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A Spectroscopic Study of the SU UMa-type Dwarf Nova YZ Cnc during its 2002 Superoutburst *

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Abstract We report on time-resolved spectroscopic observations of the SU Ursae Majoris dwarf nova, YZ Cnc for over 11 h on two nights during its 2002 January superoutburst. The spectra on the first day only showed absorption-line profiles, while on the second day the lines showed "W" profiles with blue and red troughs. The radial velocity curve of the absorption troughs and emission peaks of Hβ has an amplitude of 49 ± 10 km s^{-1} and a phase offset of -0.07 ± 0.04, which are very similar to those measured in quiescence. However, the γ velocity deviates strongly from the systemic velocity measured in quiescence, by some ± 60 km s^{-1}. Large shifts of $\sim$70 km s^{-1} in the orbital-averaged velocity and $\sim$0.09 in the phase are also found in our observations. All these features can be well explained by a precessing, eccentric disk.

Key words: accretion, accretion disks –binaries: close – novae, cataclysmic variables – stars: dwarf novae – stars: individual (YZ Cancri)

1 INTRODUCTION

YZ Cnc is a member of the class of SU UMa type dwarf novae, in which normal outbursts (i.e., short outbursts) are occasionally interspersed by longer and brighter distinctive superoutbursts, accompanying superhump phenomena. Superhumps are large amplitude luminosity variations with a period usually a few percent longer than the orbital period of the binary system. This is generally thought to arise from the interaction of the donor star orbit with a non-axisymmetric accretion disk that is slowly precessing in the prograde direction. The eccentricity of the disk arises because a 3:1 resonance occurs between the donor star orbit and motion of matter in the outer disk (for a good review, see Warner 1995).

YZ Cnc is remarkable in several respects. Photometric study showed that YZ Cnc has a visual magnitude of $\sim$14.5 when in quiescence and $\sim$10.5 during outburst and is one of the most active cataclysmic variables with its large flickering amplitude of 0.75 mag peak to peak (Moffett & Barnes 1974). It has a very short recurrence time of $\sim$11.3 days (Vorob'yeva & Kukarkin 1961).

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Patterson (1979) discovered superhumps in the light curve with a period of 0.09204 d of YZ Cnc and defined it as an SU UMa type star, and his continuing study (Patterson 1981) with high-speed photometric observations of YZ Cnc found no evidence for coherent oscillations either in quiescence or during eruptions. However, van Paradijs et al. (1994) found that orbital variability was present during quiescence.

YZ Cnc has also been studied very extensively in X-ray band with the Einstein satellite (Córdova & Mason 1984; Eracleous et al. 1991), with EXOSAT (van der Woerd 1987), with the ROSAT PSPC during the ROSAT All Sky Survey and in subsequent pointing observations (Verbunt et al. 1997, 1999; van Teeseling & Verbunt 1994), and with XMM-Newton (Hakala et al. 2004).

Spectroscopy has not been as extensive as photometry or X-ray, especially when the system is undergoing superoutburst. Sporadic spectroscopic observations have been made by several authors as part of general surveys of cataclysmic variables (Szkody 1981; Oke & Wade 1982; Wade 1982; Williams 1983). Shafter & Hessman (1988, hereafter SH) presented a detailed spectroscopic study of YZ Cnc when the star was in quiescence and gave an orbital period of 0.0868(2) d. According to this orbital period and the superhump period given by Patterson (1979), a precessing period of 1.52 day can be obtained. This prompted us to carry out a 2-day observation to study the accretion disk of YZ Cnc during its 2002 January superoutburst. In this paper we report our observations and reduction of the spectroscopic data in Section 2. In Section 3 we describe the main characteristics of the spectroscopic results and explanations for these results. In the last two sections we present a brief discussion and conclusions on this work.

2 OBSERVATIONS

The observations were conducted with the Optomechanics Research, Inc., Cassegrain spectrograph attached to the 2.16-m telescope with a TEK1024 CCD camera at Xinglong Station of the National Astronomical Observatories. Total observational time was 11 hrs, 5.3 times the orbital period. A 300 groove mm^{-1} grating blazed at 5000 Å was used, and the slit width was set to $2.5''$. Dome flats were taken at the beginning and end of each night. Exposure time for the star ranged from 600 to 1800, depending on the weather conditions. Fifteen and fourteen star spectra were collected on January 21 and 22 (Beijing time), respectively. The journal of the observations is shown in Table 1.

Table 1 Journal of Observations

Date (UT) (Year 2002)	HJD Start –2452000	Duration (hr)	Exposure (s)	Plates
Jan 21	296.1457	5.22	900,1200	15
Jan 22	297.1064	5.78	1500	14

The data processing is similar to that in Wu et al. (2001). After bias subtraction and flat field correction, we used the *IRAF*[1], task *cosmicray* to eliminate the cosmic rays roughly and then used *imedit* to get the cosmic rays rejected more clearly by hand. The lamp spectra recorded before and after every two successive star exposures were used to interpolate the coefficients of the wavelength scales. We derived a spectral resolution of 12 Å from FWHM measurement of the lamp spectra. The rms error of identified lines was less than 0.2 Å using

[1] *IRAF* is distributed by the National Optical Astronomy Observatory, which is operated by Associated of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

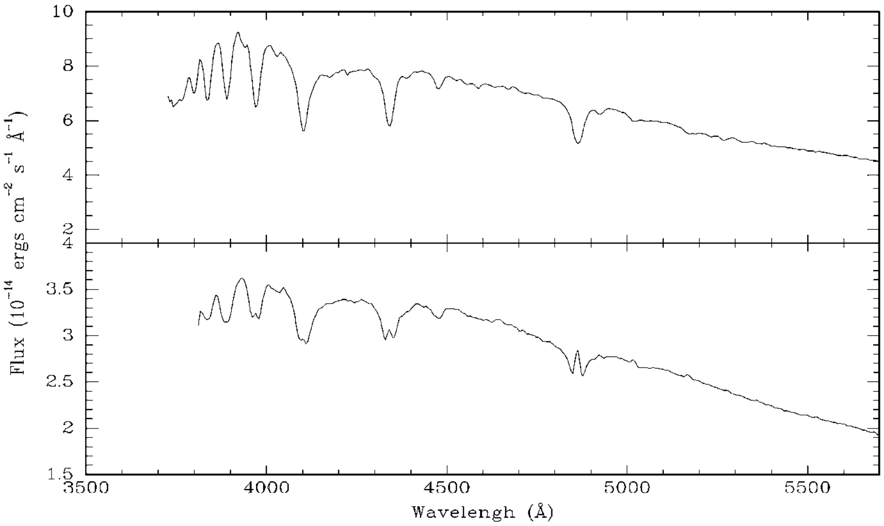

Fig. 1 Spectra of YZ Cnc during superoutburst. The top spectrum, obtained on January 21, is much bluer and the flux is also much higher than the bottom one, obtained on January 22.

a fourth-order Legendre polynomial fit of the lines, corresponding to 12 km s^{-1} near Hβ. The flux was calibrated used the standard star, HD109995, and had an estimate error of $\sim$10%.

3 RESULTS AND ANALYSIS

3.1 Average Spectra

Figure 1 shows the average spectra of YZ Cnc during its superoutburst. The upper and lower panels show, respectively, the sum of all the 15 individual spectra recorded on January 21 and the sum of all the 14 individual spectra obtained on January 22. The spectra of January 21 are characterized by broad Balmer absorption and an energy distribution significantly bluer than that of January 22, when the eruption was fading out. The spectra are typical of an optically thick accretion disk with a high accretion rate. The emission component came out clearly and was specially strong in Hβ absorption on January 22. The He I ($\lambda\lambda$4471, 4922) absorption, He I λ5015+Fe II λ5018 and Fe II λ5169 absorption (emission on January 22) are also present (seen more clearly in Fig. 2). The equivalent widths of the absorption and emission lines are summarized in Table 2.

3.2 Radial Velocity

In Figure 2A we show the normalized spectrum which is the sum of all 15 individual spectra obtained on January 21. Figure 2B shows the normalized spectrum for January 22. In combining the spectra, no radial velocity offsets were applied.

We measured the centers of Hβ absorption troughs of January 21 and emission peaks of January 22 with Gaussian fits. We used the Hβ line because it has good signal-to-noise ratios on both nights. Figure 3 shows the velocities folded on the orbital period with the best-fit sinusoidal curve superposed. The orbital phase was computed according to the ephemeris given

Table 2 Equivalent Widths of Spectral Lines

Date (2003)	Element Rest Wavelength	EW (Å)	Element Rest Wavelength	EW (Å)
Jan 21	Hζ λ3889	–6.2	Hβ λ4861	–8.5
	Hϵ λ3970	–6.9	He I λ4471	–1.7
	Hδ λ4101	–11.3	He I λ4922	–0.9
	Hγ λ4340	–8.2	He I λ5015+Fe II λ5018	–1.7
Jan 22	Hζ λ3889	–4.2	Hβ λ4861 (emission)	1.3
	Hϵ λ3970	–4.7	Hβ λ4861	–5.2
	Hδ λ4101	–8.9	He I λ4471	–1.3
	Hγ λ4340	–7.6	Fe II λ5169 (emission)	0.18

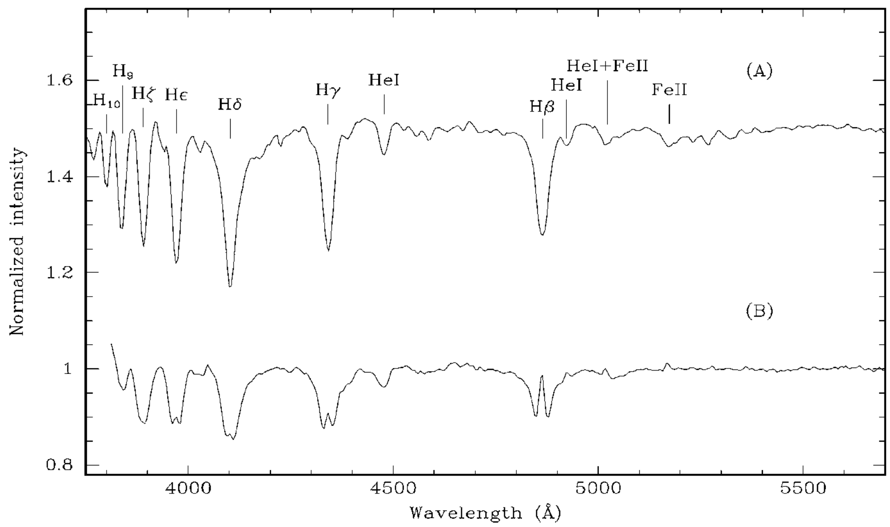

Fig. 2 Normalized average spectra of YZ Cnc during superoutburst. (A): observed on January 21; there was no emission component in *all* spectral lines. (B): observed on January 22; almost all Balmer absorptions were partially filled by emission on this day. The emission component also came out in He I λ5015+Fe II λ5018 absorption. Moreover, Fe II λ5169 has gone into emission. These differences showed that the star is going back to quiescence.

by SH,

$$T_0 = \mathrm{HJD}2,446,113.794 + 0.0868(2)E\,,$$

where T_0 is the time of γ crossover from negative to positive velocities and E is the cycle number. The best-fit sinusoidal shows that Hβ has an amplitude, K, of 49±10 km s^{-1} and a systemic velocity, γ, of 62±7 km s^{-1}. The value of K agrees well with the result of SH, 50±20 km s^{-1} measured during the quiescence. However, the γ velocity is somewhat larger than the value of ~16 km s^{-1} in SH.

It is clearly shown in Figure 3 that there are two abnormal points near phases 0.6 and 1.0 where the velocity is much larger than elsewhere. This possibly occurs at the accretion flow.

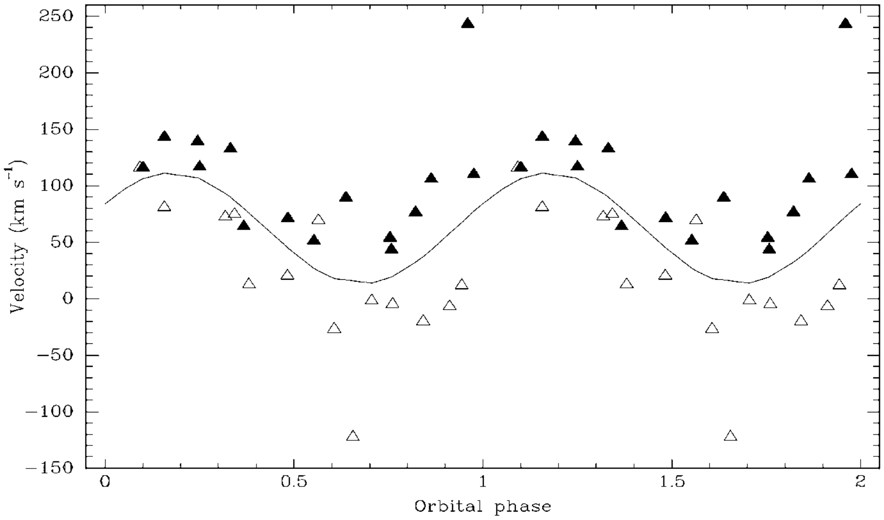

Fig. 3 Least-squares sinusoidal fit to the radial velocities of the centers of Hβ obtained on January 21 and 22, representing with filled and open triangles respectively. Note that almost all velocities are larger on the first night than on the second night. It clearly shows that there are two abnormal points near phases 0.6 and 1.0 where the velocities are much larger than at other points. This possibly occurs at the accretion flow.

3.3 An Eccentric Disk

3.3.1 The variation of γ and orbital-averaged velocity

In Figure 3, we show the radial velocities marked with filled and open triangles, corresponding to January 21 and 22, respectively. It can be seen clearly that there is a systemic discrepancy between the filled and open triangles. We have used the sky emission line 5577 Å to check whether this is due to some systemic error and the difference found between these two days is less than 0.2 Å. So we believe the difference in γ between these two days is real. From fitting sinusoidal to the data shown in Figure 3 (excluding the two abnormal points near phases 0.6 and 1.0, also see Fig. 4) the γ velocities were derived to be 91 km s^{-1} and 34 km s^{-1}, for January 21 and 22, respectively.

We also measured the centers of Hβ of the average spectra of these two days. We found that the relative velocities, averaged throughout the orbital period, are 97 km s^{-1} and 28 km s^{-1}, for January 21 and 22, respectively. This phenomenon was also found in IY UMa (Wu et al. 2001) and KS UMa (Zhao et al. 2005a). These two features of our radial velocities are summarized in Table 3.

3.3.2 The large phase shift of ∼0.09 between two days

As shown in Figure 4, there obviously exists a phase shift of ∼0.09 between the two sinusoidal velocity curves of January 21 and January 22, as shown by continuous and dashed line, respectively. This feature of the radial velocities is discovered for the first time for YZ Cnc, even for SU UMa stars. Such a big phase shift in 1 day could not be due to uncertainties of the orbital period because the error of the orbital period of 2×10^{-4} day given by SH only gives a phase

Table 3 The γ Velocity, K, Phase Offset and Orbital-averaged Velocity

Date (UT) (Year 2002)	γ (km s^{-1})	K (km s^{-1})	Phase offset	$V_{\rm average}$ (km s^{-1})
Jan 21	91±4	46±5	–0.12±0.02	97±12
Jan 22	34±6	49±9	–0.03±0.03	28±10
Shift	57±7	...	0.09±0.04	69±16
Jan 21 & 22	62±7	49±10	–0.07±04	...

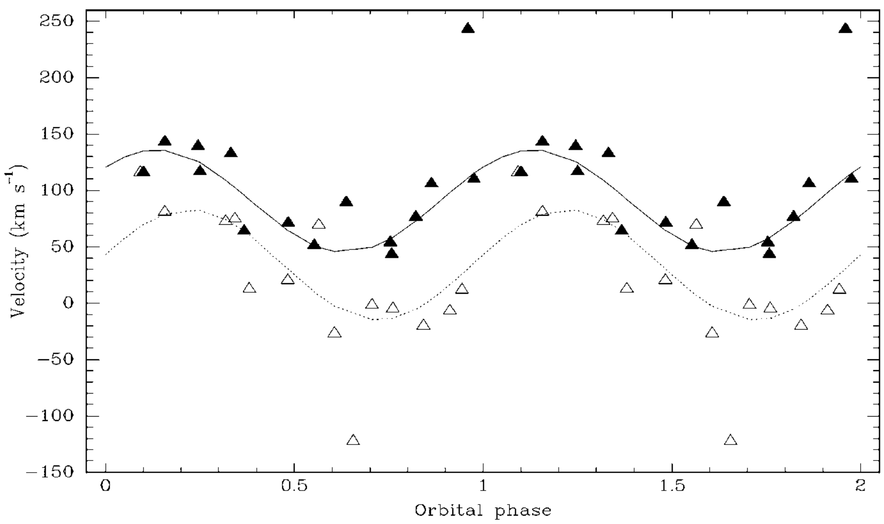

Fig. 4 Phase shifted in two days. The least-squares sinusoidal fits for the radial velocities on January 21 (filled triangles) and 22 (open triangles) are presented in solid line and dashed line, respectively. It is obvious that there exists a shift (∼0.09) in the phase between these two days.

shift of ~ 0.026, which is in agreement with the phase offset on January 22. So there must exist some other reasons for this phenomenon. This feature of phase shift of our radial velocity curve is also listed in Table 3.

3.3.3 An eccentric disk

The phenomena described above can be well explained with a slow precession of an eccentric outer disk. The relative velocity (line-of-sight component) at point $r(\theta)$ on the boundary to the white dwarf is (Wu et al. 2001)

$$V(r,\theta) = C[-e\sin(\theta_0) - \sin(\theta + \theta_0)], \qquad (1)$$

where $C = \sin i\sqrt{\frac{GM_1}{a(1-e^2)}}$ = constant; i, a and e are the inclination, the semi-major axis and eccentricity of the accretion disk, respectively. Hence, the mean velocities of the troughs of the absorption lines or the peaks of the emission lines are $V = -Ce\sin(\theta_0)$. According to this equation, the increase of θ_0 will lead to the result that the central wavelengths of spectral lines, i.e., the orbital-averaged velocity, will vary with the precessing phase of the disk.

Generally, the γ velocity is thought to represent the systemic motion of the binary. This is correct provided that the accretion disk is axis-symmetric. If the material in the ring surrounding the primary is not in circular orbits, i.e., if the accretion disk is eccentric and precessing, and then the white dwarf will be at one of the focus, and the mass center of the system (nearly located at the geometric center) would change with the precession period of the disk. Thus, the systemic velocity, i.e., the γ velocity, may also change with different precession phase of the disk.

The large phase shift of $\sim$0.09 between these two days shows that the variation of the centers of the absorption or emission peaks can not represent the movement of the white dwarf. Moreover, this phenomenon can also be interpreted with a slow precession of an eccentric disk. As described above, the position of the mass center of the system will vary with the precession of the disk. This would lead to the variation of the time (T_0) of the γ crossover from negative to positive velocities, resulting in the phase shift with the disk at different precession phase.

3.3.4 A constraint on the eccentricity

The precessing period ($P_{\rm prec}$) of the disk is the beat period of the orbital period ($P_{\rm orb}$) and the superhump period ($P_{\rm sh}$). It can be written as

$$\frac{1}{P_{\rm prec}} = \frac{1}{P_{\rm orb}} - \frac{1}{P_{\rm sh}}. \tag{2}$$

According to Eq. (2), the precessing period of YZ Cnc is 1.52 d, computed with the $P_{\rm orb} =$ 0.0868 d given by SH and the $P_{\rm sh} = 0.09204$ given by Patterson (1979). Thus, θ_0 will increase 4.12 rad within 1 day. So we have the mean velocities of the absorption troughs to be $-Ce\sin(\theta_0)$ on January 21, and the emission peaks to be $-Ce\sin(\theta_0+4.12)$ on January 22. Comparing their difference with the measured data (the shift of "$V_{\rm average}$" in Table 3), we have

$$Ce\cos(\theta_0 + 2.06) = 60. \tag{3}$$

If we know the value of C, i.e., know M_1, a, q and $P_{\rm orb}$, we can give a constraint on the eccentricity of the disk.

3.4 Mass and Inclination

The masses and inclination of binary stars are very difficult to determine when the system is not an eclipsing system. SH used the properties of the emission lines (especially the linewidth) to provide a relation between the inclination and the white dwarf mass with an empirical assumption that the velocity from the line center at 30% of the emission-line intensity best represents $V_d \sin i$. They showed that the mass of the secondary is $\sim$0.17 $M_\odot$ and that of the primary is 0.75–0.9 $M_\odot$.

Substituting $P_{\rm orb}$ with 0.0868(2) d in equation (1) of Zhao et al. (2005a), we have

$$M_1 = M_2/q,\ \ M_2 = [0.829(1+1/q)^{1/3}Q(q)]^{15/7}. \tag{4}$$

We can obtain the mass ratio by using an empirical relation found by Patterson (2001), $\epsilon =$ $0.216(\pm 0.018)q$, where $\epsilon = (P_{\rm sh} - P_{\rm orb})/P_{\rm orb}$. It gives $q = 0.28 \pm 0.03$, which is somewhat larger than that given by SH.

According to Eq. (4), it only requires $q > 0.09$ to meet the condition that the white dwarf mass should be less than 1.44 $M_\odot$. The mass ratio of 0.28$\pm$0.03 derived above is consistent with this requirement. Therefore we can obtain that $M_2 = 0.13 \pm 0.01\ M_\odot$ and $M_1 = 0.46 \pm 0.06 M_\odot$. Using the $K_1 = 49 \pm 10$ km s$^-1$ (see Sect. 3.2), the mass function $f(M) = (M_2 \sin i)^3/(M_1 + M_2)^2] = K_1^3 P_{\rm orb}/(2\pi G) = 0.00106(10)\ M_\odot$ gives $i = 34^\circ \pm 9^\circ$.

The values of M_1 and M_2 are smaller than those given by SH. This is believed to be due to systemic differences between different methods and to some unproved empirical assumptions. Hence, the masses and inclination given here are rather uncertain.

4 DISCUSSION

Variation in the γ velocity is discovered for the first time in YZ Cnc. It has been discovered before in several other SU UMa stars, i.e., Z Cha (Vogt 1982; Honey et al. 1988), KS UMa (Zhao et al. 2005a) and ER UMa (Zhao et al. 2005b). As stated by these different groups, the RV curves for these stars were *all* gotten from spectra obtained when the stars went through *eruptions*.

Vogt (1982) and Honey et al. (1988) have found that the γ velocities of Z Cha varied during its superoutburst. Vogt (1982) proposed a model that includes a precessing, elliptical ring surrounding a circular accretion disk. This gives the variation of the γ velocity on a night-to-night basis as a result of variations in the projected motion of the ring material against that of the inner (circular) disk. Honey et al. (1988) interpreted their observational result with new non-axisymmetric disk simulations as arising in an eccentric, precessing disk which is tidally distorted by the secondary.

Our results that the γ velocity varies with time and that there is a phase shift between the different days are based on the measurements of the centers of the absorption troughs of Hβ and the centers of the peaks of the emission cores. We had to do this. We cannot use the double-Gaussian convolution method (Shafter et al. 1988) to measure the RV because the wings of Hβ are blended with He I λ4922 and the other Balmer lines not only are contaminated but also have bad signal-to-noise ratios, especially on January 22. Despite this, our observational result confirms that the γ velocity does actually vary when the star was undergoing a superoutburst.

We found for the first time that the phase of the system changes. If we believe that the orbital period and the error given by SH are reliable, then the phase shift between these 2 days is real. It is not surprising that this phenomenon can be found in YZ Cnc between 2 days because the precession period of YZ Cnc is only 1.52 days. The phase shift is enough to be observed between 2 days. So our observation provides more evidence to convince us that an eccentric accretion disk is precessing when the binary system is undergoing a superoutburst. If the system has a larger inclination, we could obtain more information and do more detailed analysis as in the case of IY UMa (Wu et al. 2001) and KS UMa (Zhao et al. 2005a).

We can also estimate the eccentricity crudely by substituting the mass of the white dwarf M_1, the mass ratio q and the inclination i, with the values given above (see Sect. 3.4). We obtain

$$\cos(\theta_0 + 2.06) = 0.231/e.$$

If we use the values given by SH, we would obtain

$$\cos(\theta_0 + 2.06) = 0.184/e.$$

So e must be larger than 0.184 or 0.231, according to which set of parameters are more reliable.

5 CONCLUSIONS

We have shown the properties of our spectra and radial velocities of YZ Cnc obtained during its 2002 January superoutburst. The properties are

(1) The γ velocity (62 ± 7 km s^{-1}) obtained in these two days deviated strongly from the systemic velocity (16 ± 10 km s^{-1}) measured by SH when the binary system was in quiescence. Moreover, there is a discrepancy of $\sim$60 km s^{-1} in the γ velocities on these two days.

(2) The mean velocities averaged over the orbital period of these two days have a large difference of the order of ±70 km s^{-1}.
(3) There is large phase offset of $\sim$0.09 between these two days.

As described in detail in Sect. 3.3, we can conclude that these features can all be ascribed to the precession of an eccentric accretion disk. Therefore, we can make use of these properties to confirm whether or not the accretion disk is eccentric.

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