58123.5563       | 15             | –21.3     | 123.8               |                     |
| 20180105.1959 | TIGRE               | 58124.5832       | 15             | –21.1     | 121.9               |                     |
| 20180105.2219 | TIGRE               | 58124.6805       | 15             | –21.3     | 121.8               |                     |
| 20180106.0039 | TIGRE               | 58124.7775       | 5              | –20.7     | 121.3               |                     |
| 20180106.1923 | TIGRE               | 58125.5582       | 15             | –20.7     | 121.1               |                     |
| 20180106.2149 | TIGRE               | 58125.6594       | 15             | –21.0     | 121.0               |                     |
| 20180107.0014 | TIGRE               | 58125.7601       | 15             | –20.8     | 122.1               |                     |
| 20180126.01  | 2.0m Echelle         | 58145.2150       | 2              | –18.34    | 106.3               |                     |
| 20180126.02  | 2.0m Echelle         | 58145.2170       | 3              | –18.44    | 106.1               |                     |
| 20180126.03  | 2.0m Echelle         | 58145.2201       | 15             | –18.05    | 106.8               |                     |
| 20180126.04  | 2.0m Echelle         | 58145.2312       | 20             | –18.64    | 108.5               | 141.3               |
| 20180201.01  | 2.0m Echelle         | 58151.2218       | 20             | –18.3     | 122.4               | 141.6               |
| 20180201.02  | 2.0m Echelle         | 58151.2312       | 5              | –16.7     | 122.5               |                     |
| 20180402.01  | 2.0m Echelle         | 58211.2832       | 10             | –14.7     | 105.8               | 115.0               |
| 20180402.02  | 2.0m Echelle         | 58211.2879       | 2              | –14.5     | 103.6               |                     |
| 20180802     | TIGRE               | 58332.9723       | 10             | –17.83    |                     |                     |
| 20180818     | TIGRE               | 58348.9210       | 10             | –18.89    |                     |                     |
| 20180905     | TIGRE               | 58366.8712       | 10             | –19.62    |                     |                     |
| 20180925     | TIGRE               | 58386.8679       | 10             | –20.61    |                     |                     |
| 20181010     | TIGRE               | 58401.8028       | 10             | –21.51    |                     |                     |