Orbital motions and light curves of young binaries
XZ Tau and VY Tau

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PACS numbers: 97.10.Gz, 97.21.+a, 97.80.Di

Keywords: binaries: general – stars: variables: T Tauri, Herbig Ae/Be – stars: individual: XZ Tau – stars: individual: VY Tau – accretion, accretion discs – stars: winds, outflows.

Abstract

The results of our speckle interferometric observations of young binaries VY Tau and XZ Tau are presented. For the first time, we found a relative displacement of VY Tau components as well as a preliminary orbit for XZ Tau. It appeared that the orbit is appreciably non-circular and is inclined by $i \lesssim 47^\circ$ from the plane of the sky. It means that the rotation axis of XZ Tau A and the axis of its jet are significantly non-perpendicular to the orbital plane. We found that the average brightness of XZ Tau had been increasing from the beginning of the last century up to the mid-thirties and then it decreased by $\Delta B > 2$ mag. The maximal brightness has been reached significantly later on the time of periastron passage. The total brightness of XZ Tau’s components varied in a non-regular way from 1970 to 1985 when eruptions of hot gas from XZ Tau A presumably had occurred. In the early nineties the variations became regular following which a chaotic variability had renewed. We also report that a flare activity of VY Tau has resumed after 40 yr pause, parameters of the previous and new flares are similar, and the flares are related with the A component.

Introduction

The most obvious manifestations of so-called ‘eruptive phenomena in early stellar evolution’ (Herbig, 1977) are relatively short (from days to hundreds years) episodes of increased

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brightness observed in T Tauri stars, i.e. low-mass (< 2 − 3 M⊙) young (age < 10 Myr) stars that contracting toward the main-sequence. It is widely accepted now that such events occur due to clearing of circumstellar gas-dust envelope or/and increasing of accretion rate $\dot{M}_{\text{acc}}$ of matter from a protoplanetary disc (see, e.g. Audard et al. (2014) and references therein). The physical reasons that are responsible for the $\dot{M}_{\text{acc}}$ increasing are of special interest. In young binary systems such events can occur due to gravitational influence of each component of a system on the circumstellar disc of the neighboring star near the periastron passage. Such possibility was initially predicted theoretically (Bonnell, Bastien, 1992; Artymowicz, Lubow, 1996) and later observed in a number of young binaries (see, e.g. Jensen et al. (2007) and references therein). The aim of our paper is to search for a correlation between the orbital motion and the photometric behavior in young binaries VY Tau and XZ Tau.

The photometric variability of XZ Tau was discovered by P.F. Shain (Beljawsky, 1928). The star is projected onto the dark cloud L1551, has M3 spectral type, and its spectrum exhibits strong emission lines with equivalent width of Hα line up to 270 Å. The set of these features was the reason to include the star in the initial list of T Tauri stars (Joy, 1945) and to classify it from the present-day viewpoint as a classical T Tauri star (CTTS), i.e. low mass young star activity of which is due to accretion of protoplanetary disk’s matter. Haas et al. (1990) found that to north of the more bright (at that moment) star XZ Tau S there is a companion XZ Tau N at a distance of about 0.3 arcsec, what respects to projected distance of 42 AU if to adopt the distance to XZ Tau to be 140 pc (Elias, 1978). It was found that both stars are CTTSs, and the N component has more early spectral type (M1.5) than the S component and therefore is more massive (White, Ghez, 2001). None the less it is adopted in the literature to designate XZ Tau S as the main component of the system, i.e. as XZ Tau A, and XZ Tau N as a companion, i.e. XZ Tau B. We will also follow this tradition.

XZ Tau was identified by Mundt et al. (1990) as the source of a bipolar, collimated outflow. It appeared that the outflow occurs from each component of the binary, and that the jet of XZ Tau A is oriented along a position angle ($\theta$) of $\sim 15^\circ$ while the jet of XZ Tau B along $\theta$ of $\sim 36^\circ$ (Krist et al., 2008). Besides Krist et al. (1997) discovered in the inner parts of the outflow an unusual expanding bubble of emission nebulosity. The bubble appears to be a succession of bubbles, the outer boundary of which reached an extent of $\approx 6$ arcsec from the binary in 2005. The jet from XZ Tau A is aligned with the outflow axis of the bubbles, and Krist et al. (2008) believe that the bubbles are resulted from large velocity pulses of this jet.

Judging from the dynamical time of the bubble’s expansion one can conclude that the large velocity pulses have occurred between 1965 and 1985. Bear in mind that high velocity ejection of gas in young binary DF Tau was accompanied with a short-time increase of stellar brightness of $\Delta B \approx 6.5$ mag (Li et al., 2001), it would be interesting to search for similar flares in XZ Tau in the respective epoch. Since the distance between XZ Tau’s components gradually decreased after 1990, Krist et al. (2008) concluded that the gas ejection was not connected with the moment of periastron passage. But Carrasco-Gonzalez et al. (2009) found from their Very Large Array (VLA) observations that at 7 mm the XZ Tau A radio component resolves into a binary with 0.09 arcsec (13 AU) separation, suggesting that XZ Tau is actually a triple star system. They have assumed
that the ejection of gas from the XZ Tau system may be related to a periastron passage of this newly discovered close binary system XZ Tau AC.

But follow-up VLA-observations of Forgan et al. (2014), as well as recent observations of ALMA Partnership et al. (2015) find no evidence of XZ Tau C component, despite improved sensitivity and resolution. Three possible interpretations were offered: either XZ Tau C is transiting XZ Tau A, or the emission seen in 2004 by Carrasco-Gonzalez et al. (2009) was that of a transient, or XZ Tau C does not exist. Thus the question is open and it is a good time to analyze an additional astrometric and photometric information about the system.

VY Tau, the second target of our investigation, is also very interesting object. Its photometric variability was discovered by Beljawsky (1924), who reported that the photographic magnitude of the star varied from 13 to 9.7 mag in 1906-1922. Follow-up observations revealed VY Tau’s light curve, featuring sporadic outbursts from about $B = 14$ to 11-12 mag with duration from 100 to 700 days interspersed with many years of inactivity (see Herbig (1990) and references therein).

The star is projected onto the dark cloud L1536, has (at minimum light) M0 V spectral type with H$\alpha$ and Ca II H, K lines in emission and strong Li I 6707 Å line in absorption. Based on these features (Herbig, Kameswara Rao, 1972) have attributed VY Tau to T Tauri type stars. The relatively small equivalent width of H$\alpha$ line in a quiet state (EW$\approx 5$ Å) and the negligible near-infrared (NIR) excess emission are the reasons to conclude that the star has no accretion disk (Herbig, 1990) and thus belongs to so-called weak-lined T Tauri stars (WTTS).

According to the modern paradigm, an observed activity of WTTSs is attributed to the presence of powerful chromospheres and coronas more or less similar to solar. But it is impossible to explain sporadic outbursts of VY Tau using the analogy with solar flares. At first, the duration of the outbursts is almost three order of magnitudes larger than that of solar chromospheric flares. Secondly, while during the outburst VY Tau becomes more blue, low-level emission lines of Fe I, Si I and Mg I dominate in its spectrum, whereas higher excitation species such as Fe II and the Balmer lines are relatively weak (Herbig, 1990), as contrasted to solar flares. Herbig suggested that the outburst activity of VY Tau is connected in one way or another with binarity of the star. He also noted that his analysis of VY Tau spectrum was based on observations carried out prior to 1972, when the star was last active, and there is need for a modern reinvestigation particularly when the activity resumes. We will see below that the inactive state of the star lasted up to the end of 2012 following which outbursts apparently have renewed.

Leinert et al. (1993) discovered at a distance of about 0.7 arcsec a companion VY Tau B, which was at that moment four times weaker in K-band than the main star VY Tau A. Follow-up observations of White, Ghez (2001) and McCabe et al. (2006) have confirmed the existence of the companion, but it was impossible to state that the relative position of A and B components varies with time. Adopting the distance to VY Tau to be 160 pc (Herczeg, Hillenbrand, 2014), the projected distance between the components is $> 100$ AU, so it looks unrealistic to explain VY Tau outburst activity as a result of interaction between A and B components of the binary. Therefore, if Herbig’s hypothesis is correct, then one more component should be in the system. Thus – as in the case of XZ Tau – it is very important to obtain new photometric and astrometric information
Table 1: Results of our speckle interferometric observations

| Set  | Star | $\lambda$ | $\rho$ | $\sigma_\rho$ | $\theta$ | $\sigma_\theta$ | $\Delta m$ | $\sigma_\Delta m$ |
|------|------|----------|-------|--------------|---------|----------------|-----------|----------------|
| Feb. | VY   | 0.8      | 712   | 8            | 323.9   | 0.7            | 1.8       | 0.2           |
|      | XZ   | 0.7      | 268   | 8            | 311.6   | 1.6            | 0.0       | 0.5           |
|      |      | 0.8      | 269   | 3            | 311.4   | 0.6            | 0.0       | 0.5           |
|      |      | 0.9      | 272   | 5            | 311.6   | 1.1            | 0.0       | 0.5           |
| Apr. | XZ   | 0.8      | 268   | 4            | 311.4   | 0.9            | 0.37      | 0.35          |
|      | VY   | 0.8      | 714   | 7            | 323.5   | 0.6            | 1.84      | 0.15          |

$^a$: Central wavelength of a filter.

about VY Tau.

Observations and data reduction

Speckle interferometry of VY Tau and XZ Tau was performed with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences on the night of 2014 February 12/13. A system of speckle image detection based on a CCD with internal signal amplification was used (Maksimov et al., 2009). Speckle interferograms were obtained with filters having central wavelengths/half-widths of 700/40, 800/100, 900/60 nm in the case of XZ Tau and 800/100 nm in the case of VY Tau. 2000 speckle images were accumulated with exposure times of 50 ms per frame in each filter, to determine the position parameters and magnitude differences. The seeing was $\approx 1.5 - 2$ arcsec but we observed both binaries through the haze and the atmospheric extinction was $\sim 3$ mag. As a result we were able to accumulate the signal in the power spectrum not more than $\sim 30$ per cent of the maximum possible level. It practically did not decrease the accuracy of angular distance $\rho$ and $\theta$ measurements, but reduced significantly that of magnitude difference $\Delta m = m_B - m_A$. All the more our data are not suitable to search for the presumably faint close companion XZ Tau C (Carrasco-Gonzalez et al., 2009). Results of our measurements and their errors are presented in Table I. As can be seen from the table $\rho$ and $\theta$ values for XZ Tau derived in different bands agree within errors of measurements, and so we will use later on their averaged values.

We observed both binaries once more on night 2014 April 11/12 but with 800/100 nm filter only. 4000 speckle images were accumulated with exposure times of 50 ms. As can be seen from Table II the results of April and February observations coincide within errors of measurements. Unfortunately weather conditions were as bad as in February, so both datasets cannot help to answer the question: if XZ Tau C companion exists or not.

The extensive photographic plate collection of the Sternberg Astronomical Institute (SAI) was used to study the photometric behavior of XZ Tau. We found 262 plates with images of the vicinity of XZ Tau. 260 of them were taken with the 40-cm astrograph of the Crimean Laboratory of SAI. The plates cover a field of $10^\circ \times 10^\circ$ and have limiting magnitude $B \approx 17$. The photographic estimates were calibrated to stars USNO-A2.0. The typical uncertainty of our estimates is 0.3 mag. Two more plates were obtained at Moscow observatory of SAI in 1911-1912 by means of the 10-cm Steinheil astrograph.
Both plates have a limiting magnitude of $B \approx 14$. XZ Tau is hardly distinguishable at these plates and we adopted an upper limit 13.5 mag to its brightness.

We also carried out 28 observations of VY Tau between March 26, 2010 and October 1, 2014 with the 35-cm Schmidt-Cassegrain telescope (amateur observatory, Bourbon, USA) equipped with SBIG STL-1001E/ST-402 CCD camera and a standard Johnson V filter. The CCD images were reduced in a standard way which included dark-frame and flat-field corrections. The image scale was $1.29-2.57$ arcsec per pixel, depending on the setup, while the size of stellar images was $FWHM \approx 7-17$ arcsec. Some of these images are taken during the outbursts that allows us to determine which of two components increases its brightness by comparison of positions of the photo-centre of the system before/after and during the outburst. To measure the position of the photo-centre, 16 reference stars with small proper motion were selected from the USNO-B1.0 Catalog (Monet et al., 2003) in the field of $10 \times 10$ arcmin around the VY Tau. We used these 16 stars in order to construct the coordinate system, assuming a linear transformation between the standard and image coordinates (Zombeck, 2007). Since the same stars were used for all obtained images, then possible systematic errors of our coordinate system must be common for all images and cancel out in the position difference measurements. The position of the photo-centre was determined in the image coordinates as a weighted mean $(i_c,j_c) = \sum_{i,j}(i,j)C_{ij}/\sum_{i,j} C_{ij}$ over a small square region, covering the star. Here $C_{ij}$ is the number of (sky-subtracted) flux counts in pixel $(i,j)$. Then the image coordinates were transformed to the right ascension $\alpha$ and declination $\delta$ of our coordinate system. For convenience we will use the following coordinates expressed in arcsec: $x = (\alpha - \alpha_0) \cos \delta_0$, $y = \delta - \delta_0$, where $\alpha_0$ and $\delta_0$ are mean coordinates of the star over all frames. Variations in the position and size of the region allow us to estimate an accuracy of determining the photo-centre $\sigma_{x,y}^\star$. Quality of the constructed coordinate system is characterized by mean deviations $\sigma_{x,y}^C$ of positions of five control stars from their average positions calculated over all frames. The control stars are stars of 12-14 mag, for which shifts of the coordinates due to proper motions and parallaxes can be neglected during the period of our observations. The total uncertainty of the coordinates of the VY Tau in our system can be estimated as $\sigma_{x,y} = \sqrt{\sigma_{x,y}^\star^2 + \sigma_{x,y}^C^2}$. Results of the astrometric and photometric measurements are summarized in Table 2.

**Orbital motion**

For both binaries we searched the literature for previously published measurements of their separations. These data are presented in Table 3 along with our data averaged over different filters in the case of February data for XZ Tau. Note that to map the visual orbit of XZ Tau we use measurements obtained in optical and NIR bands but not in radio band because it is not obvious that centroids of radio emission coincide with components of the system (see Sect. ).

Variation of relative position of VY Tau and XZ Tau components based on data presented in Table 3 is shown in Fig. 1. In the case of VY Tau our measurements for the first time indicate the shift of the companion relative to the main star although its motion is indistinguishable from linear now. If the system is bounded, then its orbital period is $> 350$ yr that follows from the third Kepler’s law, if to adopt the following
| JD2456 | $V$ | $\sigma_V$ | $x$ | $\sigma_x$ | $y$ | $\sigma_y$ |
|--------|-----|-----------|-----|----------|-----|----------|
| 012.63 | 13.59 | 0.01 | -0.11 | 0.27 | 0.02 | 0.16 |
| 012.63 | 13.59 | 0.01 | 0.01 | 0.09 | -0.14 | 0.13 |
| 012.63 | 13.60 | 0.01 | -0.08 | 0.29 | -0.04 | 0.12 |
| 013.61 | 13.59 | 0.06 | 0.46 | 0.21 | 0.40 | 0.42 |
| 147.91 | 13.84 | 0.09 | 0.03 | 0.52 | -0.06 | 0.17 |
| 247.84 | 13.25 | 0.05 | -0.16 | 0.08 | 0.21 | 0.36 |
| 251.85 | 12.98 | 0.03 | -0.02 | 0.16 | -0.06 | 0.31 |
| 253.84 | 13.00 | 0.03 | 0.13 | 0.16 | 0.02 | 0.22 |
| 267.83 | 12.58 | 0.07 | 0.06 | 0.16 | 0.09 | 0.11 |
| 280.83 | 12.79 | 0.01 | -0.01 | 0.09 | -0.04 | 0.13 |
| 299.82 | 13.29 | 0.05 | -0.00 | 0.13 | -0.00 | 0.14 |
| 328.75 | 13.61 | 0.07 | -0.22 | 0.33 | -0.28 | 0.17 |
| 574.96 | 14.00 | 0.02 | 0.05 | 0.21 | -0.22 | 0.29 |
| 583.94 | 13.75 | 0.02 | -0.54 | 0.41 | -0.05 | 0.24 |
| 590.90 | 13.98 | 0.02 | 0.03 | 0.36 | 0.01 | 0.31 |
| 593.89 | 13.88 | 0.02 | -0.32 | 0.21 | 0.24 | 0.20 |
| 599.89 | 13.77 | 0.02 | -0.07 | 0.37 | 0.18 | 0.35 |
| 604.96 | 13.32 | 0.01 | 0.07 | 0.19 | 0.03 | 0.16 |
| 606.93 | 13.41 | 0.01 | 0.01 | 0.17 | -0.01 | 0.14 |
| 609.90 | 13.10 | 0.01 | -0.14 | 0.15 | -0.10 | 0.07 |
| 626.86 | 12.85 | 0.02 | 0.05 | 0.14 | 0.02 | 0.12 |
| 639.79 | 12.70 | 0.03 | 0.18 | 0.33 | -0.17 | 0.10 |
| 653.82 | 13.04 | 0.02 | 0.09 | 0.15 | -0.05 | 0.06 |
| 894.84 | 13.82 | 0.03 | 0.37 | 0.18 | 0.04 | 0.25 |
| 895.83 | 13.87 | 0.04 | -0.06 | 0.19 | -0.11 | 0.16 |
| 905.80 | 13.82 | 0.06 | 0.33 | 0.30 | -0.02 | 0.09 |
| 930.83 | 13.83 | 0.03 | 0.05 | 0.15 | -0.02 | 0.08 |
| 931.73 | 13.79 | 0.07 | -0.20 | 0.23 | 0.13 | 0.16 |
Table 3: Compilation of XZ Tau and VY Tau measurements

| Star   | JD24... | $\rho$ | $\sigma_\rho$ | $\theta$ | $\sigma_\theta$ | Ref. |
|--------|---------|--------|---------------|----------|----------------|------|
|        |         | mas    | mas           | $^\circ$ | $^\circ$        |      |
| XZ Tau | 47817   | 300    | 20            | 334      | 3              | 1    |
|        | 48550   | 311    | 6             | 333      | 2              | 2    |
|        | 49723   | 306    | 3             | 327.2    | 0.5            | 7    |
|        | 50423   | 299.8  | 5.7           | 324.5    | 1.0            | 3    |
|        | 50516   | 300    | 3             | 326.0    | 0.5            | 7    |
|        | 51213   | 301    | 3             | 324.4    | 0.5            | 7    |
|        | 51581   | 299    | 3             | 322.6    | 0.5            | 7    |
|        | 51881   | 299    | 14            | 322.6    | 2.0            | 4    |
|        | 51951   | 297    | 3             | 321.6    | 0.5            | 7    |
|        | 52318   | 291    | 3             | 321.6    | 0.5            | 7    |
|        | 53025   | 294    | 3             | 322.3    | 0.5            | 7    |
|        | 56703   | 270    | 3             | 311.5    | 0.7            | 8    |
|        | 56759   | 268    | 4             | 311.4    | 0.9            | 8    |
| VY Tau | 48231   | 660    | 20            | 317      | 2              | 6    |
|        | 50792   | 665    | 13            | 316.6    | 1.0            | 3    |
|        | 52245   | 670    | 10            | 318      | 1              | 5    |
|        | 56703   | 712    | 8             | 323.9    | 0.7            | 8    |
|        | 56759   | 714    | 7             | 323.5    | 0.6            | 8    |

1 – Haas et al. (1990); 2 – Ghez et al. (1993); 3 – White, Ghez (2001); 4 – Hartigan, Kenyon, (2003); 5 – McCabe et al. (2006); 6 – Leinert et al. (1993); 7 – Krist et al. (2008); 8 – our data.
Table 4: Allowable range of XZ Tau orbital elements

| $i$ | $e$    | $a$     | $P$  | $T_0$ | $M_{AB}$ |
|-----|--------|---------|------|-------|----------|
| $^\circ$ |        | AU      | yr   | yr    | M$_\odot$ |
| 10  | 0.62–0.64 | 27.2–27.3 | 155–156 | 1915.9–1916.4 | 0.82–0.84 |
| 20  | 0.58–0.64 | 28.3–28.4 | 158–167 | 1915.3–1919.4 | 0.80–0.90 |
| 30  | 0.52–0.56 | 28.5–28.9 | 159–169 | 1919.4–1923.4 | 0.84–0.90 |
| 35  | 0.45–0.56 | 31.4–32.0 | 190–197 | 1910.3–1913.3 | 0.80–0.90 |
| 40  | 0.38–0.52 | 33.3–34.4 | 214–219 | 1904.6–1907.5 | 0.79–0.90 |
| 45  | 0.29–0.48 | 36.1–38.2 | 241–256 | 1893.8–1899.3 | 0.80–0.90 |
| 50  | 0.27–0.84 | 32.2–37.3 | 124–206 | 1915.5–1943.0 | 0.99–2.99 |

parameters of the system: the distance to VY Tau is 160 pc (Herczeg, Hillenbrand, 2014); the semi-major axis $a$ is larger than a half of observed distance between the components ($\approx 0.7$ arcsec) i.e. $a > 56$ AU; the total mass of the system $M_A + M_B < 1.2$ M$_\odot$ (Woitas et al., 2001).

In the case of XZ Tau there is enough orbital coverage to compute preliminary orbital solutions. As far as an information on the existence of a third body in the system is absent, Kepler’s two-body problem is considered. We calculated orbital elements in a Cartesian coordinate system with the origin in the A component, Z-axis directed to the Earth and X-axis directed to the north celestial pole of J2000 epoch. The distance to XZ Tau was adopted to be 140 pc (Elias, 1978; Herczeg, Hillenbrand, 2014).

The orbital elements were found from the observational data given in Table 3 by differential corrections calculated with the least-squares method. Weights were applied using the accuracy estimates of observations. The total mass of the system was treated as a parameter of the problem therefore values of semi-major axis and mean motion were considered as independent variables.

It appeared that the available observational data do not allow to determine all orbital elements jointly due to strong correlations between them, arising from the least-squares method process. Some family of orbits represents the observations with almost equal accuracy.

For this reason we used inclination of the orbital plane from the plane of the sky $i$ as an independent parameter ($0 < i < 90^\circ$). For a set of $i$-values we used an eccentricity $e$ as the second free parameter and found that inside some range of its value the process of differential correction converges and one can derive the rest of the orbital elements.

One can impose restrictions on the total mass of the binary bearing in mind that the spectral type of each component is M. According to Hartigan, Kenyon (2003) and Herczeg, Hillenbrand (2014) the mass of XZ Tau A is $M_A = 0.29$ M$_\odot$. An estimation of mass of XZ Tau B is not so reliable because its spectrum is strongly contaminated by emission lines: Hartigan, Kenyon (2003) found $M_B = 0.37$ M$_\odot$, whereas White, Ghez (2001) found $M_B = 0.51 \pm 0.08$ M$_\odot$. Thus we adopted the total mass of XZ Tau as $M_A + M_B < 0.9$ M$_\odot$. It appeared that only orbits with $i \leq 47^\circ$ satisfy this restriction. The allowable range of orbital parameters of interest (eccentricity, semi-major axis, orbital period $P$, time of periastron passage $T_0$ and total mass of the binary $M_{AB}$) for a set of $i$-values are presented in Table 4. The last row of the table is presented for comparison.
Figure 1: Variations of relative position of components in VY Tau (left panel) and XZ Tau (right panel)—see Tabl. 3. Two orbits from the family of Table 4 are shown for XZ Tau: with \( e = 0.6 \) (solid line) and with \( e = 0.3 \) (dashed line). See text for details. In both panels the origin of a coordinate system is in the A component, north is up and east is to the left.

We conclude therefore that the parameters of XZ Tau preliminary orbit can be described as follows: \( i < 47^\circ \), \( 0.29 < e < 0.64 \), \( 27.2 < a < 37.2 \) AU, \( 155 < P < 256 \) yr. These values can be compared with orbital parameters of the binary published earlier: \( i \approx 0^\circ \), \( e \approx 0.9 \), \( a > 21 \) AU, \( P > 99 \) yr (Krist et al., 2008); \( i = 17^\circ \), \( e \sim 0.5 \pm 0.2 \), \( a = 84 \) AU, \( P = 1010 \pm 260 \) yr (Hioki et al., 2009).

Two orbits from the family of Table 4 with significantly different eccentricities are shown in the right panel of Fig. 2 to demonstrate that in both cases theory describes observational data equally good. Parameters of these orbits are: \( e = 0.6 \), \( i = 20^\circ \), \( a = 28.4 \) AU, \( P = 166 \) yr and \( e = 0.3 \), \( i = 45^\circ \), \( a = 36.4 \) AU, \( P = 244 \) yr.

**Discussion**

The orbital period of VY Tau AB binary is > 350 yr therefore it seems unreasonable to expect a direct connection between the orbital motion of the binary components and the non-regular outbursts observed in VY Tau in the last century. As was noted in the Introduction, the outburst activity has terminated at the beginning of 1970s. It can be seen from Fig. 2 based on AAVSO data (Kafka, 2015) that the inactive period lasted almost up to 2013 i.e. \( \approx 40 \) yr and then the outbursts renewed.

At the date of writing, three new outbursts have been observed. Their amplitude \( \Delta V \) reaches 1.5 mag, duration is \( \sim 100^d \) and the time interval between them is \( \approx 1 \) yr. These

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1 Short (\( \Delta t < 1^h \)) flares with amplitudes \( \Delta U \) up to 1.5 mag were observed by Khodzhaev (1987) in 1983.
parameters look like the parameters of outbursts observed in the last century. We found 9 nearly simultaneous observations of VY Tau in $B$ and $V$ filters in the AAVSO database after 2012, two of which were carried out at the epoch of increased brightness. Judging by these data, color indexes $B - V$ of the star in active and quiet states are also similar to that of previous – see the right panel of Fig. 2.

It has not been known up to now which component of VY Tau is responsible for the outbursts. Unfortunately, our speckle interferometric observations were carried out just after the end of the second outburst – see the middle panel of Fig. 2. Nevertheless, it appeared possible to solve the problem by means of our unresolved astrometric and photometric measurements presented in Table 2. Using results of our speckle interferometric observations from Table 1 one can find an unit vector $\mathbf{n} = (\sin \theta, \cos \theta)$ in the plane of the sky, directed from A to B. A shift of the photo-centre of the star along $\mathbf{n}$ can be found as $\Delta = x \sin \theta + y \cos \theta$ and its uncertainty $\sigma_\Delta = \sqrt{\sigma_x^2 \sin^2 \theta + \sigma_y^2 \cos^2 \theta}$. Here $x, y, \sigma_x, \sigma_y$ are the position of the star with corresponding uncertainties from Table 2. The shift $\Delta$ is shown in Fig. 3 as a function of the brightness of the star.

As a reference position of the star, we chose its position in a faint state. It can be easily shown that the shift of the photo-centre relative to the reference position along the straight line passing through A and B is

$$\Delta = \rho k \left[ 1 - 10^{0.4(V - V_0)} \right],$$

(1)

where $\rho$ is the separation between the components; $V, V_0$ denote the total $V$-magnitude of the binary during an outburst and in a quiet state, correspondingly. If the outbursts
occur on the A component, then $k = k_A = -(1 + r_0)^{-1}$, while in the case of outbursts on the B component $k = k_B = r_0(1 + r_0)^{-1}$. Here $r_0$ is the flux ratio of A and B components in the quiet state. Because the fainter component is cooler (Woitas et al., 2001), then the flux ratio in the $V$ band must be larger than at 800 nm, i.e. $r_0 > 5$ (Table 1) that means $-0.16 < k_A < 0$ and $0.83 < k_B < 1$.

We plot in Fig. 3 the expected shifts $\Delta$, calculated with $r_0 = 5$, for the cases when the outbursts occur on either the A or B component. It can be seen that the observations do not show any significant shift in the direction of the B component during the outburst, therefore we can conclude that the outbursts occur on (or near) the A component. It follows from Eq. (1) that a higher value of $r_0$ can only strengthen our conclusion. We also found that there is no difference in the position of the VY Tau in active and quiet states in the direction orthogonal to $n$.

The source of the outbursts can be found in a more formal way. It is possible to fit the observations by Eq. (1), re-written in a linear form $\Delta = \rho kt + b$, where $t = 1 - 10^{0.4(V - V_0)}$ and $b$ is a possible small shift due to an ambiguity of the definition of the reference position. We have found by weighted least squares (weights are $\sigma_\Delta^{-2}$) that $k = -7(\pm 3) \times 10^{-2}$, $b = (0.1\pm1.1) \times 10^{-2}$ arcsec that results in $r_0 = 9-24$ and agrees well with our expectations of $r_0 > 5$. One can definitely conclude now that the A component increases its brightness during the outbursts because the derived $k$-value differs from the low limit of $k_B$-value by 30 standard errors. These results are very important but do not reveal the nature of the outburst activity.

XZ Tau is also non-trivial object. We constructed the historical light curve of the binary (see Fig. 4) using our data along with data adopted from the literature (Beljawsky, 1928; Esch, 1929; Rügemer, 1935; Joy, 1945; Smak, 1964; Badalyan, Erastova, 1964; Cohen, Schwartz, 1976; Badalyan, Erastova, 1969; Rydgren, Vrba, 1981; Rydgren, Vrba, 1983; Rydgren et al., 1976; Rydgren et al., 1982). Unfortunately, Rügemer (1935) did not present results of his 109 estimations of XZ Tau’s brightness and wrote only that $B$-magnitude of the star varied between 10.4 and 13.5 in JD 24025528−24025513 period.

Additional data were taken from the following databases: the AAVSO (Kafka, 2015), the T Tauri database (Herbst et al., 1994) and the ASAS project (Pojmanski et al., 2005). Note that $V$-magnitudes of XZ Tau from the ASAS data could be overestimated up to 0.5 due to a contribution from HL Tau ($V \simeq 14.7$ mag according to the AAVSO data) which is at the distance $\approx 20$ arcsec from the binary. As far as a separation between A and B components of XZ Tau is $\sim 0.3$ arcsec, all mentioned above data represent their summary brightness.

As can be seen from Fig. 4 the average brightness of XZ Tau increased from the beginning of 20th century, has reached the maximum circa 1935 and then decreased significantly. We suppose that observed brightness variations are connected with variations of the accretion luminosity of XZ Tau A and/or XZ Tau B components due to changing of the distance between them. It follows from Table 4 that the periastron passage has happened before 1924, i.e. significantly earlier than the moment of XZ Tau’s maximal brightness. But a companion produces the most strong tidal perturbations in the outer-most regions of a neighbouring star’s circumstellar disk, and some time $\Delta t$ is necessary for the disturbance to propagate inward and to result in increasing of accretion rate onto the central star. Thus it looks natural that the maximum of accretion luminosity occurs
Figure 3: The shift of VY Tau’s photo-centre as a function of V magnitude. Dots with error bars are for the observations. Thick solid curves labelled as A and B are for the expected shifts with $r_0 = 5$ in the case when the outbursts occur on the A or B component, correspondingly. If $r_0 > 5$, then the slope of the A-curve will be lower, while the slope of the B-curve will be steeper according to Eq. (1). A linear regression estimated by weighted least squares and its 1-$\sigma$ uncertainties are shown by thin solid and dashed lines, respectively.
Figure 4: XZ Tau’s light curve in $B$ (upper panel) and $V$ (low panel) bands. The following designations are used: triangles are for the data adopted from the literature, open circles are for our data, points are for the ASAS data, arrows are upper limits. The large cross near JD 2.426.500 represents data from Rügemer (1935) – see text for details.
later than the moment of a periastron passage. This time delay $\Delta t$ must be of order of Keplerian time at the outer boundary of the disk (Lamzin et al., 2001).

According to Artymowicz, Lubow (1996) the outer radii $R_d$ of circumcomponent’s disks of a young binary is near 0.4 of a minimal distance between its components, it means, in our case (see Table 1), that $R_d \approx 6$ AU. The mass of XZ Tau A or B component is $\sim 0.5$ $M_\odot$ (see Sect. 4) and thus $\Delta t \sim 30$ yr. Such value of the time delay means that the time of periastron passage was circa 1905, i.e. within the range of $T_0$-values in Table 4.

We found that the orbital period of the binary is $P = 200 \pm 50$ yr therefore the maximum of the XZ Tau’s brightness corresponds to the phase $\Delta t/P \sim 0.1-0.2$ of its orbital period.

Note that in the case of another young binary DF Tau even more significant delay of a maximum of accretion luminosity relative to a time of a periastron passage is observed. The orbital period of the binary is $\approx 43.7 \pm 3.0$ yr (Schaefer et al., 2014) and that coincides with the duration of DF Tau’s photometric cycle ($\approx 44$ yr according to Tsesevich et al., 1967) and also approximately equals to a half of the time interval between two extremely strong flares observed in DF Tau in October 1918 and January 2000. As was mentioned in the Introduction (Li et al., 2001), a powerful gas ejection was observed from DF Tau during the second flare.

According to Schaefer et al. (2014) the epoch of DF Tau’s periastron passage is 1980.5$\pm$1.7 yr, therefore the second flare has occurred at an orbital phase $\approx 0.45$, when the companion was near the apastron. What is more, DF Tau’s minimal accretion luminosity was observed in June 1987 (Lamzin et al., 2001), i.e. at orbital phase $\sim 0.16$. On the other hand, it is stated that in the case of young binaries DQ Tau (Mathieu et al., 1997), UZ Tau E (Jensen et al., 2007) and AK Sco (Gomez de Castro et al., 2013) the moments of maximal accretion luminosity and periastron passage coincide within errors of measurements. Note, just in case, that the orbital periods of DQ Tau, UZ Tau E and AK Sco are of order of several tens of days whereas that of XZ Tau and DF Tau are much more longer.

As was mentioned in the Introduction, there are reasons to suppose that gas ejections from XZ Tau A occurred between 1965 and 1985. Our estimates of XZ Tau’s brightness mainly cover the period from 1970 to 1985 – see Fig. 4. During this period the brightness of the binary varied non-regularly and sometimes the variations were rapid enough: e.g. $B$-magnitude of XZ Tau was 16.0 in 1981, March 1 and $B = 13.8$ five days later. As can be seen from the figure, at the beginning of the nineties the character of XZ Tau’s photometric variability has changed radically: smooth wavy variations of XZ Tau’s brightness were observed during 1990-1993 (Grankin et al., 2007), but then a chaotic variability has renewed. It is not clear, however, if a chaotic variability of 1970-1985 was connected in some way with the gas ejection because similar variability was also observed in XZ Tau in the beginning of the sixties.

Note that it is not so obvious which component of the binary is responsible for the rapid non-regular variations of XZ Tau’s brightness. From the beginning of the nineties, when resolved photometry of the components became possible, XZ Tau B demonstrated larger photometric activity than XZ Tau A and sometimes the B component becomes brighter than A, at least at wavelengths $> 0.8$ $\mu$m – see Krist et al. (2008) and references

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2 Duration of the powerful flare observed in DF Tau in 2000 ($\Delta B \approx 6.5$ mag) was 2-3 days only, so such short event in XZ Tau can be simply missed.
therein. According to Table 1 the brightness of A and B components was the same within errors of measurements in 700/40 and 800/100 nm filters during our February observations as well as in 800/100 nm filter two months later. On the other hand, from the beginning of the forties all authors who determined the spectral type of XZ Tau have found M3 value, which is the spectral type of the A component, it apparently means that at the moments of that (unresolved) spectral observations XZ Tau A was brighter in the optical band than B.

Note one more interesting feature of XZ Tau. It looks natural to assume that a bipolar gas outflow in single CTTS occurs in the direction that is perpendicular to its accretion disk’s midplane and (approximately) along a rotation axis of the star. The jet of XZ Tau A (Krist et al., 2008) as well as the rotation axis of the star (Artemenko et al., 2012) are inclined by 63° to the line of sight. On the other hand, we found that the inclination of the XZ Tau orbital plane to the plane of the sky is < 47°, and therefore axes of XZ Tau A rotation and jet makes an angle > 16° with the normal to the orbital plane probably due to gravitational influence of the B component. It seems useful to note in this connection that position angles of XZ Tau A and XZ Tau B jets are different: ≈ 15° and ≈ 36°, respectively (Krist et al., 2008).

One can assume also that jets of the components are not parallel to each other and not perpendicular to the orbital plane, because there is a third body in the system, the orbit of which is inclined significantly to the orbital plane of XZ Tau AB binary. However recent observations of ALMA Partnership et al. (2015) as well as previous VLA-observations Forgan et al. (2014) did not confirm the existence of XZ Tau C companion.

ALMA Partnership et al. (2015) found from their observations at λ = 2.2 mm the following astrometric parameters of the binary: ρ = 0.273±0.001 arcsec, θ = 308.7±0.5°. Comparison with our data (Table 1) indicates that their ρ-value is within the error box of our measurements, but position angles in optical and radio bands differ at more than 3σ. Does it really mean that centroids of optical and radio emission have different position? We have no answer to this question, but one can not exclude such possibility. It is why we did not use results of very precise radio observations to map the orbit of XZ Tau.

Concluding remarks

Our new astrometric and photometric data reveal a number of interesting features in young binaries VY Tau and XZ Tau. Additional observational data are necessary in order to interpret this information in a proper way and we would like to mention in this Section which information seems the most crucial for us.

VY Tau. It is necessary to continue the photometric monitoring of the system because its unusual outburst activity apparently has renewed after a forty-year pause. Spectral observations of the binary at different phases of future outbursts are necessary to reveal if they are connected with chromospheric or accretion processes. But resolved spectroscopy of the binary in a quiet state is not less important, because we still did not know even a spectral type of the B component. If the outburst activity of VY Tau is indeed connected with a binarity, as it was suggested by Herbig, then one can state now that the A component should be a close binary. Indeed, if the companion of VY Tau A is a CTTS,
then it well can be that the outbursts are not connected with a chromospheric activity of
the main (WTTS) star, but are a consequence of an accretion process in a hypothetical
companion VY Tau C.

**XZ Tau.** New high-precision astrometric observations will enable 5-10 years from
now to improve significantly orbital elements of the binary, the most interesting of which
(from astrophysical viewpoint) are inclination angle, eccentricity, orbital period and the
time of a periastron passage. There is a deficit of photometric observations of the star
during last 10 years, while AAVSO data indicate that large ($\Delta V > 1$ mag) variations of
XZ Tau brightness have occurred. It would be interesting also to investigate XZ Tau’s
brightness variations, using old photographic plates of the Harvard College Observatory
Astronomical Plate Stack. Multicolor resolved photometry of XZ Tau’s components will
help to understand which component is responsible for flare activity in the optical band.
It is necessary to clarify the nature of extended structures around A and B components
of the binary observed in radio band (Carrasco-Gonzalez et al., 2009; ALMA Partnership
et al., 2015). Indeed, these structures have almost round shape and if they are accretion
disks observed nearly pole-on, then the axes of jets are significantly non-perpendicular to
the disk’s midplane that seems very unusual.

And last but not least, for both binaries the question on the existence of a third body
in a system is equally important, but still open.

**Acknowledgments**

We thank N.Samus and S.Antipin for useful discussions. We acknowledge with thanks
the variable star observations from the AAVSO International Database contributed by
observers worldwide and used in this research along with ASAS project data. This research
has made use of the SIMBAD database and the VizieR catalog access tool, operated at
CDS, Strasbourg, France. This work was supported in part by the Program for Support
of Leading Scientific Schools NSh-261.2014.2 and NSh-2043.2014.2.

**References**

ALMA Partnership et al., preprint, arXiv:1503.02649 (2015)
Artemenko S.A., Grankin K.N., Petrov P.P., Astron. Lett. 38, 783 (2012)
Artemowicz P., Lubow S.H., Astrophys. J., 467, L77 (1996)
Audard M. et al., in Beuther H., Klessen R.S., Dullemond C.P., Henning T., eds, Protostars and Planets VI. University of Arizona Press, Tucson, p.387 (2014)
Badalyan G.S., Erastova L.K., Soobscheniya Buyrakan Obs. 36, 55 (in Russian) (1964)
Badalyan G.S., Erastova L.K., Soobscheniya Buyrakan Obs. 40, 35 (in Russian) (1969)
Beljawsky S., Astron. Nachr. 220, 255 (1924)
Beljawsky S., Astron. Nachr. 234, 41 (1928)
Bonnell I., Bastien P., Astrophys. J. 401, L31 (1992)
Smak J., Astrophys. J. **139**, 1095 (1964)
Stone R.P.S., IBVS, 2380, 1 (1983)
Tsesevich V.P., Dragomirezkaya V.A., Problemi kosmicheskoj fiziki, v.2 (Kiev University, Kiev), p.110 (1967)
Pojmanski G., Pilecki B., Szczygiel D., Acta Astronomica **55**, 275 (2005)
http://www.astrouw.edu.pl/asas
Rügemer H., Astron. Nachr. **255**, 173 (1935)
Rydgren A.E., Vrba F.J., Astron. J. **86**, 1069 (1981)
Rydgren A.E., Vrba F.J., Astron. J. **88**, 1017 (1983)
Rydgren A.E., Schmelz J.T., Vrba F.J., Astrophys. J. **256**, 168 (1982)
Rydgren A.E., Schmelz J.T., Zak D.S., Vrba F.J., Publ. Naval Obs., v.XXV, p.5 (1984)
Rydgren A.E., Strom S.E., Strom K.M., Astrophys. J. Suppl. **30**, 307 (1976)
White R.J., Ghez A.M., Astrophys. J. **556**, 265 (2001)
Woitas J., Leinert C., Kohler R., Astron. Astrophys. **376**, 982 (2001)
Zombeck M., *Handbook of Space Astronomy and Astrophysics*. Cambridge University Press, Cambridge, UK. p. 665 (2007)