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PULSATIONS AND PERIOD CHANGES OF THE NON-BLAZHKO RR LYRAE VARIABLE *Y OCT* OBSERVED FROM DOME A, ANTARCTICA

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ABSTRACT

During the operation of the Chinese Small Telescope Array (CSTAR) in Dome A of Antarctica in the years 2008, 2009, and 2010, large amounts of photometric data have been obtained for variable stars in the CSTAR field. We present here the study of one of six RR Lyrae variables, *Y Oct*, observed with CSTAR in Dome A, Antarctica. Photometric data in the *i* band were obtained in 2008 and 2010, with a duty cycle (defined as the fraction of time representing scientifically available data to CSTAR observation time) of about 44% and 52%, respectively. In 2009, photometric data in the *g* and *r* bands were gathered for this star, with a duty cycle of 65% and 60%, respectively. Fourier analysis of the data in the three bands only shows the fundamental frequency and its harmonics, which is characteristic of the non-Blazhko RR Lyrae variables. Values of the fundamental frequency and the amplitudes, as well as the total pulsation amplitude, are obtained from the data in the three bands separately. The amplitude of the fundamental frequency and the total pulsation amplitude in the *g* band are the largest, and those in the *i* band the smallest. Two-hundred fifty-one times of maximum are obtained from the three seasons of data, which are analyzed together with 38 maximum times provided in the GEOS RR Lyrae database. A period change rate of -0.96 ± 0.07 days Myr^{-1} is then obtained, which is a surprisingly large negative value. Based on relations available in the literature, the following physical parameters are derived: $[\mathrm{Fe/H}] = -1.41 \pm 0.14$, $M_V = 0.696 \pm 0.014$ mag, $V - K = 1.182 \pm 0.028$ mag, $\log T_{\mathrm{eff}} = 3.802 \pm 0.003$ K, $\log g = 2.705 \pm 0.004$, $\log L/L_{\odot} = 1.625 \pm 0.013$, and $\log M/M_{\odot} = -0.240 \pm 0.019$.

Key words: stars: individual (*Y Oct*) – stars: variables: RR Lyrae – techniques: photometric

Supporting material: data behind figure

1. INTRODUCTION

Asteroseismology is currently one of the most important techniques for probing the internal structure of stars. However, observational limits like discontinuous data sampling typical for ground-based sites render asteroseismological efforts not fully implementable. Although space missions such as *Kepler* (Borucki et al. 2010) and CoRoT (Baglin et al. 2006) are able to provide high-precision, long, and consecutive time-series observations, which have led to discovery of many new properties of stars, they are much more expensive than ground-based telescopes. Antarctica provides the only opportunity on the surface of the Earth for continuous time series observations similar to the space sites with much less expense.

The Antarctic plateau, due to its high altitude, low temperature, low absolute humidity, low wind speed, and extremely stable atmosphere, makes long and uninterrupted observations with one single telescope possible (Wang et al. 2011). One of the sites on the Antarctic plateau, Dome A, is believed to be the best astronomical site on Earth (Saunders et al. 2009). As the first astronomical site of China in Antarctica, the station Kunlun at Dome A is located on the massive East Antarctic Ice Sheet with an elevation of 4093 m. An observatory called PLATO (Ashley et al. 2010) and the first-generation Chinese Antarctic optical telescope CSTAR (Chinese Small Telescope ARray, Yuan et al. 2008) were installed in 2008. During the photometric observation period of the CSTAR telescopes, six RR Lyrae variables were detected (Wang et al. 2011).

The RR Lyrae variables are radial pulsating horizontal branch stars of spectral class A (and rarely F), with a mass of around half of the Sun. Their pulsation periods are typically in the range of 0.2–1 days and their optical amplitudes between 0.3 and 2 mag. The RR Lyrae stars are divided into three main types based on the shapes of the brightness curves and pulsation properties: RRab, RRc, and RRd. RR Lyrae stars play a prominent role in many areas of astrophysics, summarized by Preston (1964), such as distance indicators, population

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indicators, galactic structure study, etc. More than 100 years ago, Blazhko (1907) noticed that there were some variations in the times of maximum light of RW Dra. Shapley (1916) first indicated that the periodic variations of the times of maxima of RR Lyr itself were always accompanied by changes in the heights of light maxima and in the shapes of the light curves with the same period. This phenomenon, called the Blazhko effect, defined as the amplitude and/or phase modulation in the light curves, has since been discovered in other RR Lyrae variables. The incidence rate of RR Lyrae stars showing the Blazhko effect is about 40%–50% (Jurcsik et al. 2009; Sódor et al. 2012).

The RR Lyrae variable *Y Oct* ($\alpha = 14^{\mathrm{h}}29^{\mathrm{m}}4\overset{\mathrm{s}}{.}38$, $\delta = -88°38'43\overset{''}{.}7$) was discovered by Hoffmeister (1943) as an RRab type variable with a period of 0.646626 days. It has a metallicity of $[\mathrm{Fe/H}] = -1.52 \pm 0.1$ (Layden 1994) and a radial velocity of $144 \pm 24\ \mathrm{km\ s^{-1}}$ (Beers et al. 2000). It has appeared in several catalogs, including GCVS (Kholopov 1985), Tycho-2 (Høg et al. 2000), UCAC2 (Zacharias et al. 2003), 2MASS (Cutri et al. 2003), ASAS (Pojmanski 2005), and CSTAR (Wang et al. 2011, with ID 034997). A few times of maximum brightness were obtained by Hoffmeister (1943), Paschke (2007), Le Borgne et al. (2007a, 2008, 2009, 2011, 2012, 2013). A detailed pulsation and period change analysis of *Y Oct* would be required to study this star and this type of star in detail.

This paper presents a detailed study of the RR Lyrae star *Y Oct* observed by CSTAR in the *i* band in 2008 and 2010, and in the *g* and *r* bands in 2009. Section 2 describes briefly the instrument, observations, and data reduction; Section 3 presents Fourier and period change analyses of *Y Oct*; Section 4 presents physical parameters derived for this star from the light curves; and the conclusions are given in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

CSTAR is the first-generation Chinese telescope array deployed at Dome A. It is composed of four Schmidt–Cassegrain wide field telescopes, with a field of view of $4\overset{\circ}{.}5 \times 4\overset{\circ}{.}5$ and a pupil entrance aperture of 145 mm for each telescope. An ANDOR DV435 $1\ K \times 1\ K$ frame-transfer CCD with 13 μm pixel size is mounted at each focal plane. Three of the telescopes are equipped with *g* , *r*, and *i* filters similar to those used by Sloan Digital Sky Survey (SDSS) (Fukugita et al. 1996), respectively, while no filter is used in the fourth telescope. The pointing of the four telescopes are fixed with the centers of the fields of view close to the south celestial pole. More details about the CSTAR telescopes can be found in Zhou et al. (2010a, 2010b).

The CSTAR telescopes were installed at Dome A in 2008, January. Due to technical problems with three telescopes in the Antarctic winter season in 2008, only the telescope equipped with the *i* filter operated successfully. Details about the observations in 2008 and the data reduction can be found in Wang et al. (2011). During the Antarctic winter season in 2009, two of the four telescopes had some technical problems while the other two telescopes equipped with the *g* and *r* filters collected data. Zong et al. (2014) gives the details about the observations in 2009 and the data reduction. In the Antarctic winter season in 2010, only the telescope equipped with the *i* filter carried out observations. More details about the observations in 2010 and the data reduction can be found in Wang et al. (2013).

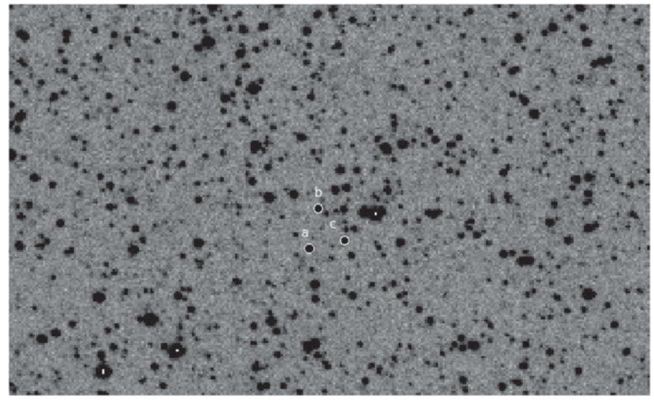

Figure 1. CCD image of CSTAR *i* band observations in 2010. The image is zoomed in by a factor of 4 for better visibility. CSTAR 034997, the comparison star, and the check star, are labeled by a, b, and c, respectively.

For the data of CSTAR 034997 in the *i* band observed in 2008 and 2010, the same comparison star (CSTAR 034001, $\alpha = 14^{\mathrm{h}}15^{\mathrm{m}}18\overset{\mathrm{s}}{.}7$, $\delta = -88°39'26\overset{''}{.}6$) and check star (CSTAR 036270, $\alpha = 14^{\mathrm{h}}25^{\mathrm{m}}25\overset{\mathrm{s}}{.}66$, $\delta = -88°42'54\overset{''}{.}66$) were used for differential photometry and the two season' data were combined together. More than 280,000 data points in the *i* band of CSTAR 034997 relative to the comparison star are obtained, while in 2009 no data from the comparison and check stars have been reduced yet. From the data collected in 2009, we obtain more than 110,000 and 250,000 data points for the *g* and *r* bands, respectively. Figure 1 shows a CCD image of CSTAR 034997, the comparison star, and the check star. Figure 2 shows light curves of the data in the three bands. Figure 3 shows the phase diagrams of the data in the three bands and the *g*–*r* color. The total amplitudes of pulsation are about 0.8, 1.3, 1.0, and 0.41 mag in *i*, *g*, *r* and *g*–*r*, respectively.

3. PULSATIONS AND PERIOD CHANGES

3.1. Fourier Analysis

Fourier analysis is performed by using the MUFRAN package (Kolláth 1990), the Period04 program (Lenz & Breger 2005), and a nonlinear fitting algorithm developed and kindly provided by Dr. Á. Sódor. A peak in the Fourier spectrum is regarded as significant here if its signal to noise ratio exceeds 4.0. Table 1 lists Fourier parameters derived from the three bands. The same fundamental frequency of $f_0 = 1.5466\ \mathrm{cd^{-1}}$ was detected in all three bands, while 15, 22, and 27 harmonic frequencies were found in the *g*, *r* and *i* data, respectively. The detected fundamental frequency and its harmonics represent the non-linear nature of the radial pulsation. By performimg frequency analysis with Period04, Wang et al. (2011) found a frequency on the left side of the fundamental frequency and thereby identified CSTAR 034997 as a Blazhko star. But our frequency analysis based on Period04 and other tools showed no sidelope frequencies around the fundamental frequency and its harmonics. It turned out that the author improperly used Period04. Considering that we applied different Fourier analysis packages without detection of any triplets and no sign of modulation can be seen from the light curves, we classified CSTAR 034997 as a

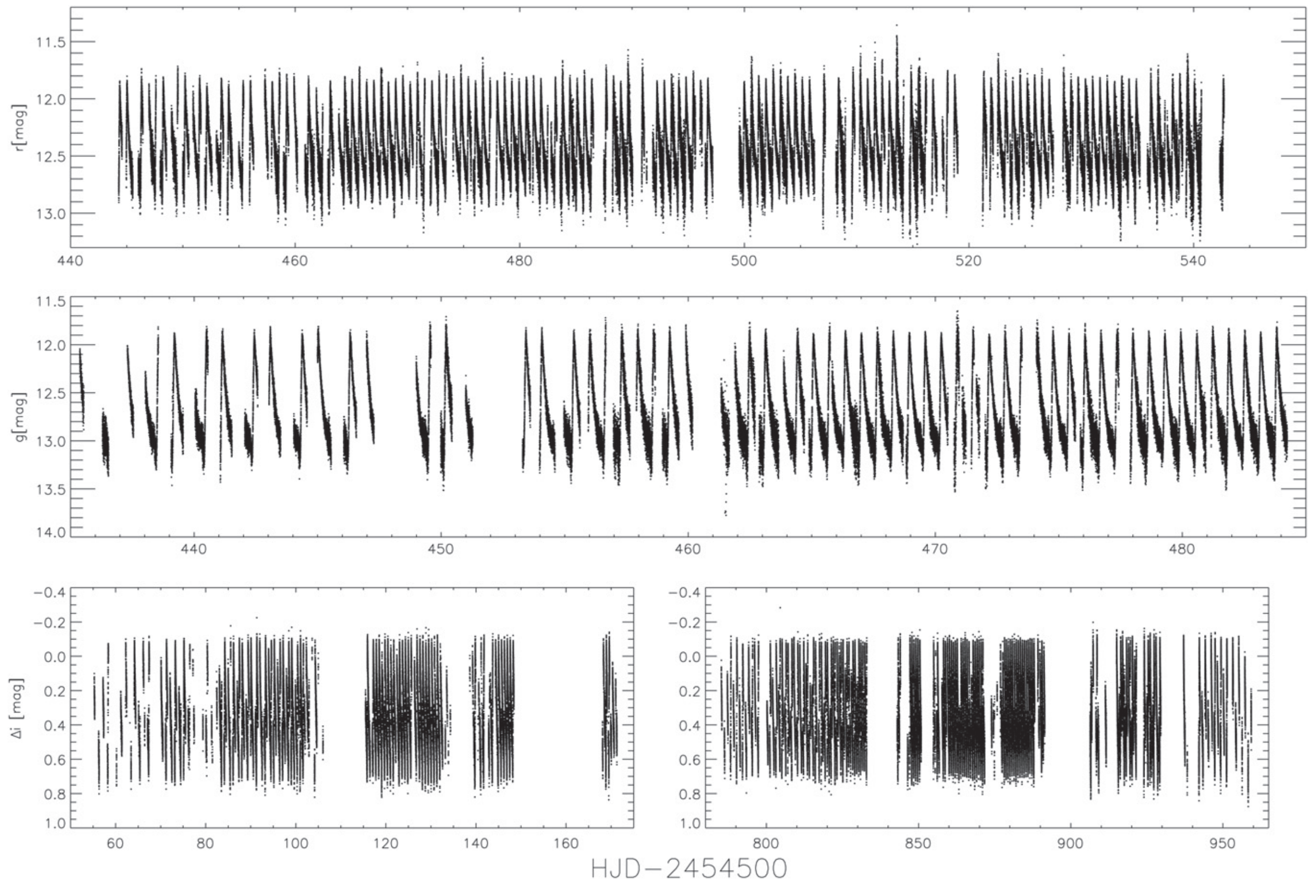

Figure 2. Light curves of CSTAR 034997 observed with the CSTAR telescopes. The top panel shows the light curves in *r* band; the middle panel in *g* band; the bottom left panel and right panel in 2008 and 2010 *i* band, respectively. The data used to create this figure are available.

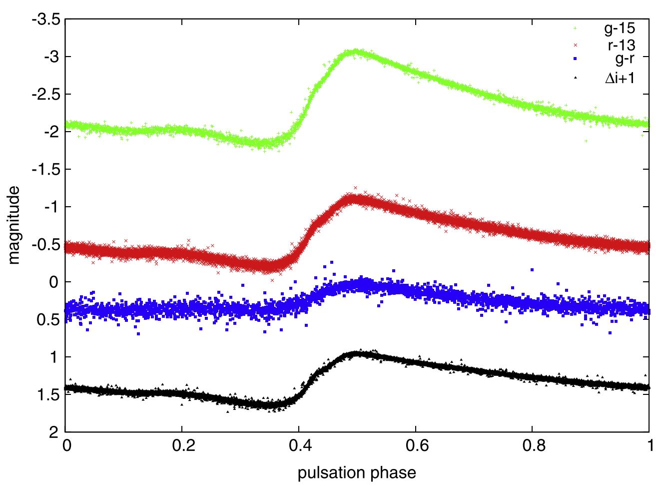

Figure 3. Phase diagrams of the data in the three bands and *g*–*r* color. The three bands' phase diagrams are shifted vertically for better visibility, and are denoted by green pluses, red multiplication signs, and black triangles for the *g*, *r*, and *i* bands, respectively. The *g*–*r* color is denoted by blue squares.

non-Blazhko star. Figure 4 shows the Fourier amplitude spectra in the three bands, with the detected frequencies marked by arrows. It can be seen that the amplitude of the fundamental frequency in the *g* band is the largest among those in the three bands, in accordance with the total amplitude in the *g* band being the largest. Pulsation frequencies are detected up to the 19th order of harmonic in the Fourier spectrum in the *g* band but no significant peaks appear at the location of the 10th, 11th, and 18th order of harmonic. The rms values of the residuals are 0.039, 0.081, and 0.077 mag in the *i*, *g*, and *r* bands, respectively.

The amplitudes of the harmonics and the amplitude ratios of the harmonics to the fundamental frequency were plotted respectively in the left and right panels of Figure 5 for the three bands. Green, red, and blue symbols denote the *g*, *r*, and *i* bands, respectively. It can be seen that the amplitudes of the first few harmonics in the *g* band are the largest, followed by those in the *r* band, and those in the *i* band are the smallest. For the higher harmonic orders, the amplitudes in the three bands are very close to each other. The amplitude ratios of the harmonics to the fundamental frequency are quite similar in the three bands, showing monotonic decrease, with the *g* band having a slightly smaller ratio than the other two bands for each harmonic order.

3.2. *O–C Diagram and Period Change Rate*

Maximum times of CSTAR 034997 were derived for the three seasons by applying polynomial fitting to light curves around the light maxima. Two-hundred fifty-one maximum times were derived from the light curves in the three years. For the common observations of *g* and *r* in 2009, the times of maximum are nearly the same and no phase shifts exist between the two colors. After excluding some maximum times deviating significantly from the others, 38 maximum times,

Table 1
Fourier Parameters from the Three Bands' Data

ID	*g* band Frequency (cd^{-1})	*g* band Amplitude (mag)	*g* band Phase (rad)	*r* band Frequency (cd^{-1})	*r* band Amplitude (mag)	*r* band Phase (rad)	*i* band Frequency (cd^{-1})	*i* band Amplitude (mag)	*i* band Phase (rad)
f_0	1.5466	0.4238	0.788	1.5466	0.2972	0.175	1.5466	0.2268	2.402
$2f_0$	3.0932	0.2186	3.995	3.0932	0.1602	2.964	3.0932	0.1217	1.310
$3f_0$	4.6398	0.1394	1.187	4.6398	0.1026	5.975	4.6398	0.0795	0.427
$4f_0$	6.1864	0.0922	4.853	6.1864	0.0680	2.841	6.1864	0.0526	5.933
$5f_0$	7.7330	0.0473	2.159	7.7330	0.0348	5.931	7.7330	0.0272	5.070
$6f_0$	9.2796	0.0274	5.415	9.2796	0.0204	2.466	9.2796	0.0162	3.936
$7f_0$	10.8262	0.0187	2.811	10.8262	0.0148	5.571	10.8262	0.0111	3.160
$8f_0$	12.3728	0.0097	0.126	12.3728	0.0075	2.599	12.3728	0.0061	2.604
$9f_0$	13.9194	0.0046	3.575	13.9194	0.0034	5.562	13.9194	0.0030	2.169
$10f_0$	…	…	…	15.4660	0.0032	3.220	15.4660	0.0022	1.641
$11f_0$	…	…	…	17.0126	0.0032	0.674	17.0126	0.0026	1.026
$12f_0$	18.5592	0.0031	3.530	18.5592	0.0038	4.048	18.5592	0.0032	0.331
$13f_0$	20.1058	0.0035	0.859	20.1058	0.0033	0.058	20.1058	0.0028	5.723
$14f_0$	21.6524	0.0031	4.136	21.6524	0.0035	3.637	21.6524	0.0031	4.808
$15f_0$	23.1990	0.0033	1.346	23.1990	0.0037	0.498	23.1990	0.0030	4.014
$16f_0$	24.7456	0.0033	4.970	24.7456	0.0028	3.474	24.7456	0.0028	2.916
$17f_0$	26.2922	0.0033	2.815	26.2922	0.0032	0.140	26.2922	0.0024	1.673
$18f_0$	…	…	…	27.8388	0.0026	3.098	27.8388	0.0023	0.731
$19f_0$	29.3854	0.0032	3.105	29.3854	0.0025	6.178	29.3854	0.0021	0.238
$20f_0$	…	…	…	30.9320	0.0020	2.921	30.9320	0.0019	5.767
$21f_0$	…	…	…	32.4786	0.0023	5.559	32.4786	0.0018	4.710
$22f_0$	…	…	…	34.0252	0.0017	2.459	34.0252	0.0017	3.536
$23f_0$	…	…	…	35.5718	0.0014	6.100	35.5718	0.0016	2.697
$24f_0$	…	…	…	…	…	…	37.1184	0.0011	1.245
$25f_0$	…	…	…	…	…	…	38.6650	0.0011	1.009
$26f_0$	…	…	…	…	…	…	40.2116	0.0009	0.075
$27f_0$	…	…	…	…	…	…	41.7582	0.0007	6.238
$28f_0$	…	…	…	…	…	…	43.3048	0.0008	4.342

which span from 2007 to 2013 (Le Borgne et al. 2007a, 2008, 2009, 2011, 2012, 2013), were derived from the GEOS RR Lyr database (Le Borgne et al. 2007b), and those in 2013 are unpublished and kindly provided to us by Dr. Le Borgne. The total of 289 maximum times were used to plot the *O–C* diagram and to calculate the period change rate.

The top panel of Figure 6 shows the *O–C* diagram by plotting the differences between the observed and calculated times of maximum light (i.e., the *O–C* values) versus the elapsed cycles. The equation used to calculate the times of maximum light is (Le Borgne et al. 2007b),

$$T_{\max} = HJD2454191.764 + E \times 0.6465768d \quad (1)$$

The dashed curve in the top panel of Figure 6 shows the fitting of the times of maximum light with the equation,

$$C = T_0 + P_0 \times E + a_3 \times E^2 \quad (2)$$

where P_0 is the period (in days) at epoch T_0 and E is the cycle number. A negative parabolic term a_3 is obtained from the fitting, indicating decreasing period. A widely used parameter (in $\mathrm{d\,Myr^{-1}}$) in the literature (Le Borgne et al. 2007b) to indicate the rate of period changes is

$$\beta = 0.0732 \times 10^{10} \times a_3 / < P > \quad (3)$$

From the fitting one obtains a period change rate of $\beta = -0.96 \pm 0.07$ days $\mathrm{Myr^{-1}}$. This absolute value of the rate of period decrease is much larger than that of the mean $\beta = -0.20$ days $\mathrm{Myr^{-1}}$ provided in Le Borgne et al. (2007b) for 21 RR Lyrae stars showing period decreases. Excluding maximum times separately from 2008, 2009 and 2010, we derived period change rates of -0.78 ± 0.09 days $\mathrm{Myr^{-1}}$, -0.59 ± 0.06 days $\mathrm{Myr^{-1}}$, -1.43 ± 0.09 days $\mathrm{Myr^{-1}}$, respectively. The decreasing period change of CSTAR 034997 indicates that this RRab variable is evolving from the red to the blue, crossing the instability strip. The bottom panel of Figure 6 shows the residuals of the fitting.

4. PHYSICAL PARAMETERS FROM LIGHT CURVES

Jurcsik & Kovács (1996) and Jurcsik (1998) used Fourier decomposition to calculate [Fe/H] and other fundamental physical parameters from Johnson–Cousins *V* band light curves of well-behaved RRab stars. As *Y Oct* is a non-Blazhko RRab star and data in two bands are available in 2009, light curves in the Johnson–Cousins *V* band in 2009 were obtained by using the "Lupton set" provided at the SDSS website,[13]

$$V = g - 0.5784 \times (g - r) - 0.0038; \sigma = 0.0054 \quad (4)$$

Fourier decomposition of the obtained light curves in the *V* band gave $P = 0.646573$ days, $\varphi_{31} = 5.292$, $A_1 = 0.349$ mag, and $\varphi_{41} = 1.915$. Then these Fourier parameters were used to calculate the metallicity and other fundamental physical parameters with the following equations (Jurcsik & Kovács 1996; Jurcsik 1998)

$$[\mathrm{Fe/H}] = -5.038 - 5.394\,P + 1.345\varphi_{31} \quad (5)$$

[13] See http://www.sdss.org/dr4/algorithms/sdssUBVRITransform.html.

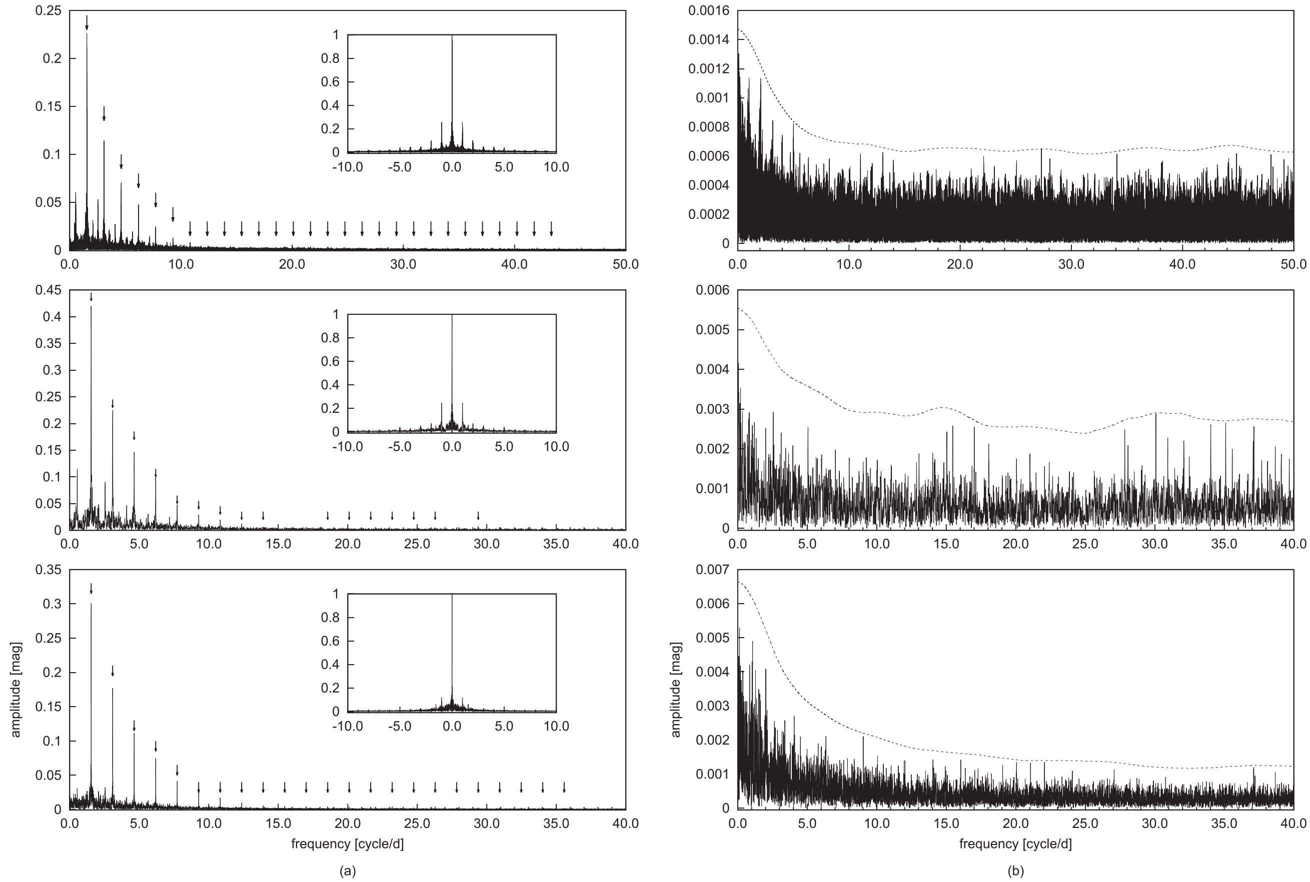

Figure 4. Fourier amplitude spectra in the three bands. The diagrams in (a) denote from top to bottom the original amplitude spectra in *i*, *g*, and *r* band, respectively. The diagrams in (b) denote from top to bottom the residual spectra after removal of fundamental frequency and its harmonics in *i*, *g*, and *r* band, respectively. Arrows mark the fundamental frequency and its harmonic frequencies detected in the three bands. Please note the *y*-axis scales are different in different panels. The spectral windows are insets in the original amplitude spectra panels.

$$M_V = 1.221 - 1.396\,P - 0.477A_1 + 0.103\varphi_{31} \quad (6)$$

$$V - K = 1.585 + 1.257\,P - 0.273A_1 - 0.234\varphi_{31} + 0.062\varphi_{41} \quad (7)$$

$$\log T_{\rm eff} = 3.9291 - 0.1112(V - K) - 0.0032[{\rm Fe/H}] \quad (8)$$

$$\log g = 2.473 - 1.226\,\log P \quad (9)$$

$$\log L = 10.26 - 0.062[{\rm Fe/H}] - 2.294\,\log T_{\rm eff} \quad (10)$$

$$\log M = -0.328 - 0.062[{\rm Fe/H}] \quad (11)$$

From the above equations the fundamental physical parameters were calculated for CSTAR 034997, with $[{\rm Fe/H}] = -1.41 \pm 0.14$, $M_V = 0.696 \pm 0.014$ mag, $V - K = 1.182 \pm 0.028$ mag. $\log T_{\rm eff} = 3.802$ K $\pm$ 0.003, $\log g = 2.705 \pm 0.004$, $\log L/L_\odot = 1.625 \pm 0.013$ and $\log M/M_\odot = -0.240 \pm 0.019$. Layden (1994) showed that the [Fe/H] derived from a spectroscopic study for CSTAR 034997 was -1.52 ± 0.1, which is similar to that of our calculation.

5. CONCLUSIONS

Three seasons of photometric observations for *Y Oct* with the CSTAR telescopes have yielded a large amount of data for this star. Fourier analysis of these data leads to detection of only the fundamental frequency and its harmonic frequencies in three bands, indicating that CSTAR 034997 is a non-Blazhko RRab star. Both the amplitude of the fundamental frequency and the total amplitudes in the *g* band are the largest. The amplitudes of the harmonics versus harmonic order in the three bands show a similar monotonic decreasing pattern.

The times of maximum light both obtained from the CSTAR observations and gathered from the GEOS RR Lyrae database were used to derive a period change rate of -0.96 ± 0.07 days $\rm Myr^{-1}$, which is much smaller than the decreasing period change rates of RRab stars from the literature. Excluding maximum times separately from 2008, 2009, and 2010, period change rates of -0.78 ± 0.09 days $\rm Myr^{-1}$, -0.59 ± 0.06 days $\rm Myr^{-1}$, -1.43 ± 0.09 days $\rm Myr^{-1}$ were derived, respectively. Therefore this star is believed to be in the evolutionary stage of moving toward the blue side of the instability strip, but the large negative period variation rate is surprising.

V-band light curves for *Y Oct* in 2009 were derived by using a transformation equation from the SDSS system to the Johnson–Cousins system, the Fourier decomposition of which was used to calculate metallicity and other fundamental physical parameters of this star. The physical parameters of CSTAR 034997 are derived to be $[{\rm Fe/H}] = -1.41 \pm 0.14$, $M_V = 0.696 \pm 0.014$ mag, $V - K = 1.182 \pm 0.028$ mag. $\log T_{\rm eff} = 3.802$ K $\pm$ 0.003, $\log g = 2.705 \pm 0.004$, $\log L/L_\odot = 1.625 \pm 0.013$ and $\log M/M_\odot = -0.240 \pm 0.019$. The

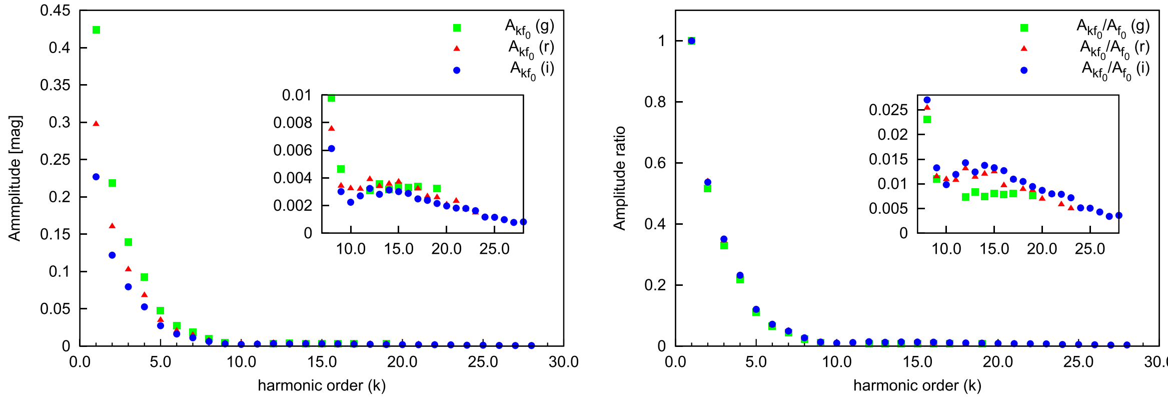

Figure 5. Amplitudes of pulsation frequencies and amplitude ratios of harmonics to the fundamental frequency. Left panel shows the amplitudes of pulsation frequencies of the three bands, with green squares, red triangles, and blue circles denoting *g*, *r*, and *i* bands, respectively. Right panel shows the amplitude ratios of harmonics to the fundamental frequency, with green squares, red triangles, and blue circles denoting *g*, *r*, and *i* bands, respectively. The diagrams inserted in the two panels are the enlargement of the amplitudes and amplitude ratios of the eighth harmonics to 28th harmonics in the three bands, respectively.

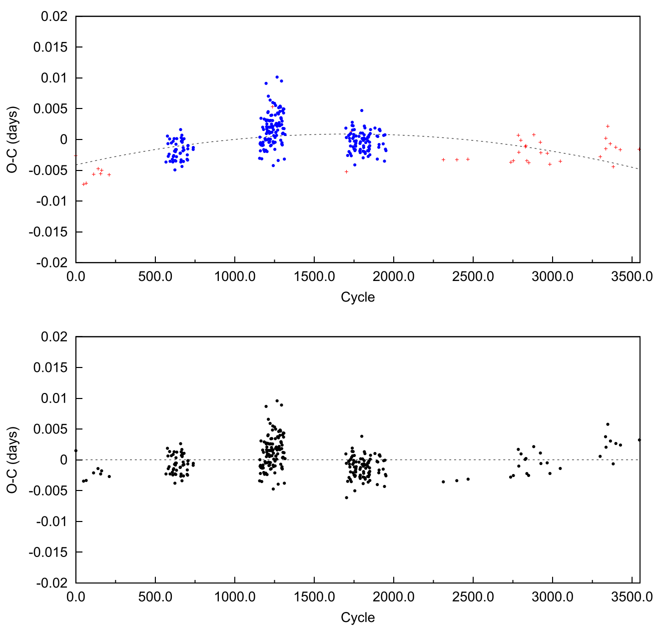

Figure 6. *O–C* values vs. elapsed cycles. The top panel shows the fitting of times of maximum light with a quadratic dashed curve, indicating a parabolic pattern with a decreasing period change. Blue points are determined from the times of maximum light of CSTAR observations, while red pluses are from the GEOS RR Lyrae database. The bottom panel shows the residuals of the fitting, with the horizontal dash line representing zero level.

metallicity derived from our calculation is similar to that from the spectroscopic study in the literature.

We point out that in addition to white light observations in space and low duty cycle observations at other ground-based sites, multicolor observations in Antarctica with high duty cycle provide good opportunity of detailed study for variable stars.

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