$\mathcal{R}$esearch in
$\mathcal{A}$stronomy and
$\mathcal{A}$strophysics

Pulsations of the High-Amplitude δ Scuti star YZ Bootis

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Abstract We present a study on pulsations of the high-amplitude δ Scuti star YZ Boo based on photometric observations in Johnson V and R bands with both the Nanshan 1-m telescope of Xinjiang Astronomical Observatory (XAO) and the Xinglong 85-cm telescope of National Astronomical Observatories, Chinese Academy of Sciences (NAOC). Fourier analysis of the light curves reveals the fundamental radial mode and its five harmonics, with the fourth and fifth being newly detected. Thirty-nine new times of maximum light are determined from the light curves, and combined with those in the literature, we construct the $O - C$ diagram, derive a new ephemeris and determine a new value for the updated period of 0.104091579(2). In addition, the $O - C$ diagram reveals an increasing rate of period change for YZ Boo. Theoretical models are calculated and constrained with the observationally determined parameters of YZ Boo. The mass and age of YZ Boo are hence derived as $M = 1.61 \pm 0.05\,M_{\odot}$ and age $= (1.44 \pm 0.14) \times 10^9$ yr, respectively. With both the frequency of the fundamental radial mode and the rate of period change, YZ Boo is located at the post main sequence stage.

Key words: stars: variables: δ Scuti star — stars: individual (YZ Boo) — stars: oscillations

1 INTRODUCTION

δ Scuti stars are pulsators with short periods, located inside the classical Cepheid instability strip crossing the main sequence on or above the Hertzsprung-Russell (H-R) diagram. With masses between 1.5 and 2.5 $M_{\odot}$, the pulsation periods of these stars are in the range of 18 minutes to 7.2 hours and amplitudes range from milli-mag up to several tenths of a mag. High-amplitude δ Scuti (HADS) stars, as either Population I or II, are found to have one or two dominant radial modes and peak-to-peak light amplitude variations larger than 0.3 mag. According to their heavy element abundance, stars can be classified as Population I or Population II. Generally for δ Scuti stars, Population I stars, as slow rotators with $v \sin i \leq 30\,\mathrm{km\,s^{-1}}$, are young and have relatively higher metallicity. They are usually found closer to the main se-

quence. However, Population II (SX Phoenicis) stars are usually metal-poor, more evolved stars and are located in globular clusters (McNamara 2000).

YZ Bootis (= HIP 75373, $\langle V \rangle = 10.57$ mag, $P_0 = 0.1041$ d, A6-F1) is an HADS star with a peak-to-peak amplitude of about 0.42 mag (Breger & Pamyatnykh 1998; Zhou 2006). Based on $uvby\beta$ photometry, Joner & McNamara (1983) classified YZ Bootis as a Population I star because of the typical m_1 index of Population I stars. This star has a relatively long observational history, dating back to earlier studies of the star's light variations (Eggen 1955; Broglia & Masani 1957; Spinrad 1959; Heiser & Hardie 1964; Gieren et al. 1974) and the classification used to be either RR Lyrae or Population I HADS.

Regarding the period variability of YZ Boo, Broglia & Masani (1957) revealed that variations exist in the

light curves from night to night and the largest varia-
tions of amplitude can be up to 0.07 mag in the blue band.
They also found that the times of maximum seem to ex-
hibit periodicity of about ± 0.0015 d (Broglia & Masani
1957; Heiser & Hardie 1964). Subsequent observations
(Szeidl & Mahdy 1981; Jiang 1985; Peniche et al. 1985;
Hamdy et al. 1986) appeared to indicate that YZ Boo has
different continuous period increases around a value of
$(1/P)dP/dt =\sim 3 \times 10^{-8}$ yr^{-1}. Recently, Zhou (2006)
presented an investigation on stability in the period of
YZ Boo and claimed that the period change of YZ Boo
is still inconclusive. Ward et al. (2008) gave a new value
of $(1/P)dP/dt = 6.3(6) \times 10^{-9}$ yr^{-1}, assuming this star
is increasing and changing smoothly. However, it is still
not an easy task to decide whether its period is constant
or varying.

The aim of this work is to report a detailed study of
the period changes of YZ Boo, mainly using extensive
time-series CCD photometry observations from 2008 to
2015 at both the Nanshan Station and Xinglong Station
in China. The paper is organized as follows. In Section 2,
we describe our new observations and present the data
reduction procedure. In Section 3, analysis of the pulsa-
tions of YZ Boo is performed, hence giving the corre-
sponding results. We construct the classical $O - C$ dia-
gram and show a new ephemeris in Section 4. The theo-
retical model and calculation of eigen-frequency and rate
of frequency change are given in Section 5. Discussion
and conclusions are provided in the last section.

2 OBSERVATIONS AND DATA REDUCTION

In order to investigate the variability in period, YZ Boo
was observed from 2008 Feb to 2015 May. The CCD
images collected between 2008 and 2013 were mainly
from the Xinglong 85-cm telescope, and the data from
2014 to 2015 were obtained with the Nanshan 1-m tele-
scope (hereafter called NOWT). The Xinglong 85-cm is
equipped with a PI MicroMax: 1024BFT CCD camera
and the field of view is $16.5' \times 16.5'$, corresponding to an
image scale of $0.96''$ pixel^{-1} (Zhou et al. 2009). NOWT
is equipped with a standard Johnson multi-color filter
system (i.e. $UBVRI$ filters) (e.g. Cousins 1976) and an
E2V CCD203-82 (blue) camera mounted on the primary
focus. The CCD camera has 4096×4196 pixels, corre-
sponding to a field of view of $1.3° \times 1.3°$ at a focal ratio of
2.159 with a full image size of 49.15×49.15 mm^2 (Song
et al. 2016).

Table 1 lists the journal of observations for YZ Boo.

All the time-series CCD images were reduced with
the standard IRAF [1] routines. Firstly, all the CCD frames
were calibrated by removing the bias level using the over-
scan data, and flat fielding using master flat fields. For the
data from NOWT, dark correction was not considered
since the CCD camera was operating at about $-120°$C
with liquid nitrogen cooling, hence the thermionic noise
was less than 1 e pix^{-1} h^{-1} at the temperature, and at
about $-45°$C for images from the Xinglong 85-cm tele-
scope, so dark correction was also not considered. Then,
the IRAF APPHOT package was employed to perform
aperture photometry. In order to optimize the sizes of
the aperture, five to ten different apertures were used
for the data in each night and the apertures which ex-
hibited minimum variance of magnitude differences for
the check star relative to the comparison star were taken.
The star $C1 = GSC2569 - 1184$ ($V = 11.6$ mag) was
detected as a non-variable within observational error and
then used as the comparison to obtain differential magni-
tudes for the variable. This comparison star was also used
by Derekas et al. (2003). The star $C2 = GSC2569 - 1050$
($V = 11.4$ mag) was used as the check star.

Figure 1 shows an image of the field of YZ Boo taken
with NOWT, on which the variable, comparison and
check stars are marked. The standard deviations of dif-
ferential magnitudes between C2 and C1 yielded an esti-
mate of the mean observational error of about 0.005 mag.
In total, we obtained 11 885 measurements in the V band
during 48 nights for YZ Boo.

Figures 2 and 3 show the light curves of YZ Boo in
the Johnson V band observed with the Xinglong 85-cm
telescope from 2008 to 2013 and NOWT from 2014 to
2015, respectively.

3 PULSATION ANALYSIS

To study the pulsations of YZ Boo, we performed Fourier
analysis with all the data in the V band using PERIOD04
(Lenz & Breger 2005), which applies Fourier transforma-
tions on the light curves to search for significant peaks in
the amplitude spectra. The light curves are fitted with the
following formula

$$m = m_0 + \Sigma A_i \sin\left[2\pi(f_i t + \phi_i)\right]. \qquad (1)$$

Apart from the fundamental frequency f_0 and its
harmonics $2f_0$, $3f_0$ and $4f_0$, as mentioned in Zhou

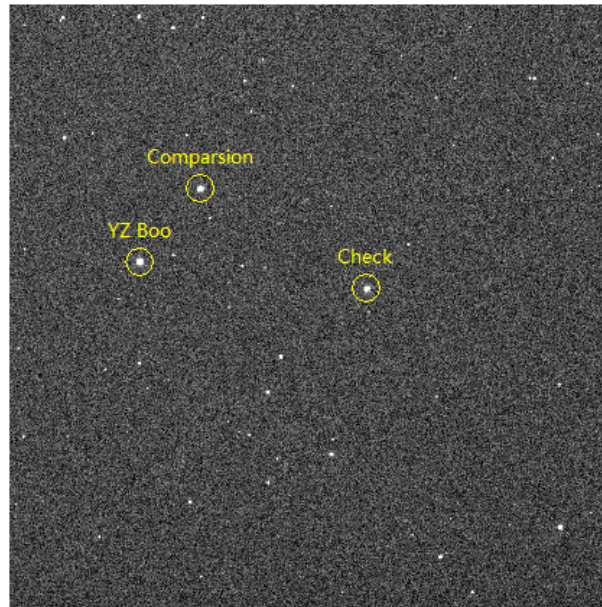[1] *Image Reduction and Analysis Facility, http://iraf.noao.edu/*

Fig. 1 CCD image ($18.75' \times 18.75'$) of YZ Boo (RA = 15:24:07.0, Dec = 36:52:00.6, 2000.0) taken with NOWT. North is up and east is to the left. YZ Boo, the comparison and check stars are marked.
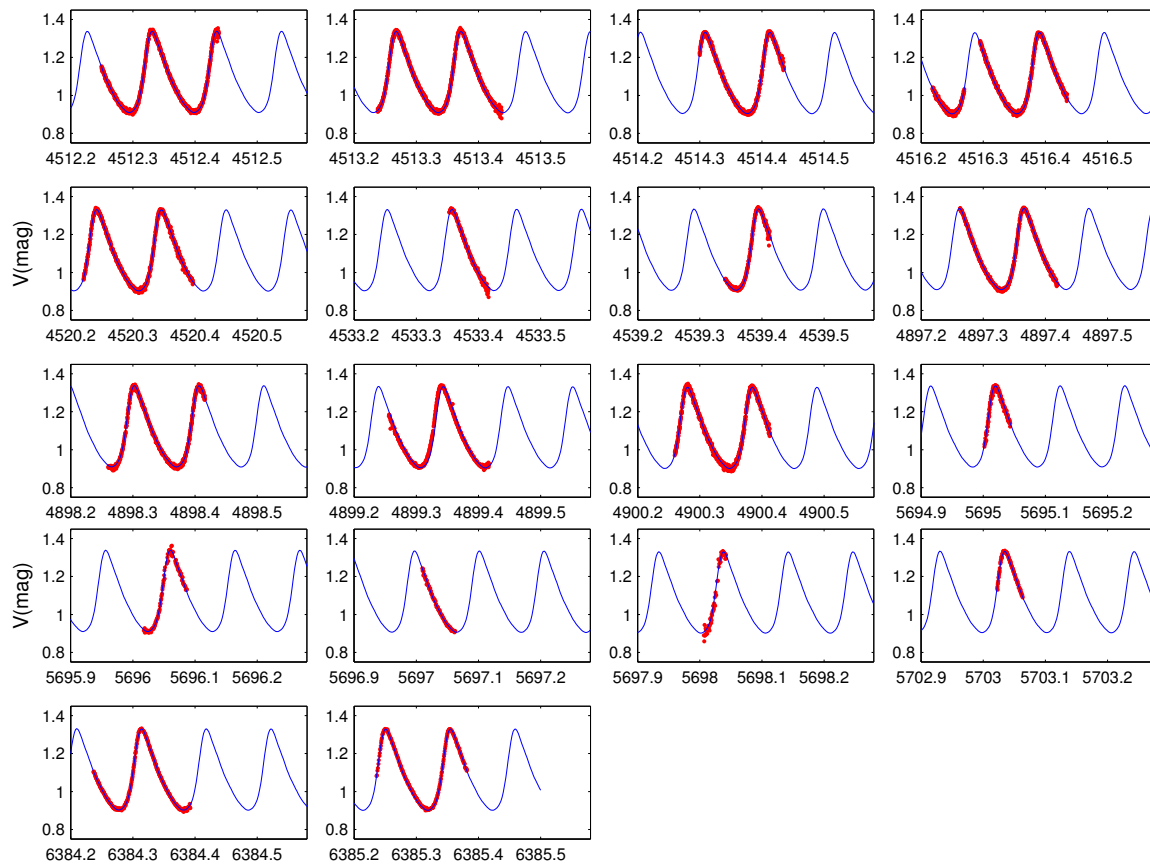

Fig. 2 Light curves of YZ Boo in the *V* band from 2008 to 2013 observed with the Xinglong 85-cm telescope. The *solid curves* represent the fitting with the six frequency solutions listed in Table 2.

Table 1 Journal of Photometric Observations for YZ Boo. Xinglong 85-cm stands for the 85-cm telescope at Xinglong station of NAOC and Nanshan 1-m is the Nanshan 1-m wide-field telescope at XAO.

Telescope	Year	Number of images	Filter	Number of hours
Xinglong 85-cm	2008	5231	V	25.2
(1024BFT CCD)	2009	2794	V	13.0
	2011	565	V	5.8
	2013	642	V, R	7.2
Nanshan 1-m	2014	685	V, R	24.6
(E2V CCD203-82)	2015	1968	V, R	52.9
Total		11 885		128.7

Table 2 Results of the Frequency Analysis for YZ Boo

	Frequency (c/d)	Amplitude (mmag)	Phase $(0-1)$	S/N
f_0	9.6069	191.3	0.633	177.8
$2f_0$	19.2138	59.2	0.475	97.0
$3f_0$	28.8207	21.9	0.765	79.2
$4f_0$	38.4277	9.5	0.639	33.6
$5f_0$	48.0346	4.8	0.873	18.0
$6f_0$	57.6435	2.2	0.869	4.6

(2006), another two harmonics $5f_0$ and $6f_0$ are detected. Generally, it is reasonable that a frequency whose signal-to-noise ratio is larger than 4 (i.e. S/N > 4.0) is considered significant (Breger et al. 1993; Kuschnig et al. 1997).

Table 2 lists all the significant frequency solutions including f_0 and its five harmonic frequencies.

Figure 4 shows the amplitude spectra and the pre-whitening procedures for the light curves in the V band observed from 2014 to 2015. The residuals of YZ Boo after fitting all the six significant frequencies are only 0.0087 mag, which indicate the modeled curves fit the light curves well. One should note that we usually do not consider peaks in the low-frequency domain (typically in the range of 0–3 cycles d^{-1}) as significant signals of a variable star, because they originate from instability in instrument sensitivity and variations of sky transparency in the low-frequency domain (Yang et al. 2012).

As can be seen from Figures 2 and 3, the modeled curves fit the observed light curves well, which demonstrates that the fundamental frequency and its harmonics can explain the pulsation behavior of YZ Boo. Therefore, YZ Boo is considered as a mono-period variable star since there is only one dependent frequency in the derived frequency.

4 TIMES OF MAXIMUM LIGHT AND $O - C$ DIAGRAM

To examine potential long-term period changes, the classical $O - C$ diagram was constructed. Firstly, the new times of maximum light for the light curves were derived. We fitted the light curves around the light maxima using a third or fourth order polynomial. The fitting errors are within uncertainties that are estimated with Monte Carlo simulations of 200 iterations for each light maximum. The error in determination of maximum is from 6 s to 60 s, depending on the data. Thirty-nine new maximum times were obtained in the V band and listed in Table 4.

Secondly, we combined the newly determined times of maximum light with those provided by earlier studies (Eggen 1955; Broglia & Masani 1957; Spinrad 1959; Broglia 1961; Heiser & Hardie 1964; Fitch et al. 1966; Gieren et al. 1974; Langford 1976; Szeidl & Mahdy 1981; Joner & McNamara 1983; Jiang 1985; Peniche et al. 1985; Hamdy et al. 1986; Kim & Joner 1994; Agerer et al. 1999; Agerer & Hubscher 2000, 2003; Derekas et al. 2003; Jin et al. 2003; Hubscher 2005; Hubscher et al. 2006; Klingenberg et al. 2006; Zhou 2006; Ward et al. 2008).

A total of 248 times of maximum light was collected. As in previous studies, we do not consider the maxima that have been derived from either photographic or visual observations. The seven photometrically determined data points omitted by Zhou (2006) and Ward et al. (2008) have also been discarded in this study.

To calculate the $O - C$ values and their corresponding cycle numbers, we adopted the revised ephemeris (Ward et al. 2008),

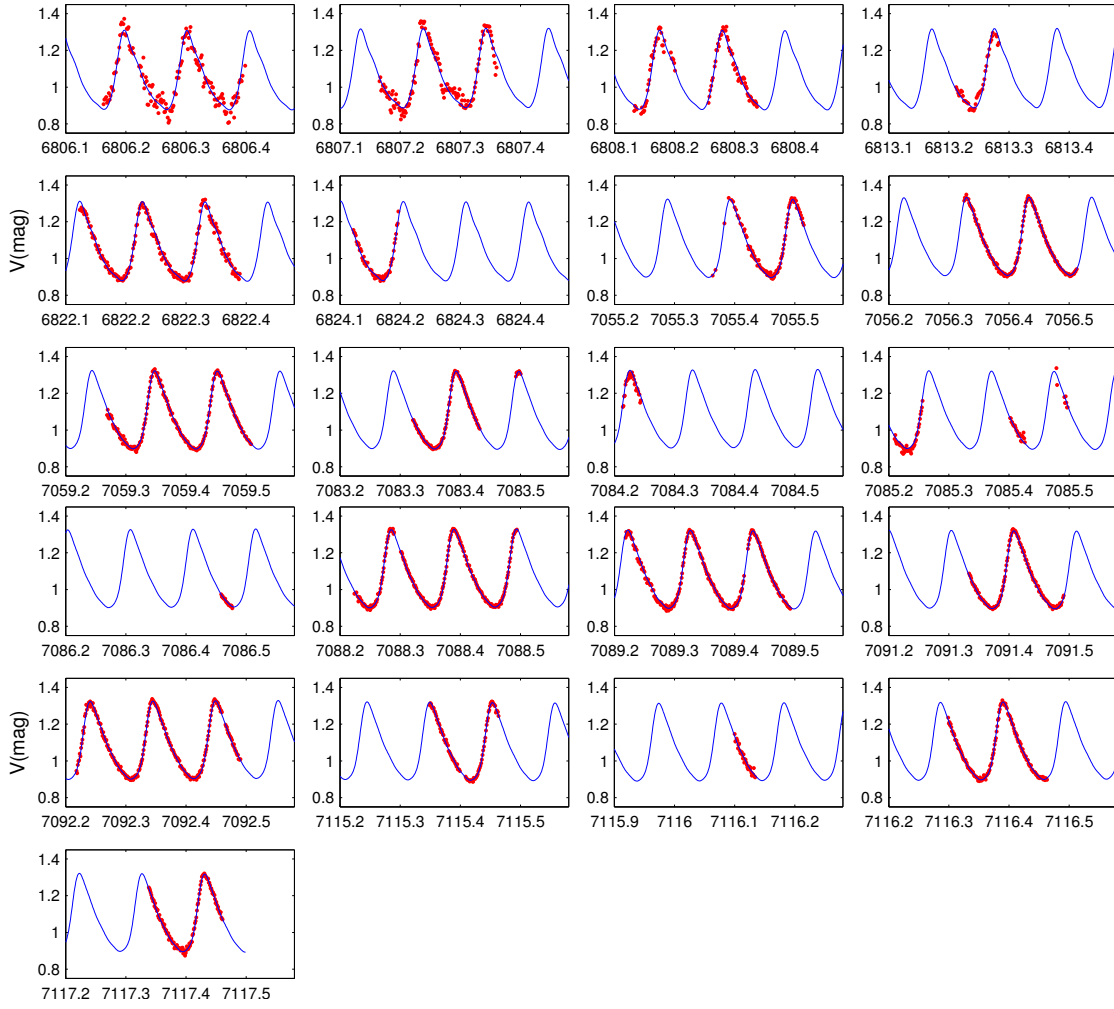$$\mathrm{HJD_{max}} = 2442146.3552(2) + 0.104091576(3) \times E.$$
$$(2)$$

Fig. 3 Light curves of YZ Boo in the *V* band from 2014 to 2015 observed with NOWT. The *solid curves* represent the fitting with the six frequency solutions listed in Table 2.

In this way, the period of YZ Boo is determined as 0.104091579(2), which is near that of Ward et al. (2008). The new period result is a more precise linear ephemeris of

$$\mathrm{HJD}_{\mathrm{max}} = 2442146.3552(2) + 0.104091579(2) \times E. \tag{3}$$

Figure 5 plots the $O - C$ value versus the cycle number of YZ Boo. The standard deviation of the residuals in the linear fit of $O - C$ values is 0.0013^{d}.

As in previous studies, we make a parabolic fit to the 241 data points and obtain a continuously changing period. The new ephemeris is

$$\mathrm{HJD}_{\mathrm{max}} = 2442146.3550(2) + 0.104091570(3) \times E$$
$$+ 1.00(13) \times 10^{-13} \times E^2, \tag{4}$$

with the standard deviation of residuals for the parabolic fit to the $O - C$ values being 0.0012^{d}. The rate of period change $(1/P)dP/dt$ is derived as $6.7(9) \times 10^{-9}$ yr^{-1}, which is similar to the results of Zhou (2006) of $5.0(\pm 3) \times 10^{-9}$ yr^{-1}, Ward et al. (2008) of $6.3(6) \times 10^{-9}$ yr^{-1} and Boonyarak et al. (2011) of 5.86×10^{-9} yr^{-1}. As the standard deviations for the residuals of both the linear and parabolic fits are close to each other, we compared the significance for the fits with these two methods using a two-sided F-test with a 95% confidence interval. From this test, no significant difference was found in these two fits. However, the parabolic fits were still meaningful, since we can obtain that the rate of period change for YZ Boo was positive and the order was comparable to the theoretical value. Hence, the two fits are equally acceptable.
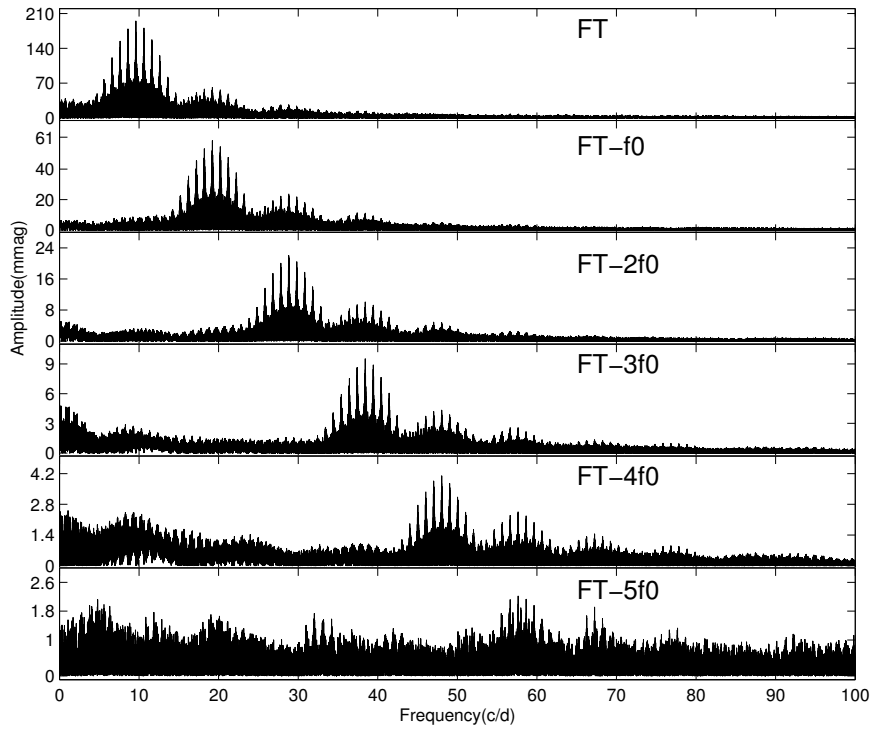
Fig. 4 Fourier amplitude spectra of the frequency pre-whitening process for the light curves in V observed from 2014 to 2015 with NOWT.

Table 3 Times of Maximum Light Derived from the New Light Curves

| HJD (2450000+)	σ	HJD (2450000+)	σ
4512.3314	0.0001	6385.2508	0.0002
4513.2683	0.0001	6385.3547	0.0002
4513.3716	0.0001	7055.4971	0.0004
4514.3081	0.0001	7056.4334	0.0002
4514.4125	0.0001	7059.3482	0.0002
4516.3906	0.0001	7059.4520	0.0002
4520.2418	0.0001	7083.3933	0.0001
4520.3458	0.0001	7084.2263	0.0007
4539.3942	0.0002	7088.2864	0.0003
4897.3655	0.0001	7088.3894	0.0002
4898.3024	0.0001	7089.3267	0.0002
4898.4061	0.0002	7089.4303	0.0002
4899.3408	0.0001	7091.4089	0.0002
4900.2802	0.0001	7092.2407	0.0002
4900.3843	0.0002	7092.3456	0.0002
5695.0198	0.0002	7092.4493	0.0002
5696.0620	0.0003	7115.4530	0.0002
5698.0375	0.0003	7116.3902	0.0002
5703.0345	0.0001	7117.4317	0.0002
6384.3147	0.0003		
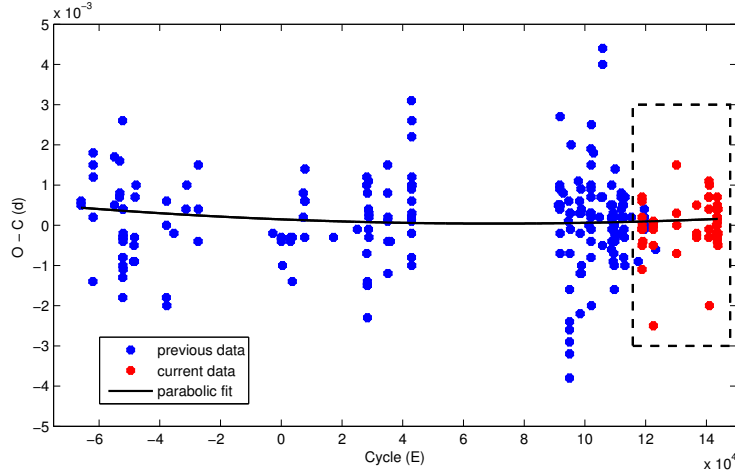
Fig. 5 $O - C$ diagram of YZ Boo. The $O - C$ values are in days. *Blue dots* represent the previous 202 points and *red dots* in the *dashed box* are the 39 new points. The *black solid line* indicates the parabolic fit related to a continuously increasing period change.
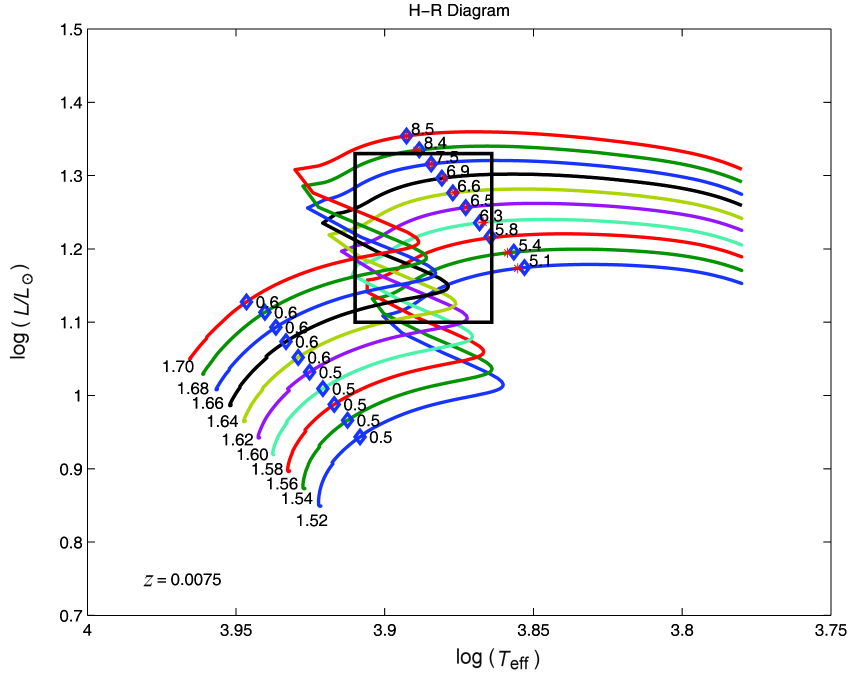

Fig. 6 Evolutionary tracks of models with $Z = 0.0075$ for masses from $1.52 \, M_\odot$ to $1.70 \, M_\odot$. The *rectangle* is determined from the observed parameters of YZ Boo. *Diamonds* on the tracks indicate the rates of period change in the unit of $10^{-9} \, \mathrm{yr}^{-1}$. *Asterisks* indicate the location of models with $f_0 = 9.6069 \, \mathrm{d}^{-1}$.

5 CONSTRAINTS FROM THE THEORETICAL MODELS

5.1 Physical Parameters

We investigate previous studies of YZ Boo to collect its basic physical parameters. Based on $ubvy\beta$ photo-metric observations for YZ Boo, Joner & McNamara (1983) provided some basic information, e.g. the effective temperature $\langle T_{\mathrm{eff}} \rangle$, average surface gravity $\langle \log g \rangle$ and its variation range, and metal abundance [Fe/H] and its bolometric magnitude M_{bol}. According to the calibration given by McNamara & Powell (1985), McNamara

Table 4 Physical Parameters of YZ Boo

Parameters	Joner et al. (1983)	McNamara (1997)	Interval
[Fe/H]	-0.25 ± 0.20	-0.60 ± 0.20	[$-0.80, -0.05$]
M_{bol}	$+1.7$	1.59	[$+1.4, +2.0$]
$\log g$	$3.81 - 4.05$	$3.83 - 3.90$	[3.83, 4.02]
$\log(L/L_{\odot})$	–	–	[1.1, 1.34]
T_{eff} (K)	7590	7490	[7310, 8130]
$M/M_{\odot}$	–	1.57	–
Age (yr)	–	1.58×10^{9}	–

Table 5 Gridpoints of the Model

Parameters	Interval	Step
Initial Z	[0.0025, 0.0150]	0.0025
M	[1.40, 1.80]	0.02

Table 6 The Parameters Determined with the Constraint from f_0

Parameters	Minimum	Maximum
Initial Z	0.0075	0.0150
M	1.50	1.70

(1997) provided a new value of metal abundance, and got the values of mass, bolometric magnitude, age, average surface gravity and its variation range. All the parameters of YZ Boo mentioned above are listed in Table 4.

5.2 Constraints from f_0

Modules for Experiments in Stellar Astrophysics (MESA) is a group of source-open, powerful, efficient and thread-safe libraries for a wide range of applications in computational stellar astrophysics (Paxton et al. 2011). A one-dimensional stellar evolution module, MESAstar, combines many of the numerical and physical modules for simulations of a large number of stellar evolution scenarios ranging from very-low mass to massive stars, including advanced evolutionary phases. Based on the adiabatic code ADIPLS (Christensen-Dalsgaard 2008), the "astero" extension to MESAstar provides an integrated method that passes results automatically between MESAstar and the new MESA module (Pavlović et al. 2013).

To obtain more precise values of the physical parameters, we calculated models with different masses and metal abundances. We use the formula [Fe/H] = $\log(Z/X) - \log(Z/X)_{\odot}$ and the formula $X + Y + Z = 1$ to calculate the initial Z.

Table 5 lists the intervals of parameters and the steps used in calculations of models. In all the calculations, we fixed the mixing-length parameter $\alpha_{\mathrm{MLT}} = 1.89$, as this choice has a very small effect on our theoretical models (Yang et al. 2012). Moreover, the convective overshooting parameter $f_{\mathrm{ov}} = 0.015$ was taken as the initial value of MESA.

As a result, we found the models with pulsation frequency of the fundamental radial mode, $f_0 = 9.6069\,\mathrm{d}^{-1}$ along with stellar evolution tracks within the constraints of the photometric data from Joner & McNamara (1983),

and obtained the intervals for parameters as listed in Table 6.

5.3 Constraints from the Period Variations

The rate of period change for YZ Boo shows a positive change based on a long interval of observations. From a theoretical point of view, the period changes caused by stellar evolution in and across the lower instability strip permit an observational test of stellar evolution theory, provided that other physical reasons for period changes can be neglected (Breger & Pamyatnykh 1998).

As indicated by Breger & Pamyatnykh (1998), HADS lie at the intersection of the main sequence and the classical instability strip on the H-R diagram. Consequently, we construct evolutionary models from the zero age main sequence and then evolve them to the end of the post main sequence. As mentioned above, the same values of α_{MLT} and f_{ov} were adopted, and the effect of rotation was not considered since YZ Boo is a low-speed rotator with a total velocity of $35\,\mathrm{km\,s}^{-1}$ (cf. Joner & McNamara 1983).

The evolutionary tracks constructed with $Z = 0.0075$ for mass from $1.52\,M_{\odot}$ to $1.70\,M_{\odot}$ are shown in Figure 6.

The rates of period change for individual models are also estimated by calculating the slopes of frequencies for adjacent models along the evolutionary tracks versus the corresponding ages. The frequency differences divided by the corresponding time intervals are taken as the rates of period change and marked along the evolutionary tracks on Figure 6.

By comparing both calculated frequencies of the fundamental radial modes of the models with the observed frequencies of YZ Boo, and the theoretical rate of period change and the observationally determined value

of YZ Boo, one can obtain: (1) the evolutionary mass of YZ Boo is $M = 1.61 \pm 0.05\,M_\odot$, (2) the age of YZ Boo is between 1.30×10^9 yr and 1.58×10^9 yr, and (3) the metal abundance [Fe/H] is about -0.43.

6 DISCUSSION AND CONCLUSIONS

With photometric data observed between 2008 and 2015 from both the Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences (NAOC) and Nanshan Station of Xinjiang Astronomical Observatory (XAO), we analyzed the pulsations of YZ Boo, and extracted six frequencies, including its fundamental frequency of $f_0 = 9.6069$ d^{-1} and its six harmonics, two of which are newly detected. There is no additional frequency found in the residual spectrum after removing these six frequencies. The theoretical light variations of YZ Boo are produced.

The $O - C$ diagram was constructed with 248 times of maximum light either determined from our new observations or collected from the literature, leading to determination of the updated pulsation period of $0.104091579(2)$ d. In addition, a new ephemeris with a quadratic solution hints at a continuously increasing period change for YZ Boo of $(1/P)dP/dt = 6.7(9) \times 10^{-9}$ yr^{-1}. This is consistent with the value predicted from our newly calculated stellar models with masses between 1.4 and 1.8 $M_\odot$. The mass of YZ Boo is then determined as $M = 1.61 \pm 0.05\,M_\odot$ and the location of this variable star on the H-R diagram is limited to post main sequence of the evolutionary tracks.

More observations, especially from multi-site campaigns, would help us to search for more potential pulsation frequencies of YZ Boo and provide clues to interpret the observed rate of period change.

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