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A triplet of the only pulsation mode detected in the DAV star G132–12

Wen-Chao Su[1], Jian-Ning Fu[1], Jian-Xing Chen[2,3], Lester Fox-Machado[4], Shi-Jie Zhao[1], Carmen Ayala-Loera[4,5], Jiang-Tao Wang[1] and Yang Pan[1]

[1] Department of Astronomy, Beijing Normal University, Beijing 100012, China; *jnfu@bnu.edu.cn*
[2] Dipartimento di Fisica e Astronomia, Alma Mater Studiorum Universita' di Bologna, via Piero Gobetti 93/2, I-40129 Bologna, Italy
[3] INAF-Osservatorio di Astrofisica e Scienze dello Spazio di Bologna, Via Piero Gobetti 93/3 I-40129 Bologna, Italy
[4] Instituto de Astronomía, Universidad Nacional Autónoma de México, Apartado Postal 877, 22800 Ensenada, Baja California, México
[5] Institute of Astronomy & Astrophysics, Academia Sinica, Taipei, China

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Abstract Hydrogen atmosphere pulsating white dwarfs, also known as DAV stars, are the most abundant type of pulsating white dwarfs. High-temperature DAV stars in general exhibit a small number of pulsation modes and stable frequencies. G132–12 is one of the pulsating hydrogen atmosphere white dwarf stars which lies close to the blue edge of the instability strip. Previous researches reported that G132–12 might have only one pulsation mode with the period of 212.69 s. To study the pulsation properties of G132–12 in detail, we carried out a bi-site observation campaign in October 2019. Time series photometric data were collected during around 154 h in total. A Fourier analysis reveals three frequencies which are identified as the triplet of an $l = 1$ g-mode pulsation with the period of 212.499 s. The rotational period is derived as $P_{\rm rot} = 35.0 \pm 6.7$ h and the inclination of the rotational axis to the line of sight is $70°$. G132–12 could be an ideal target for measuring the cooling scale of this white dwarf star with only one excited pulsation mode detected.

Key words: white dwarfs — oscillations — photometric

1 INTRODUCTION

White dwarfs are the final products of the majority of stars in the universe. About 95% of stars should end their lives as C/O-core white dwarfs. The white dwarfs with a hydrogen atmosphere, also named DA type white dwarfs, which account for about 74% of the number of known members (Córsico et al. 2019), are the most classical type of white dwarfs.

Since the discovery of the first pulsating hydrogen atmosphere white dwarf star (DAV or ZZ Ceti star) HL Tau 76 (Landolt 1968), 270 DAV stars have been confirmed (Córsico et al. 2019; Vincent et al. 2020). These stars define an experimental instability strip in the Hertzsprung–Russell (H-R) diagram (Tremblay et al. 2015) with temperatures ranging in 10 500 – 13 000 K (Bognár et al. 2019). They show different pulsation characteristics on different positions in the instability strip, from the blue edge to the red edge: (i) DAV stars close to the blue edge of the instability strip exhibit a few modes with periods of 100–300 s and low amplitudes of about 1 mmag; (ii) For the DAV stars cooler by a few hundred degrees than the members close to the blue edge, they manifest short-period pulsations with larger amplitudes; (iii) DAV stars located in the middle of the instability strip display pulsations with periods up to 300 s and even larger amplitudes. There are usually a large number of nonlinear combination frequencies detected in the amplitude spectra; (iv) The cooler DAV stars have longer but more unstable pulsation periods. Meanwhile, outbursts start to be detected; (v) The coolest DAV stars tend to have the longest pulsation periods with relatively low amplitudes ($<$ 1 mmag) (Hermes et al. 2017; Chen et al. 2019).

G132–12, also named EGGR167, was discovered to be a DAV star based on 10 h of time-series photometry by Gianninas et al. (2006) with only one period of 212.7 s detected. As far as the atmospheric parameters of G132–12 are concerned, Gianninas et al. (2006) reported the effective temperature of $12\,080 \pm 145$ K and log g of

Table 1 Journal of the Bi-site Photometric Observations of G132–12

UT Date (October 2019)	Observation-Duration SPM-84 cm (h)	XL-85 cm (h)
19	8.71	
20	9.63	9.71
21	9.51	9.67
22	9.43	8.50
23	8.68	4.15
24	8.76	6.45
25	9.10	9.33
26	9.20	9.17
27	9.13	5.81
28		8.87
Total	82.15	71.66

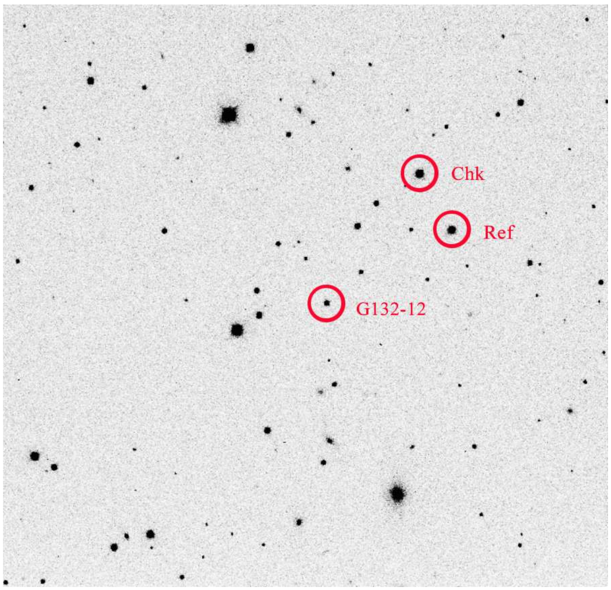

Fig. 1 An original observation image with the SPM-84 cm telescope. The target star G132–12, the reference star and the check star are marked with *red circles*.

7.94 ± 0.04. After that, Gianninas et al. (2011) provided a new result for G132–12 through a new generation 3-D atmosphere model with the effective temperature of $12\,610 \pm 222$ K and log g of 8.01 ± 0.06. Chen et al. (2019) collected nearly 90 h of time-series photometry from single-site observations in 2017 and also detected only one period of 212.69 s.

For DAV stars close to the blue edge, the pulsations show few stable modes. The high-temperature DAV stars such as G117-B12A and R548 have been proven to be stable optical clocks, with stability timescales of the order of 2 Gyr (Mukadam et al. 2013; Kepler et al. 2021). G132–12, as a DAV close to the blue edge, has become one interesting target of our research. In order to explore the pulsation characteristics of G132–12 in detail, we conducted the first international bi-site observation campaign for G132–12 in 2019.

In this paper, we describe the observations of G132–12 and data reduction in Section 2; In Section 3, we report the results of Fourier analysis; Finally, we provide a discussion in Section 4 and present a summary in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

In October of 2019, we carried out time-series photometric observations for G132–12 with both the 85-cm telescope at Xinglong Station (XL) of National Astronomical Observatories, Chinese Academy of Sciences and the 84-cm telescope at San Pedro Martir (SPM) Observatory in Mexico. Johnson V filters were used and 40 s of exposure time was applied for the bi-site observations. In total, about 154 hours of data were collected. The journal of observations is listed in Table 1.

We perform data reduction on all the photometric data with the Image Reduction and Analysis Facility (IRAF) package (Tody 1986). First, the pre-reduction for bias and flat field is made to the original images. As the exposure time is shorter than 1 minute, the dark current is ignored. We perform aperture photometry on the science images with the APPHOT task that is part of the IRAF package. We select two constant stars as reference star and check star in the field, respectively, which is the same selection as Chen et al. (2019), as shown in Figure 1.

In order to determine the optimal aperture, we take the full width at half maximum (FWHM) of 0.5–3 times with a step of 0.1, and calculate the standard deviations of each group of differential magnitudes between the two constant stars. We select the aperture corresponding to the smallest standard deviation as the optimal aperture. Considering the data obtained from bi-site observations, we subtract the average value of each night's light curve to avoid the difference of zero points caused by different facilities on different nights. In addition, as changes in atmospheric transparency and instability of the instrument system during overnight observations may cause long-term trends in the light curves, we calibrate by dividing the light curves by the fitted polynomials. Considering the difference in observation conditions on different nights, we rely on two or three order polynomial fitting in order to address long-term trends for each light curve. The reduced light curves from SPM and XL observatories are plotted in Figure 2.

3 AMPLITUDE SPECTRA AND FREQUENCY ANALYSIS

We perform Fourier transformation on the total light curves of G132–12 with the Period04 program (Lenz & Breger 2005). Bi-site observations effectively suppress the influence of daily aliasing. According to the acceptance standard with a signal-to-noise ratio (SNR) larger than

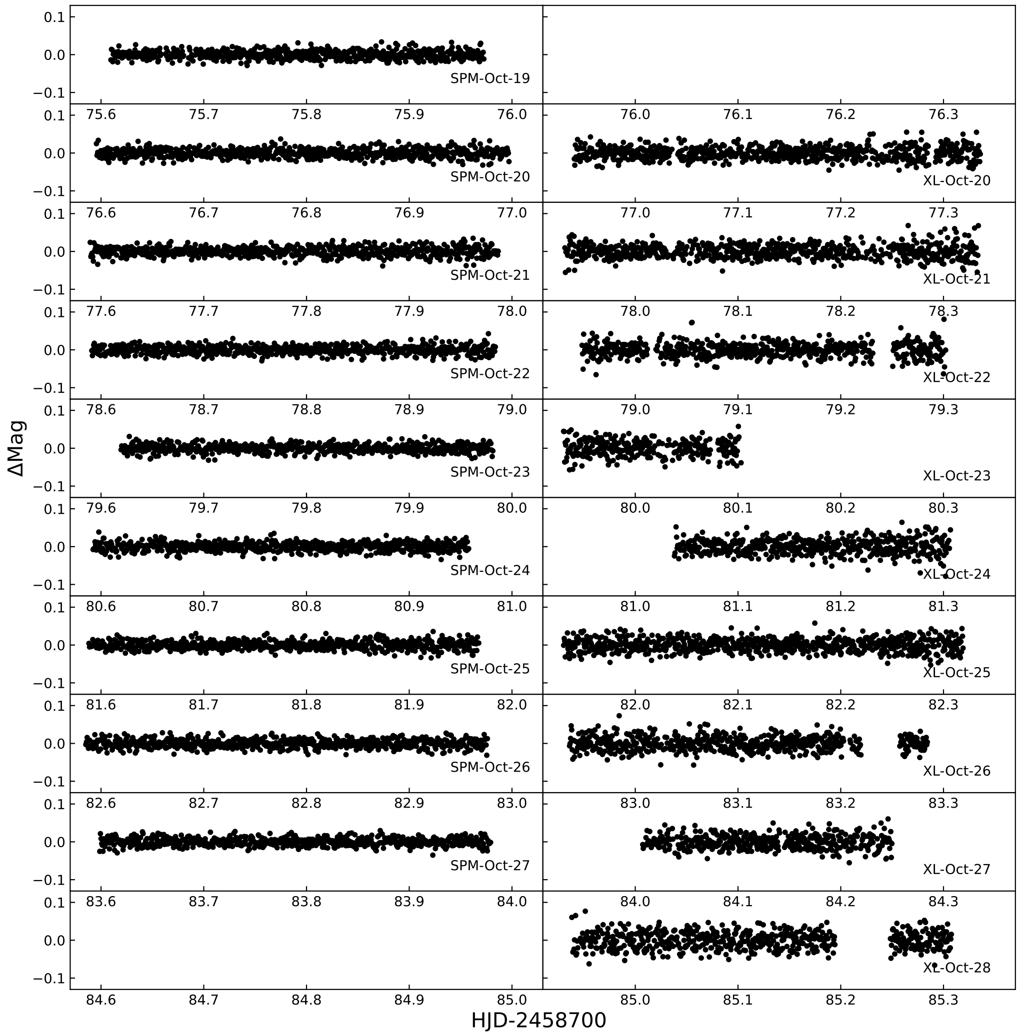

Fig. 2 Light curves of G132–12 from the SPM-84 cm telescope and the XL-85 cm telescope in October 2019. The abscissa is Heliocentric Julian Day (HJD) − 2458700.

4 (Breger et al. 1993; Kuschnig et al. 1997), we detect in total three frequencies from the Fourier spectrum: 4701.68 ± 0.17 µHz, 4705.91 ± 0.47 µHz and 4709.64 ± 0.33 µHz. The Fourier spectrum and the spectrum of the residuals after the three frequencies are prewhitened are depicted in Figure 3. The detected frequencies are listed in Table 2. The uncertainties of frequencies and amplitudes are calculated with a Monte-Carlo simulation (Fu et al. 2013).

As the frequency intervals between the three frequencies of G132–12 are approximately equal and the average is 3.98 ± 0.65 µHz, we identify the three frequencies as a triplet due to rotation with $l = 1$. The frequency of the eigenmode should be 4705.91 ± 0.33 µHz corresponding to the period of 212.499 s. The mode with the period of 212.7 s detected by Gianninas et al. (2006) and the one

Table 2 Frequency List of G132–12

ID	Frequency (µHz)	Amplitude (mmag)	Period (s)	SNR
F1	4701.68 ± 0.17	2.7 ± 0.13	212.690 ± 0.007	10.64
F2	4709.64 ± 0.33	1.5 ± 0.14	212.330 ± 0.015	6.05
F3	4705.91 ± 0.47	1.0 ± 0.13	212.499 ± 0.021	4.05

with the period of 212.69 s detected by Chen et al. (2019) should be the split mode with $m = -1$.

For g-mode non-radial pulsations, if all terms higher than second order are negligible, frequency splitting can be expressed by the following formula (Dziembowski & Goode 1992)

$$\omega_{k,l,m} = \omega_{k,l} - m\Omega(1 - \frac{1}{\eta}) \,, \qquad (1)$$

where ω is the frequencies of different m-values of the mode under the same l-value and k-value, $\eta = l(l+1)$, and Ω is the solid-body rotation angular velocity of the star.

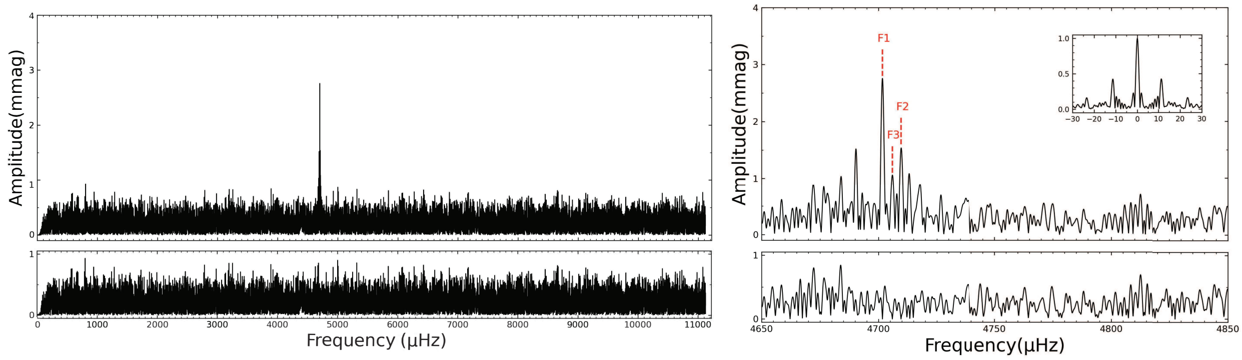

Fig. 3 *Left*: Amplitude spectra of G132–12 from light curves with bi-site data in Oct 2019. *Right*: Enlarged view of the part of the spectrum near the significant peaks. The spectral window is displayed as an inset on the right top. Three frequencies are marked in *red*.

From the calculation, the rotation period of G132–12 is derived as 35.0±6.7 h. This is in agreement with the mean value of rotational periods from asteroseismology studies of 31 known pulsating white dwarfs (Hermes et al. 2017). In the 31 samples summarized by them, the mean rotation period is about 35 h.

In addition, assuming that the ratio of amplitude of a triplet is only due to geometric effects, and the pulsation axis is aligned with the rotation axis of this star, we can estimate the angle of the rotation axis and sight line (Fu et al. 2013). In this triplet, the central mode ($m = 0$) shows a weaker amplitude than the $m = -1$ and $+1$ modes. Then we calculate the ratio of the average amplitudes of the $m = \pm 1$ mode to that of the $m = 0$ mode. The result is 2.1, which means that the angle of the rotation axis to the sight line is about 70° (Pesnell 1985).

4 DISCUSSION

4.1 *TESS* Data

The *Transiting Exoplanet Survey Satellite* (*TESS*), an all-sky survey mission, records pulsation signatures from some bright white dwarfs over the entire sky. We note that G132–12 (TIC 267687713) has been observed in sector 17 by *TESS* at 2-minute cadence. We downloaded all 2-minute light curves of this star for asteroseismic analysis. Unfortunately, there is no obvious signal in the Fourier spectrum. Considering that *TESS* only has a 10 cm effective pupil diameter, we believe that this is because the luminosity of G132–12 is too low ($M_{TESS} = 17.33$ mag) for *TESS* to observe the pulsations effectively. In addition, the 2-minute observation cadence of *TESS* exceeds half of the pulsation period of G132–12, which also causes difficulty in detecting the pulsations.

4.2 Measuring the Cooling Rate

Non-radial g-modes of high-temperature DAV stars often exhibit extremely slow period changes caused by the gradual cooling of stars, which can be used to measure the cooling rate of white dwarfs. G117-B15A and R548 (ZZ Ceti itself) are two of the long-studied high-temperature DAV stars which have been observed since the 1970s. Six independent modes had been detected in G117-B15A. The rate of period change, dP/dt, of the 215.2 s mode in G117-B15A was measured to be $(5.12 \pm 0.82) \times 10^{-15}\,\mathrm{s\,s^{-1}}$ with the $O - C$ method (Kepler et al. 2021). For R548, Mukadam et al. (2013) found five independent modes and measured dP/dt of the 213.1 s mode as $(3.3 \pm 1.1) \times 10^{-15}\,\mathrm{s\,s^{-1}}$. The two stars show considerably stable frequencies in their largest-amplitude modes. Furthermore, Hermes et al. (2013) reported a rapidly cooling DAV star WD 0111+0018. After more than nine years of monitoring, they measured dP/dt for each of the two independent modes. All periods are changing at rates faster than $10^{-12}\,\mathrm{s\,s^{-1}}$.

Constructing the $O - C$ diagram is a common method for measuring the long-term period changes of DAV stars. If we assume that all terms higher than second order are negligible, we get the $O - C$ equation following Kepler et al. (1991)

$$O - C = \Delta t_0 + \Delta P_0 E + \frac{1}{2} P_0 \dot{P} E^2 \,, \tag{2}$$

where Δt_0 is the uncertainty in the first maximum, P_0 the period at the first maximum and ΔP_0 the error in the period P_0.

It should be noted that for multi-mode stars, the stable largest-amplitude modes are selected to measure $\dot{P}$ in general, since the maximum times O of the largest-amplitude mode at a different epoch E can be obtained from the observed light curves. Because a light curve is coupled by all its independent modes, the change of any mode will affect the result of the Fourier transform of light curves. The calculations of $O - C$ caused by the drift of other modes have inherent errors that cannot be eliminated. Hence, if confirmed as a one-mode DAV star by long-term observations in the following years, G132-12 could be an ideal object for measuring the period change rate and the cooling scale of white dwarf stars.

5 SUMMARY

We obtain high-cadence photometric data for the DAV star G132–12 through 154 h of time-series bi-site observations. After data reduction and Fourier analysis, we detect three frequencies with SNR larger than 4 and identify them as a triplet due to rotation. This is the first time that the rotation of G132–12 has been detected. We calculate the rotation period of 35.0 ± 6.7 h. Furthermore, we correct the period value of the only mode detected as 212.499 ± 0.021 s. In addition, we estimate the angle of the rotation axis to the line of sight at about $70°$.

G132–12 is worthy of long-term observations and deep research. Comparing the pulsation period in 2006, 2017 and 2019, the only mode of G132–12 displayed considerable stability, which means that it could be an ideal optical clock whose rate of period changes can be accurately measured. Moreover, we hope that there will be more photometric observations with larger ground-based telescopes in following years for this star to confirm G132–12 is the first one-mode DAV pulsator. If confirmed, G132–12 is promising to define the blue edge of the instability strip of DAV stars. The pure frequency spectrum with only one mode will allow one to get an excellent measurement of the cooling timescale without inherent errors of multiple modes, which may help to limit the lower boundary of the age of the Galaxy and the universe.

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