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DETECTION OF A DEGENERATE COMPANION OF THE SX PHOENICIS STAR KZ HYDRAE BY STUDYING ITS LONG-TERM VARIABILITY

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ABSTRACT

We present 109 new times of maximum light of the SX Phoenicis (SX Phe) star KZ Hydrae (KZ Hya) based mainly on our extensive photometric observations for two decades, leading to determination of a general ephemeris combined with the data in the literature. The $O - C$ diagram reveals a continuously increasing period change combined with the light traveling time effect of the orbital motion of KZ Hya in a binary system with an orbital period of 26.8 ± 0.2 years. The deduced mass of the companion cannot be smaller than 0.83 $M_{\odot}$. Since no sign of the companion has ever been observed spectroscopically and the observed color index $b - y$ excludes the possibility of the companion being a late-type main-sequence or dwarf star, KZ Hya becomes the first SX Phe star for which a degenerate companion is detected. The pulsation properties are studied by analyzing the Fourier spectra of the observed light curves while the fundamental parameters are deduced with the simultaneous multicolor $uvby\beta$ data, showing this star to be a strong low-metallicity high-amplitude SX Phe-type variable pulsating in the fundamental radial mode. No signs of multiperiodicity or significant long-term changes in amplitude are detected in the pulsation of this variable.

Key words: stars: individual (KZ Hya) – stars: variables: other – techniques: photometric

Online-only material: machine-readable table

1. INTRODUCTION

KZ Hydrae (KZ Hya) = HD 94033 = SAO 179271 ($V = 9\overset{m}{.}498 - 10\overset{m}{.}243$) is one of the 13 known field SX Phoenicis (SX Phe) stars (see Table 9 of Rodríguez & Breger 2001). Since the discovery of its light variation in a photometric survey of early-type stars with high proper motion in 1975 (Przybylski & Bessell 1979), KZ Hya has been observed and studied extensively.

Due to its high velocity and deficiency in metals, KZ Hya becomes one of a few known SX Phe stars which clearly belong to Population II. Twenty-five maxima of the star were observed in subsequent observations (Przybylski & Bessell 1979). Yang et al. (1985) provided 16 times of maximum light from photoelectric photometry, suggesting periodic variation of the $O - C$ values with a period of approximately nine years. Hence, a binary hypothesis was proposed for KZ Hya. McNamara & Budge (1985) made photometric and spectrographic observations of KZ Hya. Their data show that KZ Hya has unusually large light amplitude and radial-velocity amplitude. Four times of maximum light were determined while two of them were revised by Jiang (1986), who also reported five new times. A binary solution was formulated, and the period variation was measured as $(1.55 \pm 0.61) \times 10^{-12}$ day c^{-1}, which translates to the value of $(1.60 \pm 0.63) \times 10^{-7}\mathrm{yr}^{-1}$. Hobart et al. (1985) reported 38 new times of maximum light based on their photoelectric photometry of KZ Hya and provided a new ephemeris formula. Liu et al. (1991) contributed two new times of light maxima with a re-determination of the binary solution. The observations of Doncel et al. (2004) covered 12 maximum phases of KZ Hya. However, this work had a significant error in the computation of Julian Dates which took UT = 0^{h} as the reference time of the Julian Date calculation instead of UT = 12^{h}. Table 2 of the paper lists 102 maximum times and the corresponding cycle numbers, while the calculated $O - C$ points show a very "strange" distribution on its Figure 6. Doncel et al. (2004) stated on the observed light curves: "There is a secondary maximum at phase 0.7. Therefore, KZ Hya is probably a multi-component star." Bonnardeau (2005) observed three pulses of the star in order to determine three new maximum times. Bonnardeau (2006, 2007) carried out new observations to get eight and six times of maximum light, respectively. Watanabe (1998) and Napoleão (2003) published on the Web one night of light curves of KZ Hya observed in 1998 and 2003, respectively. However, the study of KZ Hya over the 31 years since its light-variation discovery does not provide a generally-accepted ephemeris and a convincing interpretation of its long-term period change based on the $O - C$ diagram. Very recently, Kim et al. (2007) presented some new observations for KZ Hya, showing a quasi-sinusoidal character of the $O - C$ diagram which was interpreted as a light traveling time effect due to a companion. Nine harmonic frequencies were also resolved using the Fourier decomposition method.

KZ Hya has been one of the key targets in our efforts to study the SX Phe stars; hence, extensive observations have been made from 1988 to 2007 at different sites. The present paper describes our observations in Section 2, showing the multiple frequency analysis in Section 3. In Section 4, the newly-determined times of maximum light are tabulated together with all those in the literature and the $O - C$ values are calculated; hence, the period change is analyzed. Section 5 presents a discussion on the pulsation, the $O - C$ diagram analysis, and the physical parameters derived for KZ Hya. Finally, Section 6 summarizes the conclusions of our study.

Table 1
Journal of Observations

Date	Observatory	Telescope (cm)	Detector	Filter	Nights	Hours
1988 Nov	LS	50	smt	*uvbyβ*	5	6.4
1994 Feb	XL	60	pmt	*V*	3	9.8
1998 Nov	SNO	90	smt	*uvby*	2	2.2
1999 Jan	SNO	90	smt	*uvby*	2	3.4
Apr	XL	85	CCD	*V*	2	6.5
2000 Mar	XL	85	CCD	*V*	4	9.1
2001 Jan	SNO	90	smt	*uvby*	1	2.2
2003 Feb	SNO	90	smt	*uvby*	2	2.4
2005 Feb	SNO	90	smt	*uvby*	2	5.5
	NRS	40	CCD	*W*	3	7.4
2006 Feb–Apr	NRS	40	CCD	*W*	14	32.5
Mar	YNO	100	CCD	*VRW*	5	27.1
2007 Jan–Mar	NRS	40	CCD	*W*	9	24.6

Notes.
Observatory symbols: LS—ESO La Silla (Chile), XL—Xinglong station (China), SNO—Sierra Nevada Observatory (Spain), NRS—Naresuan University (Thailand), YNO—Yunnan Observatory (China). Detector symbols: smt—spectrophotometer, pmt—photoelectric photometer. Filter symbols: V, R—Johnson V, R, $uvby\beta$—Strömgren $uvby\beta$, W—white light.

2. OBSERVATIONS

Table 1 lists the journal of our new observations for KZ Hya from 1988 to 2007. In total, more than 135 h of data were collected on 54 nights at five observatories with either photometers or CCD cameras. Figure 1 shows an image of KZ Hya taken with the 100 cm telescope at Yunnan Observatory, on which the variable, the comparison (HD 93998 = SAO 179270, $\alpha = 10^{\mathrm{h}}50^{\mathrm{m}}42.94^{\mathrm{s}}$, $\delta = -25°21'26.2''$, 2000.0, $V = 10\overset{\mathrm{m}}{.}219$) and the check star (USNO-A2.0 0600-13691180, $\alpha = 10^{\mathrm{h}}50^{\mathrm{m}}51.59^{\mathrm{s}}$, $\delta = -25°16'35.4''$, 2000.0, $V = 13\overset{\mathrm{m}}{.}562$) are marked, for the observations in Johnson V, R filters or in white light (W). For the multicolor $uvby\beta$ observations, the star HD 93474 ($V = 8\overset{\mathrm{m}}{.}13$, A8V) was used as a comparison C1 with HD 94312 ($V = 8\overset{\mathrm{m}}{.}56$, A2V) as a check star C2. Using the observations reported here, neither of the comparison and check stars showed any sign of variability within our observational uncertainties.

To transform the $uvby\beta$ data obtained at ESO La Silla Observatory into the standard system, a set of 32 standard stars was carefully selected from different lists (mainly from Grønbech & Olsen 1976, 1977). The typical deviations obtained in the transformation equations were $0\overset{\mathrm{m}}{.}007$, $0\overset{\mathrm{m}}{.}006$, $0\overset{\mathrm{m}}{.}007$, $0\overset{\mathrm{m}}{.}007$, and $0\overset{\mathrm{m}}{.}004$ for V, $b-y$, m_1, c_1, and β, respectively. The resulting photometric indices and error bars are listed in Table 2. As seen, they are in very good agreement with those available in the literature. Using the derived transformation equations, our instrumental $uvby\beta$ magnitude differences relative to C1 were transformed into the standard system. A similar procedure was applied to the $uvby\beta$ data collected at SNO leading to similar results.

The collected raw data in Johnson V, R filters or in white light were reduced by the standard procedure, then the magnitude values of the variable, the comparison, and the check star were extracted. Figure 2 shows the reduced light curves in (a) R taken with the 100 cm telescope at Yunnan Observatory (China) in 2006, and (b) W collected with the 40 cm telescope at Naresuan University (Thailand) in 2006 and 2007, as open circles.

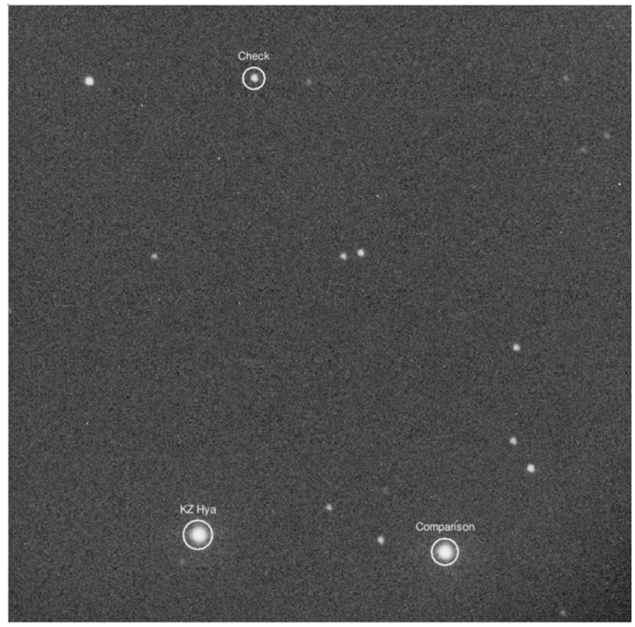

Figure 1. A CCD image ($6.5' \times 6.5'$) of KZ Hya ($\alpha = 10^{\mathrm{h}}50^{\mathrm{m}}54.08^{\mathrm{s}}$, $\delta = -25°21'14.7''$, 2000.0) taken in Johnson R filter with a 100 cm telescope at Yunnan Observatory. North is up and east is to the left. KZ Hya, the comparison and the check star are marked.

Table 2
$uvby\beta$ Indices Obtained for KZ Hya and Comparison Stars, together with the Corresponding Error Bars

Object	V (mag)	$b-y$ (mag)	m_1 (mag)	c_1 (mag)	β (mag)	S
KZ Hya	10.007	0.218	0.098	0.764	2.758	1
(455, 90)	58	12	4	31	14	
C1 = HD 93474	8.112	0.249	0.120	0.672	...	1
(157, -)	6	5	6	9		
C2 = HD 94312	8.569	0.090	0.170	1.016	...	1
(157, -)	10	5	7	9		
C1 = HD 93474	8.115	0.239	0.125	0.680	...	2
	8.128	0.247	0.127	0.684	...	3
C2 = HD 94312	8.568	0.084	0.173	1.020	...	3

Notes.
$uvby\beta$ indices are calculated as standard deviations, σ, for the comparison stars. The values listed for the variable are "mean values" based on the normal points over the pulsation cycle (Table 4) and the error bars are calculated as standard errors, $\sigma/(n-1)^{1/2}$, over the pulsation cycle. The pairs below the star names are the number of points collected for each object in $uvby$ and β. For comparison, the values available in the bibliography are listed in the lower part. Source (S): (1) this work, (2) Olsen (1983), (3) Hauck & Mermilliod (1998).

3. PULSATION ANALYSIS

3.1. Data in R and in White Light

Since most observations listed in Table 1 were made at the phases of the variable star around the times of maximum light, while the light curves in R collected at Yunnan Observatory in 2006 covered the complete phases with relatively high precision (typically 0.007 mag), the latter data are analyzed with the software PERIOD04 (Lenz & Breger 2005), which calculates the amplitude spectra of Fourier transformation to search for significant frequency peaks and fits the observed light curves

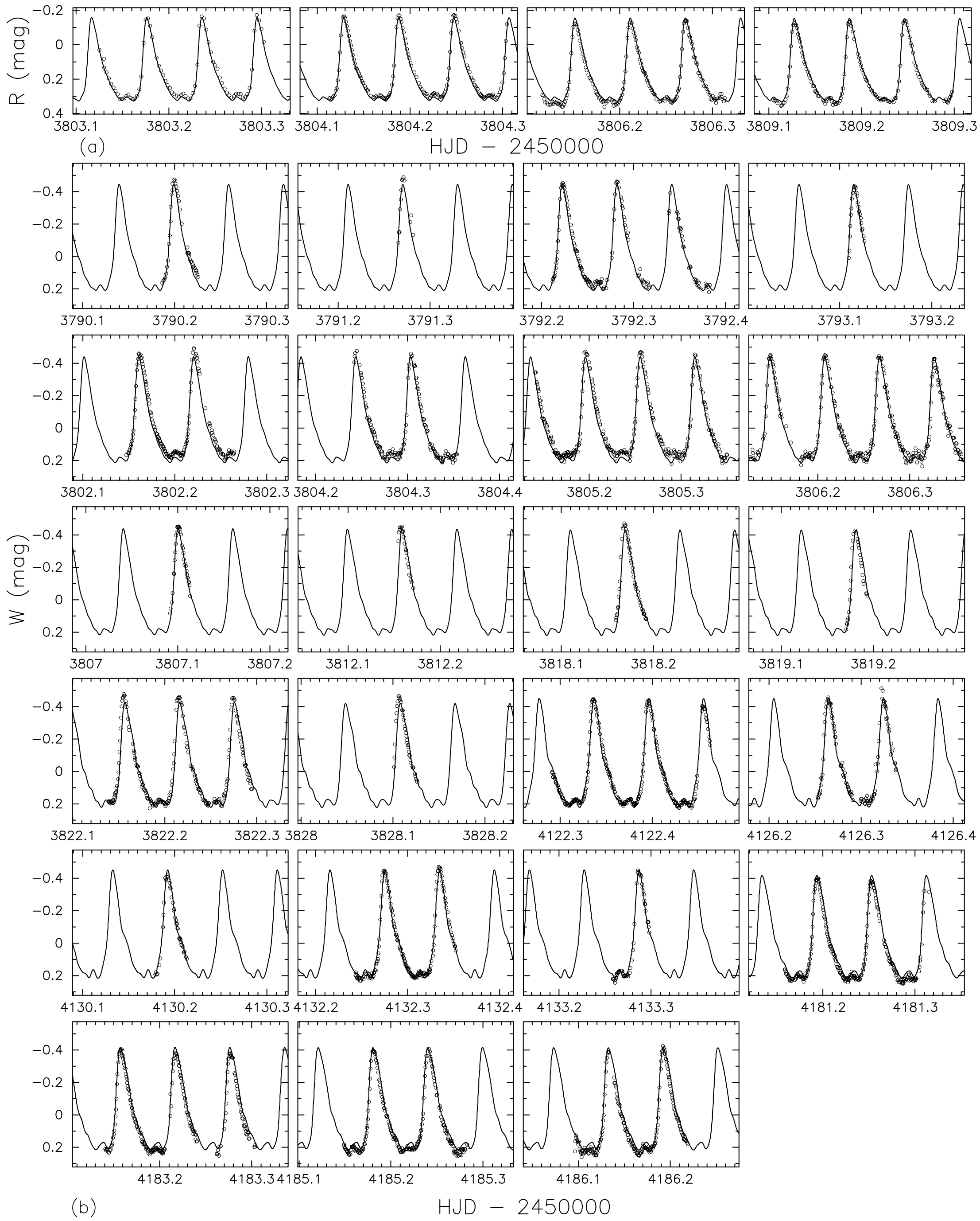

Figure 2. Light curves of KZ Hya in (a) R in 2006 and (b) W in 2006 and 2007 plotted as open circles. The solid curves show the fitting with the nine frequencies in R and W listed in Table 3.

with the formula,

$$m = m_0 + \sum_i A_i \sin(2\pi(f_i t + \phi_i)).$$

Table 3 lists the solution of nine frequencies, whose signal-to-noise ratios (S/Ns) are higher than 4.0 (as listed in the fourth column of Table 3, following the criterion of Breger et al. 1993 and Kuschnig et al. 1997). The top panel of Figure 3 shows the amplitude spectra of the Yunnan data in R. Figure 2(a) shows the fitting curves with the nine-frequency solution in R listed in Table 3 by solid curves. Figure 4 shows the amplitude spectra of the frequency pre-whitening process of the R data analysis. Since the low-frequency domain (0–10 c day^{-1}) of the amplitude spectra is heavily affected by the noise of sky transparency change and the instrument sensitivity instability, the peaks located in this domain are not taken into account in the analysis.

The amplitude spectra of the data collected at Naresuan University in W in 2006 and 2007 are shown in the bottom panel of Figure 3. As one may see from Figures 2 and 3, these

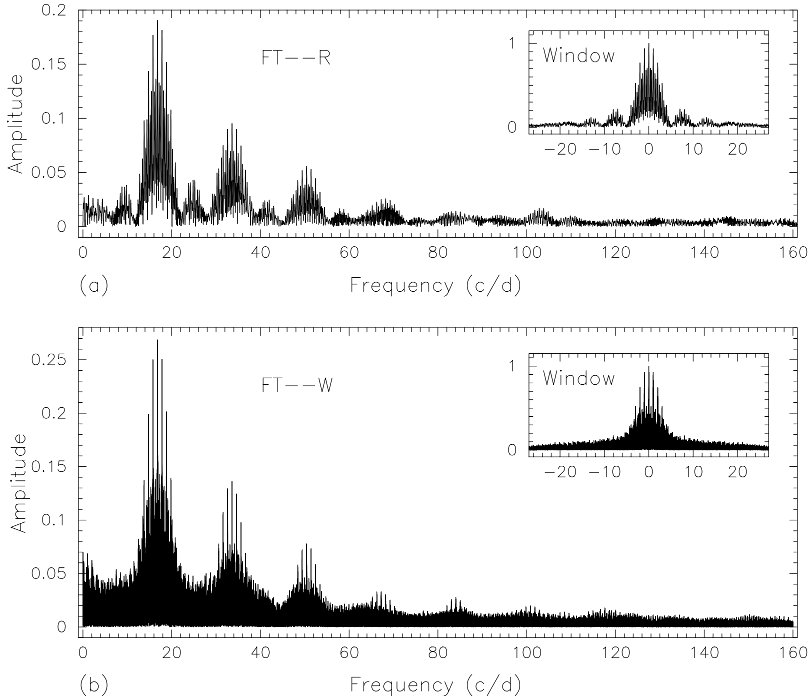

Figure 3. Fourier amplitude spectra of the (a) Yunnan data in R in 2006, and (b) Naresuan data in W in 2006 and 2007. The corresponding window functions are shown in the insets.

Table 3
Multi-Frequency Solution of the Light Curves in R in 2006 and in W in 2006 and 2007 for KZ Hya

	R			W	
	Frequency	Amplitude	S/N	Frequency	Amplitude
f_0	16.8023	0.192	143.9	16.8033	0.260
$2f_0$	33.6066	0.085	76.0	33.6066	0.112
$3f_0$	50.4100	0.052	35.4	50.4099	0.068
$4f_0$	67.2154	0.023	26.4	67.2160	0.029
$5f_0$	84.0212	0.014	22.7	84.0220	0.014
$6f_0$	100.8230	0.012	24.8	100.8227	0.014
$7f_0$	117.6222	0.006	11.0	117.6231	0.008
$8f_0$	134.4163	0.004	10.9	134.4138	0.004
$9f_0$	151.2348	0.004	9.3	151.2353	0.005

Notes. The frequency is in day^{-1}. The amplitude is in mag.

data show a relatively higher noise level than the R data in 2006. Hence, instead of independent multi-frequency analysis, fitting of the W data with the nine frequencies resolved from the R data in 2006 was made. The result is listed in Table 3. The solid curves in Figure 2(b) show the fitting of W in 2006 and 2007.

As seen from Figure 2, the constructed curves fit the observed light curves very well, including the phases around the secondary maxima. This shows that the primary frequency, f_0, and its eight harmonics, can explain the pulsation behavior of KZ Hya without invoking the existence of other companion, as stated by Doncel et al. (2004). Table 3 shows that KZ Hya is a one-mode SX Phe star.

3.2. *The uvby Data*

Table 4 lists the results of the Fourier decomposition applied to the *uvby* data together with the $b - y$ and c_1 indices. Eleven terms are significant. On the other hand, Table 4 shows that the light maximum in the V band occurs slightly later than both maxima in v, b, and $b - y$. For the first harmonic, we obtain ϕ_v–ϕ_V = 0°.5 (±0.5), ϕ_b–ϕ_V = 0°.3 (±0.5), and ϕ_{b-y}–ϕ_V = 2°.2 (±0.7). Similar results can be found if only the 1988 data set is considered (see Garrido et al. 1990). This is an indication of radial pulsation, common among the monoperiodic high-amplitude pulsators in the lower instability strip (see Rodríguez et al. 1995).

4. TIMES OF MAXIMUM LIGHT AND $O - C$ ANALYSIS

4.1. *New Times of Maximum Light*

All the new observations from 1988 to 2007 are used to determine the maximum times of KZ Hya, with a typical uncertainty of 0$^{\rm d}$.0003. Table 5 lists the newly-determined 101 times of maximum light.

In addition, heliocentric correction was made for the online-published light curves of Watanabe (1998) and Napoleão (2003); hence, two and six times of maximum light were determined respectively, as listed in Table 6.

4.2. *$O - C$ Diagram*

Combining the 109 newly-determined times of maximum light of KZ Hya (Tables 5 and 6) with those listed in the literature (Doncel et al. 2004; Bonnardeau 2005, 2006, 2007; Kim et al. 2007), 271 maximum times are tabulated in the second column of Table 7. The corresponding cycle numbers of all the 271 times of maximum light are checked or re-calculated and then listed in the third column of Table 7. The weights, as listed in the sixth column of Table 7, are assigned mainly according to the quality of the data.

The straight-line fit to the 271 times of maximum light with the weight taken into account yields the ephemeris formula

$$C = \text{HJD } 2442516.1833 + 0.059510413 \times E \qquad (1)$$

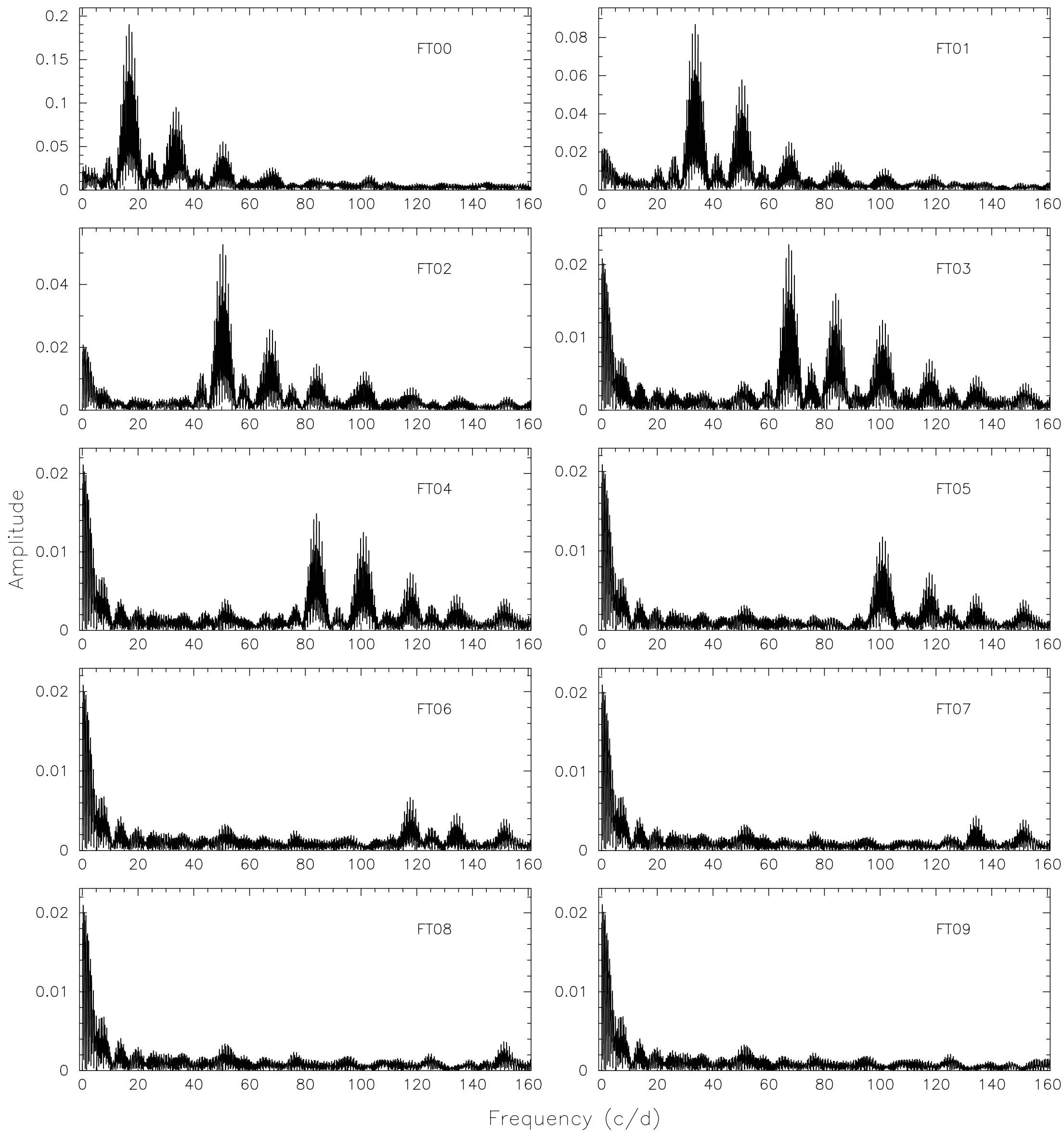

Figure 4. Fourier amplitude spectra of the Yunnan data in R with the frequency pre-whitening process shown.

where the uncertainties of the fit to T_0 and P are 0.0021 day and 0.000000014 day, respectively.

The $O - C$ values were obtained and listed in the fourth column of Table 7. The $O - C$ diagram is shown in Figure 5.

As can be seen from Figure 5, the $O - C$ diagram shows very strong and clear cyclic variation. Hence, we fit the 271 times of maximum light with a quadratic plus a sine function of the form

$$C = \text{HJD}_0 + P \times E + \frac{1}{2}\beta E^2 + A \sin\phi + B \cos\phi, \quad (2)$$

where ϕ is the solution of Kepler's equation

$$\phi - e \sin\phi = \frac{2\pi}{P_{\text{orb}}}(P \times E - t_0). \quad (3)$$

Equation (2) is equivalent to Equation (2) of Irwin (1952) and Equation (1) of Ribas et al. (2002) and describes the light traveling time effect (where P_{orb} is the orbital period; P the pulsation period of the variable star; t_0 the time of periastron passage; β the coefficient of the quadratic term related to period change). The solid curves in Figure 5 show the fitting. The fitting parameters are semi-amplitude = 2505 ± 51 s, P = 0.059510033 ± 0.000000044 day, $\beta = (0.17 \pm 0.02) \times 10^{-11}$ day. This translates to $dP/P\,dt = (1.7 \pm 0.2) \times 10^{-7}$ yr^{-1}, $e = 0.25 \pm 0.01$, $P_{\text{orb}} = 26.8 \pm 0.2$ yr. The periastron time is HJD 2444891 ± 27. The residuals of the fitting are shown in Figure 6 as open circles.

5. DISCUSSION

5.1. *The Pulsation*

KZ Hya shows one of the most extreme cases of nonsinusoidal light curves among the high-amplitude pulsators in the lower instability strip, including both the δ Sct and SX Phe pulsators (Rodríguez 2003). As can be seen from Figure 2, the increasing branch covers only about the 20% of the full cycle. Moreover, a hump is clearly visible during the phases of minimum light.

Table 4
Results from the Fourier Fitting Applied to the *uvby* Data

Frequency (c day^{-1})	A_u (mmag)	φ_u (rad)	A_v (mmag)	φ_v (rad)	A_b (mmag)	φ_b (rad)	A_y (mmag)	φ_y (rad)	A_{b-y} (mmag)	φ_{b-y} (rad)	A_{c_1} (mmag)	φ_{c_1} (rad)
	±2.0		±1.8		±1.6		±1.4		±0.7		±1.8	
f_0	328.6	4.449	446.5	4.324	397.8	4.322	326.3	4.316	71.6	4.353	173.9	0.946
		6		4		4		4		9		10
$2f_0$	142.2	4.474	186.0	4.302	163.9	4.308	137.2	4.304	26.7	4.328	72.5	0.806
		14		10		10		10		25		25
$3f_0$	91.9	4.762	110.5	4.657	98.5	4.672	83.4	4.678	15.0	4.641	33.1	1.176
		22		16		17		17		44		55
$4f_0$	42.9	5.133	49.6	5.047	42.8	5.089	36.2	5.075	6.7	5.163	14.8	1.525
		48		37		38		39		98		124
$5f_0$	25.6	5.254	27.9	5.331	24.9	5.360	22.1	5.285	3.3	5.880	5.6	2.406
		80		65		65		64		197		322
$6f_0$	20.0	5.719	23.7	5.896	21.0	5.929	17.8	5.872	3.4	6.230	7.2	3.156
		102		76		77		80		192		254
$7f_0$	8.2	6.089	15.8	6.193	13.4	6.252	11.5	6.219	2.0	0.161	10.0	3.058
		242		111		117		120		326		177
$8f_0$	7.3	5.846	9.5	0.401	7.3	0.447	7.0	0.518	...	...	8.4	4.196
		278		191		221		202				215
$9f_0$	5.9	1.091	6.4	0.988	6.3	1.022	4.7	0.844	1.9	1.491		
		345		281		258		301		355		
$10f_0$			5.8	1.410	4.6	1.362	4.1	1.437				
				310		349		343				
$11f_0$			5.1	2.069	4.6	2.085	3.8	1.953				
				346		357		359				
Mean value	1.8507		1.8117		1.8646		1.8957		−0.0310		0.0921	
(mag)	14		13		11		10		5		13	
Residuals	29.1		25.6		22.9		20.1		9.3		26.0	
(mamag)												
T_{or}(Phase)	0.0											

Table 5
Times of Maximum Light of KZ Hya Determined from Our Observations

T_{max}	Filter	T_{max}	Filter	T_{max}	Filter	T_{max}	Filter	T_{max}	Filter
47468.8352	*y*	51625.1831	*V*	53790.3781	*W*	53806.2711	*V*	54122.3956	*W*
47470.8573	*y*	51627.1472	*V*	53791.2111	*W*	53807.1005	*W*	54122.4551	*W*
47472.8226	*y*	51627.2063	*V*	53791.2712	*W*	53807.1601	*W*	54126.2640	*W*
47473.8342	*y*	51628.1591	*V*	53792.2233	*W*	53807.2197	*W*	54126.3232	*W*
49399.2699	*V*	51628.2186	*V*	53792.2825	*W*	53809.1276	*V*	54130.1916	*W*
49400.2222	*V*	51635.1806	*V*	53793.1162	*W*	53809.1870	*V*	54132.2748	*W*
49400.2823	*V*	51930.5908	*y*	53802.1615	*W*	53809.2472	*V*	54132.3340	*W*
49400.3413	*V*	51930.6514	*y*	53802.2207	*W*	53812.1571	*W*	54133.2866	*W*
49401.2339	*V*	52671.6226	*y*	53803.1763	*V*	53812.2170	*W*	54181.1938	*W*
49401.2939	*V*	52672.5747	*y*	53803.2362	*V*	53812.2761	*W*	54181.2529	*W*
51139.6978	*y*	53409.2625	*W*	53803.2952	*V*	53818.1690	*W*	54183.1577	*W*
51140.7095	*y*	53409.3218	*W*	53804.1289	*V*	53818.2276	*W*	54183.2173	*W*
51204.5640	*y*	53411.2866	*W*	53804.1883	*V*	53818.2872	*W*	54183.2769	*W*
51204.6226	*y*	53411.3466	*W*	53804.2476	*V*	53819.1798	*W*	54185.1807	*W*
51205.5759	*y*	53412.2966	*W*	53804.3044	*W*	53822.1553	*W*	54185.2407	*W*
51274.0709	*V*	53412.3564	*W*	53805.1407	*V*	53822.2151	*W*	54186.1333	*W*
51274.1309	*V*	53420.5161	*y*	53805.1996	*V*	53822.2750	*W*	54186.1924	*W*
51274.1896	*V*	53420.5757	*y*	53805.2591	*V*	53828.1066	*W*		
51275.0834	*V*	53421.5278	*y*	53805.3159	*W*	53828.1665	*W*		
51275.1415	*V*	53421.5869	*y*	53806.1520	*V*	53828.2258	*W*		
51625.1236	*V*	53790.2003	*W*	53806.2117	*V*	54122.3358	*W*		

Note. T_{max} is in HJD-2400000 (filter symbols as in Table 1).

The pulsation analysis of the data in R, white light, and *uvby* presents up to 11 significant frequencies, as listed in Tables 3 and 4. One notes that the resolved terms are composed of the primary frequency and its harmonics, which explain the observed light curves very well, as shown in Figure 2, including the part of the earlier-noticed secondary maximum at the phase 0.7. Hence, the existence of the secondary maximum of the light curves cannot be seen as the signature of possible companions

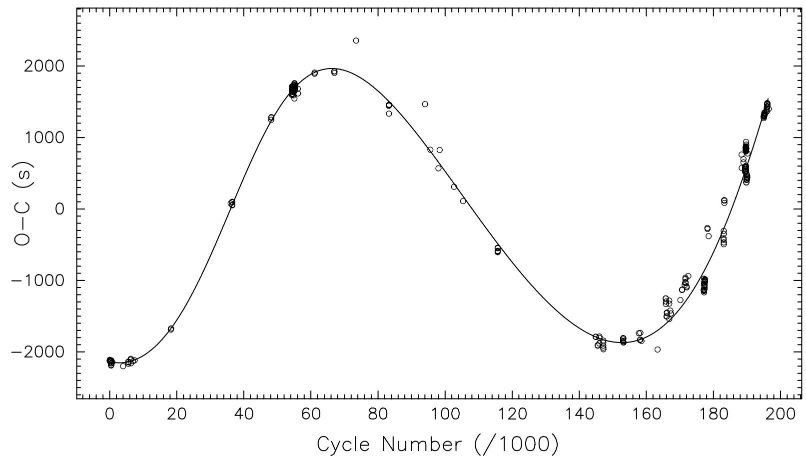

Figure 5. $O - C$ diagram for KZ Hya using the ephemeris of Equation (1). The solid curves show the fit concerning a continuously increasing period change and the light traveling time effect of a binary system.

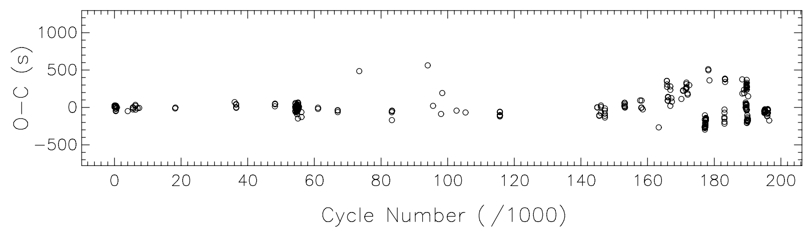

Figure 6. Residual $O - C$ diagram for KZ Hya concerning a continuously increasing period change and the light traveling time effect caused by a binary system.

Table 6
Times of Maximum Light of KZ Hya Determined from Watanabe (1998) and Napoleão (2003)

T_{max}	S	T_{max}	S
51175.2836	1	52732.6815	2
51175.3432	1	52732.7409	2
52732.5632	2	52732.8005	2
52732.6225	2	52732.8599	2

Notes. T_{max} is in HJD-2400000. Source (S) symbols: 1—Watanabe (1998), 2—Napoleão (2003).

Table 7
Times of Maximum Light, $O - C$ and Residuals for KZ Hya

No.	T_{max}	E	$O - C$	Res	WT	S
1	42516.1585	0	−0.02484	0.00011	1.0	1
2	42517.9440	30	−0.02465	0.00030	1.0	1
3	42518.0034	31	−0.02476	0.00019	1.0	1
4	42518.1223	33	−0.02488	0.00007	1.0	1
5	42541.9266	433	−0.02475	0.00025	1.0	1

Notes.
T_{max} is in HJD-2400000. E: cycle number. $O - C$ is in day. Res: fit residual concerning a binary system. WT: weight. S: source (1: Doncel et al. (2004); 2: Bonnardeau (2005); 3: Bonnardeau (2006); 4: Bonnardeau (2007); 5/6: Table 5/6 of the present paper; 7: Kim et al. (2007)). Note no. 96: T_{max} following Liu et al. (1991), incorrect in Table II of Doncel et al. (2004). Note no. 131–134 and no. 136–143: T_{max} subtracted 0.5 days from the values listed in Table II of Doncel et al. (2004).
(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content)

of KZ Hya, as stated by Doncel et al. (2004). By looking at Tables 3 and 4 as well as Figures 2 and 3, one finds that the pulsation amplitudes in R, W, and u, v, b, y are different from each other, which is common among pulsating variable stars.

In order to obtain some insights about possible changes in the pulsation amplitude of KZ Hya with long-term timescale, the data sets corresponding to different years were analyzed separately following the method described in Rodríguez (1999). The results are listed in Table 8. The data sets corresponding to the years 2001 and 2003 are too small and unreliable for this analysis. The amplitudes listed in this table are "semi-amplitudes" of the full light curves. To transform v and b amplitudes to $y = V$ amplitudes, we considered the transformation factors derived from Table 4. As result, we do not find significant changes in the luminosity amplitude of KZ Hya in different years. From our analysis, a mean value of $\Delta V = 0\overset{m}{.}4073$ (±0.0048) is obtained for the full V light curve.

5.2. *The $O - C$ Diagram and the Companions*

Equation (1) gives an up-to-date value of the pulsation period of KZ Hya. Figure 5 shows very clear cyclic variation of the $O - C$ data points, leading to the solution concerning the quadratic function plus light traveling time effect of a binary system. The quadratic term leads to a rate of period change of $(1.7 \pm 0.2) \times 10^{-7}$ yr^{-1}, which is consistent with the evolutionary change calculated for early post-main-sequence (PMS) models in both the positive direction and the ratio value of period change (e.g., Breger 2000 predicts a positive sign and a value of 10^{-7} yr^{-1} for the δ Scuti variables of PMS stars). However, we note that Breger (2000) uses only evolutionary tracks with solar abundances while, as indicated in Section 5.3, KZ Hya is a strongly metal-deficient SX Phe star.

Figure 5 shows a convincing solution of the $O - C$ diagram concerning the light traveling time effect of KZ Hya in a binary system. Some parameters of the binary system are estimated. The projection of the orbit radius is estimated as

Table 8
Amplitudes, as Determined by Means of the Fourier Analysis (i.e. Semi-amplitudes), of the Full Light Curves Corresponding to Different Data Sets

Year	Filter	N	Ampl (mag)	σ (mag)	ΔV Equiv Ampl (mag)	$\langle \Delta V \rangle$ (mag)
1988	v	117	0.5478	0.0151	0.4032	0.4020
			31		56	50
	b	117	0.4886	0.0150	0.4046	
			30		69	
	y	117	0.3981	0.0124	0.3981	
			25		25	
1998	v	55	0.5625	0.0101	0.4140	0.4116
			26		53	47
	b	55	0.4949	0.0086	0.4098	
			21		62	
	y	55	0.4110	0.0076	0.4110	
			26		26	
1999	v	76	0.5562	0.0141	0.4094	0.4085
			32		57	52
	b	76	0.4935	0.0135	0.4086	
			30		69	
	y	76	0.4076	0.0128	0.4076	
			31		31	
2005	v	122	0.5539	0.0108	0.4077	0.4072
			19		47	41
	b	122	0.4910	0.0101	0.4065	
			18		59	
	y	122	0.4073	0.0096	0.4073	
			18		18	

Notes.
The last column lists the annual mean amplitudes together with the corresponding standard errors. N is the number of points, σ is the standard deviation of the residuals. The ΔV equivalent amplitudes are calculated using the transformation factors derived from Table 4.

Table 9
Orbital Semi-Major Axes of KZ Hya and the Companion (a_1 and a_2) and Mass of the Companion (m_2) Calculated at Different Inclinations (i) Based on the Orbital Solution

i (deg)	a_1 (AU)	a_2 (AU)	m_2 ($M_\odot$)
26.0	11.45	3.24	3.43
36.0	8.54	4.25	1.95
44.0	7.23	4.80	1.46
52.0	6.37	5.19	1.19
60.0	5.80	5.51	1.02
67.0	5.45	5.63	0.94
84.0	5.05	5.83	0.84
88.0	5.02	5.87	0.83

Notes. See the details in the text in Section 5.2. Note that the smallest mass value of the companion star is 0.83 $M_\odot$.

$a_1 \sin i = 5.02 \pm 0.10$ AU with the semi-amplitude value of the sine function shown in Figure 5. The mass function is derived as $f(m) = (a_1 \sin i)^3 / P_{\mathrm{orb}}^2 = 0.176 \pm 0.008$. Concerning the formula $f(m) = (m_2 \sin i)^3/(m_1+m_2)^2$, an iteration procedure is carried out to calculate the companion mass (m_2) under different inclination angles (i), taking the mass value of KZ Hya of $m = 0.97$ $M_\odot$ (McNamara 1997). The values of the orbital semi-major axes of KZ Hya (a_1) are calculated under the same inclination angles. By using the formula $a_2/a_1 = m_1/m_2$, the values of the orbital semi-major axes of the companion (a_2) are also derived. Some results are listed in Table 9.

From Table 9, one finds that the mass of the companion cannot be smaller than 0.83 $M_\odot$, and the lowest mass estimate

Table 10
Photometry (Normal Points) of KZ Hya

Phase	V	$b-y$	m_1	c_1	β
0.00	9.498	0.113	0.124	0.984	2.874
0.05	9.547	0.121	0.122	1.007	2.866
0.10	9.663	0.142	0.120	0.988	2.842
0.15	9.788	0.169	0.115	0.929	2.812
0.20	9.898	0.194	0.107	0.866	2.783
0.25	9.985	0.213	0.101	0.814	2.760
0.30	10.056	0.229	0.097	0.767	2.740
0.35	10.118	0.244	0.091	0.724	2.724
0.40	10.168	0.256	0.086	0.692	2.713
0.45	10.208	0.265	0.082	0.671	2.708
0.50	10.238	0.269	0.079	0.658	2.704
0.55	10.243	0.271	0.078	0.650	2.703
0.60	10.231	0.270	0.080	0.645	2.701
0.65	10.220	0.267	0.082	0.642	2.701
0.70	10.221	0.263	0.084	0.640	2.706
0.75	10.219	0.259	0.087	0.637	2.710
0.80	10.189	0.252	0.090	0.644	2.720
0.85	10.097	0.231	0.099	0.677	2.748
0.90	9.903	0.189	0.115	0.762	2.801
0.95	9.642	0.139	0.124	0.891	2.850

is unlikely since there is no evidence that the system is eclipsing. As can be seen in Table 10 (Section 5.3), the value of color index $b-y$ varies from 0.113 at the time of maximum light to 0.271 at the time of minimum light of KZ Hya, corresponding to the spectral type A to F3, while the age of KZ Hya is estimated to be 7.59×10^9 yr as a metal-deficient population II star (McNamara 1997). However, if we assume the companion is a G-type main-sequence star whose value of $b-y$ should be between 0.6 and 0.9, the color index $b-y$ of the system at the time of minimum light of KZ Hya, when both stars have brightness similar to each other, should be larger than 0.43. This is in conflict with the observed $b-y$ value. Hence, the observed color index $b-y$ excludes the possibility of the companion being a late-type main-sequence or dwarf star.

In addition, no sign of any companion of KZ Hya has ever been observed spectroscopically. McNamara & Budge (1985) made 24 spectrograms of KZ Hya in 1984 with the image-tube spectrograph attached to the 1 m telescope at CTIO, to measure the radial velocities of KZ Hya through a full period phase of KZ Hya (see Figure 3 of that paper). The spectrum dispersion is 4.5 nm mm^{-1}. In spite of the high quality of the spectrograms, they failed to detect any lines other than the hydrogen and K lines. Przybylski & Bessell (1979) secured nine spectra of KZ Hya with the 38 cm coudé camera and RCA image tube of the 1.88 m telescope at Mount Stromlo Observatory with spectrum dispersion of 2 nm mm^{-1}; they could use only hydrogen lines and the ionized calcium line at 393.3 nm for the determination of radial velocity. If the companion is a late-type main-sequence star, rich metal lines should be visible in the spectra, especially at the time of minimum light of KZ Hya. The lack of rich metal lines in the spectra is strong evidence that the companion is a degenerate star. Concerning the lower mass limit of the companion (0.83 $M_\odot$), we deduce that the companion should be a white dwarf, a neutron star, or a black hole. Noting the age value of KZ Hya of 7.59×10^9 yr, the companion could quite possibly be a massive white dwarf star.

We noted the binary hypothesis proposed by earlier authors (e.g., Yang et al. 1985; Liu et al. 1991) with the orbital period

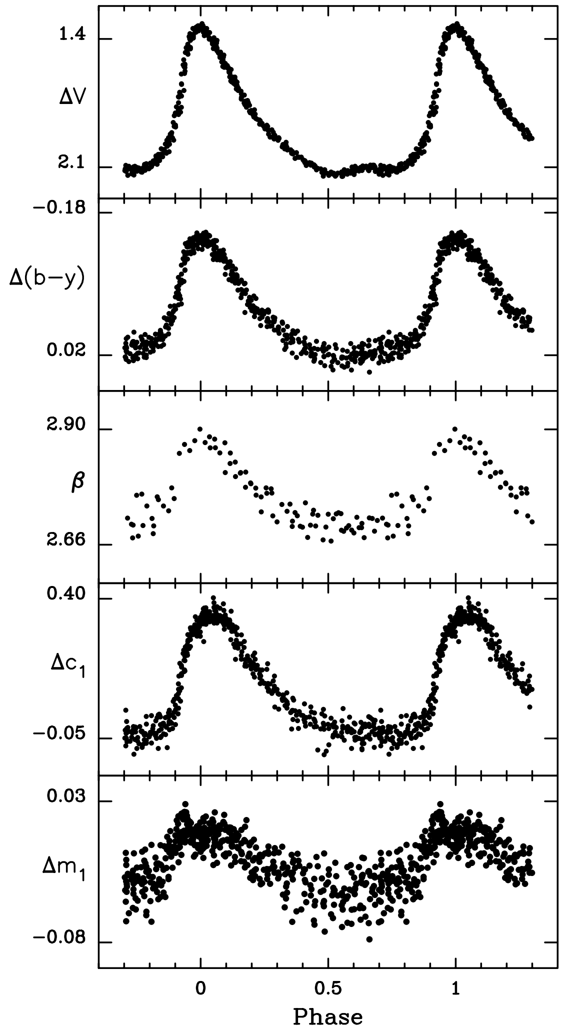

Figure 7. Light and color-index variations over the pulsation cycle.

of approximate nine years. However, as can be seen from Figure 6, the residual $O - C$ diagram, after the fit concerning the continuously increasing period change and the light traveling time effect of the binary system with the orbital period of 26.8 years, does not show significant evidence of a companion with approximately nine years of orbital period. We also tried to fit the residual $O - C$ points with the binary model of nine years of orbital period but no converged fit could be achieved.

5.3. Physical Parameters

The *uvby*β data were phased according to the ephemeris derived in Section 4. Figure 7 shows the resulting V light and color index variations over the pulsation cycle. This figure clearly shows that the $b - y$ and β curves are phased with the V curve, while the maximum in the c_1-index occurs about 0.05 cycles later than the maximum in V, due to the temperature and gravity variations along the pulsation (Garrido & Rodríguez 1990). Moreover, the m_1-index curve shows a clear variation of about $\Delta m_1 = 0^{m}.05$ in the same sense as the light curve. This is an indication that KZ Hya is a strongly metal-deficient star (Rodríguez et al. 1991), in very good agreement with its SX Phe nature suggested by earlier authors (Przybylski & Bessell 1979; McNamara & Budge 1985; Rodríguez & Breger 2001, and references therein).

Table 11
Reddening and Derived Physical Parameters for KZ Hya

Parameter	Mean value	Sigma/Error	Range
E_{b-y}	$0^{m}.041$	$0^{m}.006$	...
$(b-y)_0$	$0^{m}.177$	$0^{m}.054$	$0^{m}.072 - 0^{m}.230$
m_0	$0^{m}.111$	$0^{m}.017$	$0^{m}.137 - 0^{m}.091$
c_0	$0^{m}.756$	$0^{m}.133$	$0^{m}.999 - 0^{m}.629$
δm_1	$0^{m}.076$	$0^{m}.003$	$0^{m}.066 - 0^{m}.081$
δc_1	$0^{m}.082$	$0^{m}.055$	$-0^{m}.029 - 0^{m}.143$
[Me/H] (dex)	−0.99	0.1	...
M_v	$2^{m}.21$	$0^{m}.3$	...
M_{bol}	$2^{m}.22$	$0^{m}.3$	...
T_e (K)	7300	530	8410 − 6800
log g (dex)	4.00	0.18	4.36 − 3.81

In order to discuss the variations of the physical parameters of KZ Hya, the individual *uvby*β observations were sorted by phase into 20 equally spaced bins over the cycle. Normal points every 0.05 units of phase were calculated and are listed in Table 10. Their standard errors are typically $0^{m}.006$, $0^{m}.002$, $0^{m}.003$, $0^{m}.007$, and $0^{m}.010$ in V, $b - y$, m_1, c_1, and β, respectively. The method described in Rodríguez et al. (2001) was used to estimate the physical parameters of KZ Hya and their variation along the pulsation cycle. Thus, using Crawford's (1979) calibrations, the reddening can be derived by comparing the intrinsic and observed $b - y$ values at normal points along the cycle. In this way, a mean color excess of $E_{b-y} = 0^{m}.041(\pm 0.006)$ is obtained. The results are summarized in Table 11, indicating this star as a strongly metal-deficient SX Phe star, in good agreement with the photometric parameters estimated by earlier authors (Rodríguez & Breger 2001, and references therein).

In deriving its luminosity, only a photometric value (M_v(ph) = $2^{m}.21(\pm 0.3)$) can be obtained, because there are no available parallax measurements by the *Hipparcos* satellite (ESA 1997). The metal content [Me/H] was calculated from the δm_1 parameter at minimum light (phases between 0.5 and 0.75) where the metal lines are strongest, and m_1 is most sensitive to abundance differences. In this case $\delta m_{1\mathrm{min}} = 0^{m}.078$, $\beta_{\mathrm{min}} = 2^{m}.701$ and a value of [Me/H] = −0.99 is obtained using Nissen's (1988) calibration for metal abundances. Due to the very large amplitude of the luminosity variations in KZ Hya, its effective temperature and surface gravity also experience very large variations, of about 1600 K (from 6800 K to 8410 K) and 0.55 dex (from 3.81 to 4.36 dex) respectively. They were computed using the (c_1, $b - y$) versus (T_e, log g) grids of Smalley & Kupka (1997) for [Me/H] = −1.0. Finally, a value of Q = $0^{d}.025$ with an uncertainty of $\pm 0^{d}.005$ (Breger 1990) is found for the pulsation constant using the period–mean-density relation of Petersen & Jørgensen (1972). However, if we assume that the photometric luminosity estimated above for KZ Hya is underestimated by about $0^{m}.5$, due to its strong metal deficiency, similar to that occurring in the star SX Phe itself (see Rodríguez & Breger 2001), this means that log g is also underestimated by about 0.2 dex. Then, a new value of the pulsation constant is found to be $Q = 0^{d}.036$ ($\pm$0.006), indicating pulsation in the fundamental mode. This is in good agreement with that proposed by earlier authors (see McNamara 1997) and with the results from the observed phase shifts between light curves in different filters, as mentioned previously.

6. CONCLUSIONS

Our pulsation analysis resolves up to 11 frequencies of KZ Hya, composed of the fundamental mode frequency and its harmonics, in multiple passbands, which explains the observed light curves well without invoking the contribution of any companions. Hence, KZ Hya is confirmed as a single-mode SX Phe star.

The new observed data, combined with the data collected (some corrected) in the literature, puts the updated value of pulsation period as $0.059510413 \pm 0.000000014$ days. The representation of the $O - C$ diagram by a combination of continuously increasing period change and the light traveling time effect in a binary system with the orbital period of 26.8 ± 0.2 years is reasonable. Some parameters of the binary system are estimated. In particular, the deduced mass of the companion cannot be smaller than $0.83\ M_{\odot}$.

Since no sign of the companion has ever been observed spectroscopically and the observed color index $b - y$ excludes the possibility of the companion being a late-type main sequence or dwarf star, KZ Hya is then the first SX Phe star where a degenerate companion has been discovered unambiguously, based on the $O-C$ diagram. With the $uvby\beta$ data, some physical parameters of KZ Hya are derived, indicating the star to be a strongly metal-deficient SX Phe star, coincident with the results of earlier investigators.

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