

Mode Identification Revisit and Asteroseismology of the DAV Star TIC 231277791 (Postprint)

Authors: Z. K. Yao, Y. H. Chen and M. Y. Tang

Date: 2025-05-09T08:40:03+00:00

Abstract

White dwarfs (WDs) are the final stage for most low and intermediate mass stars, which play an important role in understanding stellar evolution and galactic history. Here we performed an asteroseismological analysis on TIC 231277791 based on 10 independent modes reported by Romero et al. Two groups of modes were identified with frequency splitting: mode identification_1 with one $l = 1, m = 0$ mode, two $l = 2, m = 0$ modes, and three $l = 1$ or $2, m = 0$ modes, and mode identification_2 with one $l = 1, m = 0$ mode, three $l = 2, m = 0$ modes, and one $l = 1$ or $2, m = 0$ mode. The rotation period is derived to be 41.64 ± 2.73 hr for TIC 231277791. We established a large sample (7,558,272) of DAV star models using the White Dwarf Evolution Code (WDEC; 2018, v16), resulting of optimal models with model_1 (mode identification_1): $M^* = 0.570 \pm 0.005 M$, $T_{\text{eff}} = 11300 \pm 10$ K, $-\log(MH/M) = 9.15 \pm 0.01$, $-\log(MHe/M) = 4.94 \pm 0.01$, and $\sigma_{\text{rms}} = 0.06$ s, and model_2 (mode identification_2): $M^* = 0.720 \pm 0.005 M$, $T_{\text{eff}} = 1910 \pm 10$ K, $-\log(MH/M) = 6.11 \pm 0.01$, $-\log(MHe/M) = 3.09 \pm 0.01$, and $\sigma_{\text{rms}} = 0.04$ s. The central oxygen abundances are 0.71 (optimal model_1) and 0.72 (optimal model_2), respectively, which are consistent with the results of stellar structure and evolution theory.

Full Text

Preamble

Research in Astronomy and Astrophysics, 25:045010 (9pp), 2025 April
© 2025 National Astronomical Observatories, CAS and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved. Printed in China.

<https://doi.org/10.1088/1674-4527/adc64e>

CSTR: 32081.14.RAA.adc64e

Mode Identification Revisit and Asteroseismology of the DAV Star TIC 231277791

Z. K. Yao^{1,2,3}, Y. H. Chen^{1,2,3}, and M. Y. Tang²

¹ Faculty of Science, Kunming University of Science and Technology, Kunming 650093, China; 1931824997@qq.com, yanhuichen1987@126.com

² International Centre of Supernovae (ICESUN), Yunnan Key Laboratory, Kunming 650216, China

Received 2024 September 11; revised 2025 March 20; accepted 2025 March 27; published 2025 April 15

Abstract

White dwarfs (WDs) represent the final evolutionary stage for most low- and intermediate-mass stars and play a crucial role in understanding stellar evolution and galactic history. Here we present an asteroseismological analysis of TIC 231277791 based on 10 independent modes reported by Romero et al. We identified two groups of modes with frequency splitting: mode identification_1 comprising one $\ell = 1, m = 0$ mode, two $\ell = 2, m = 0$ modes, and three $\ell = 1$ or $2, m = 0$ modes; and mode identification_2 comprising one $\ell = 1, m = 0$ mode, three $\ell = 2, m = 0$ modes, and one $\ell = 1$ or $2, m = 0$ mode. The rotation period of TIC 231277791 is derived to be 41.64 ± 2.73 hr. We constructed a large sample (7,558,272) of DAV star models using the White Dwarf Evolution Code (WDEC; 2018, v16), yielding optimal models as follows: model_1 (mode identification_1): $M^* = 0.570 \pm 0.005 M_\odot$, $T_{\text{eff}} = 11300 \pm 10$ K, $-\log(\text{MH}/M) = 9.15 \pm 0.01$, $-\log(\text{MHe}/M) = 4.94 \pm 0.01$, and $\sigma_{\text{rms}} = 0.06$ s; and model_2 (mode identification_2): $M^* = 0.720 \pm 0.005 M_\odot$, $T_{\text{eff}} = 1910 \pm 10$ K, $-\log(\text{MH}/M) = 6.11 \pm 0.01$, $-\log(\text{MHe}/M) = 3.09 \pm 0.01$, and $\sigma_{\text{rms}} = 0.04$ s. The central oxygen abundances are 0.71 (optimal model_1) and 0.72 (optimal model_2), respectively, which are consistent with theoretical predictions of stellar structure and evolution.

Key words: asteroseismology — (stars:) white dwarfs — (stars:) pulsars: individual (TIC 231277791)

1. Introduction

White dwarfs (WDs) represent the final evolutionary stage for the majority of stars in the universe (Saumon et al. 2022). Composed of electron-degenerate cores and ideal-gas atmospheres, they play a vital role in understanding stellar evolution and galactic history. The spectral type of a WD is determined by its atmospheric chemical composition. Kepler et al. (2021) reported that approximately 80% of WDs have hydrogen-rich atmospheres (spectral class DA), while about 20% have helium-rich atmospheres. The latter are classified as DB and DO WDs based on whether they have neutral helium-rich or ionized helium-rich atmospheres, respectively. With nuclear fusion halted in the core, WD evolu-

tion is dominated by cooling and contraction (Althaus et al. 2010b), with the cooling rate depending on parameters such as effective temperature (T_{eff}), mass (M^*), core chemistry, and atmospheric chemistry (Winget & Kepler 2008).

The first variable white dwarf was discovered by Arlo Landolt, with a dominant period of approximately 750 s (Landolt 1968). Variable WDs exhibit non-radial g-mode pulsations with multi-periodic brightness variations. The excitation of pulsations in WDs is driven by a combination of the $-\gamma$ mechanism (Dolez & Vauclair 1981; Winget et al. 1982) and the convective driving mechanism (Brickhill 1991; Goldreich & Wu 1999). Variable DA WDs, also known as ZZ Ceti stars or DAVs, constitute the most common class of pulsating white dwarfs. To date, more than 500 DAVs have been confirmed (Romero et al. 2024). The pulsating instability strip for DAVs spans roughly $T_{\text{eff}} = 12,270$ to $10,850$ K (Gianninas et al. 2011), with pulsation periods ranging from 100 to 1400 s and amplitudes from 0.01 to 0.3 mag (Córscico et al. 2019).

The internal structure of pulsating white dwarf stars can be probed through asteroseismology (see, e.g., Córscico et al. 2019 and references therein). Rapid progress in this field has been enabled by photometric observations from single-station and multi-station campaigns, as well as Whole Earth Telescope (WET) runs (Nather et al. 1990). Today, space-based photometry from missions such as the Kepler Telescope (Borucki et al. 2010), the K2 mission (Howell et al. 2014), and the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) has revolutionized WD asteroseismology in two key ways (Córscico 2020, 2022). First, it provides more accurate pulsation period measurements than ever before—for instance, TESS has achieved 10^{-4} s accuracy (Giammichele et al. 2022). Second, it has yielded numerous new pulsating WDs. Romero et al. (2022, 2024) discovered 106 new DAVs using TESS data from the first five years (Sectors 1–69). Hermes et al. (2017) reported a mean rotation period of 35 ± 28 hr for 0.51–0.73 M_{\odot} WDs based on K2 photometry. The long, continuous photometric data have also revealed a new and interesting phenomenon in pulsating WDs: amplitude modulation of pulsation modes, as documented in Zong et al. (2016). This feature can aid mode identification and has established a profound foundation for unprecedentedly precise chemical profiling in pulsating WD stars (Giammichele et al. 2018), leading to ongoing debate in the community about the abundance of carbon and oxygen in WD central cores (Giammichele et al. 2018, 2022).

Currently, there are three main methods for constructing WD grid models. The first method builds pure static WD models with parameterized chemical profiles (Giammichele et al. 2018, 2022). The second employs fully evolutionary models that calculate stellar evolution from the zero-age main sequence to the target WD stage (Althaus et al. 2010a; Paxton et al. 2011). The third method calculates only the WD evolution process, known as the quasi-static WD model (Bischoff-Kim & Montgomery 2018). In 2022, Romero et al. reported 74 new bright DAVs from TESS Sectors 1–39, possibly including 13 low-mass and one extremely low-mass WD candidate. TIC 231277791 (R.A. = 02:49:18.23, decl. = $-53:34:35.4$) is one of the targets, observed with a cadence of 120 s in Sector

29 and 20 s in Sector 30. Subsequently, Romero et al. conducted spectroscopic observations, including TIC 231277791, to refine atmospheric parameters and confirm its DA spectral characteristics. TIC 231277791 was ultimately identified as a DAV star. According to Romero et al. (2022), TIC 231277791 exhibits 10 independent modes within a very narrow period range (497–768 s), which should produce a clear frequency splitting effect and opens possibilities for mode identification and model fitting.

In this work, we first conducted detailed mode identifications for TIC 231277791. We then evolved a large sample of 7.56 million DAV star models. Finally, we performed a detailed asteroseismological model fitting for the DAV star TIC 231277791. The article is structured as follows: Section 2 presents the mode identifications of TIC 231277791 and the model calculations. Section 3 presents the asteroseismological study of TIC 231277791. Finally, Section 4 provides discussion and conclusions.

2. Mode Identifications and Model Calculations

In this section, we present detailed mode identifications for the DAV star TIC 231277791 and describe the input physics and model calculations.

2.1. Mode Identifications of TIC 231277791

Non-radial pulsation modes are characterized by three integer indicators: k , l , and m , representing the radial order, spherical harmonic degree, and azimuthal number, respectively (Unno et al. 1989). Brickhill (1975) investigated the relationship between the rotation period (P_{rot}) and the corresponding frequency splitting value (δk), deriving an approximate relationship truncated to first order in rotational perturbation as:

$$\delta k = m \left[-\frac{P_{\text{rot}}}{2\pi} \frac{d\omega}{dP_{\text{rot}}} + \frac{1}{2} \right].$$

Observed triplets correspond to $l = 1$ modes, while quintuplets are associated with $l = 2$ modes. According to this relationship, the ratio between $\delta k,1$ and $\delta k,2$ is:

This proportional relationship is crucial for mode identifications in WDs. Romero et al. (2022) reported 10 independent modes for TIC 231277791. The detailed mode identifications are presented in Table 1, where the third column lists the frequency intervals between adjacent modes (δF) in Hz.

The δF value between modes f05 and f06 is 3.13 Hz, while that between f06 and f07 is 3.30 Hz. Consequently, modes f05, f06, and f07 can be identified as a complete triplet. The average of 3.13 and 3.30 Hz is 3.215 Hz ($\delta k,1$). According to Equation (2), $\delta k,2$ is 5.358 Hz. The δF value (11.56 Hz) between modes f01 and f02, or f03 and f04, is approximately twice $\delta k,2$, suggesting these four modes are likely components of two incomplete quintuplets with $\Delta m = 2$. As shown in the fifth column, the amplitudes of modes f05, f06, and f07 are 3.20, 5.14, and 2.85 ppt, respectively. The amplitude of the $m = 0$ mode is roughly

1.6–1.8 times that of the $m = \pm 1$ modes. Considering the larger amplitudes of modes f01 and f03, we identify them as $m = 0$ modes and assign f02 and f04 to the $m = \pm 2$ modes, respectively, as shown in the last four columns of Table 1. Using Equation (1), we derive a rotation period of 41.64 ± 2.73 hr for TIC 231277791, which is broadly consistent with previous estimates for other WDs (Hermes et al. 2017; Romero et al. 2022; Bognár & Sódor 2024).

In Table 1, we present two mode identifications. In mode identification_1 (MID_1), we assume modes f08, f09, and f10 to be $l = 1$ or 2, $m = 0$ modes. We note that the frequency interval (21.13 Hz) between f08 and f09 is approximately four times δk . In mode identification_2 (MID_2), we assume f08 and f09 are $m = +2$ and -2 modes of an incomplete quintuplet, with the $m = 0$ mode assumed to be at 1321.25 Hz. Mode f10 is also assumed to be an $l = 1$ or 2, $m = 0$ mode. In MID_1, we obtain one $l = 1$, $m = 0$ mode, two $l = 2$, $m = 0$ modes, and three $l = 1$ or 2, $m = 0$ modes. In MID_2, we obtain one $l = 1$, $m = 0$ mode, three $l = 2$, $m = 0$ modes, and one $l = 1$ or 2, $m = 0$ mode. These two mode identifications are used to constrain the fitting models.

Additionally, in MID_1, the period intervals among modes f06, f08, f09, and f10 are very close, suggesting the possibility of mode trapping effects (Winget et al. 1981).

2.2. Input Physics and Model Calculations

The White Dwarf Evolution Code (WDEC) is a program designed to study the cooling process of white dwarfs, taking into account the abundances of hydrogen, helium, carbon, and oxygen. Originally developed by Martin Schwarzschild, it has undergone multiple revisions by Kutter & Savedoff (1969), Lamb & Van Horn (1975), and Wood (1990). The updated version was released by Bischoff-Kim & Montgomery (2018). WDEC (2018) adopts the equation of state (EOS) and opacity tables from the Modules for Experiments in Stellar Astrophysics (MESA, Paxton et al. 2011, and subsequent references) in version r8118. We use WDEC (2018, v16) to evolve our grid of DAV star models.

The standard mixing length theory (Bóhm & Cassinelli 1971) is adopted with a mixing length parameter of $\alpha = 0.6$ (Bergeron et al. 1995). WDEC (2018, v16) is a quasi-static program that calculates WD evolution from approximately 10,000 K to the required T_{eff} , with theoretical pulsation modes calculated synchronously with the WD models.

The grid parameters for our large sample of DAV star models are listed in Table 2. A total of 7,558,272 DAV star models were constructed using the specified initial ranges and steps. WDEC (2018, v16) requires approximately 12 s to evolve a single DAV star model. Using a standard four-core computer with four parallel terminals, it took nearly a year to evolve this extensive model sample. The calculated modes are first used to fit the observed modes and select an initial optimal model. Subsequently, using medium steps near the parameters of this initial optimal model, theoretical pulsation periods are recalculated and

used to fit the observed modes again, yielding a medium optimal model. Finally, using fine steps near the medium optimal model, theoretical pulsation periods are calculated and used to fit the observed modes until a final optimal model is obtained.

3. An Asteroseismological Study on TIC 231277791

From Table 1, we obtained two plausible mode identification groups. The $m = 0$ modes from Table 1 are used to constrain the fitting models.

3.1. The Model Fittings

The quality of the fitting results is evaluated using a root-mean-square (σ_{rms}) equation:

Here, P_{obs} and P_{cal} represent the observed and calculated periods of the modes, respectively, and n is the number of observed modes. For TIC 231277791, $n = 6$ in MID_1 and $n = 5$ in MID_2.

We identified an initial optimal model among the 7.56 million DAV star models based on the initial parameter space in Table 2. Near this initial optimal model, we adopted medium step sizes to evolve DAV star models. First, we fixed the central core XO parameters (h1-3, w1-3) and adjusted the six global parameters, using five grid points with medium steps to evolve 15,625 DAV star models. Then, we fixed the six global parameters and adjusted the central core XO parameters, again using five grid points with medium steps to evolve another 15,625 DAV star models. These two steps were repeated iteratively to obtain a medium optimal model. Similarly, near the medium optimal model, we adopted fine step sizes from Table 2 to obtain a final optimal fitting model. More detailed fitting procedures can be found in previous works (Duan et al. 2021; Chen 2022; Guo et al. 2023, 2024; Yang et al. 2023). After repeated model fitting, we obtained optimal model_1 and optimal model_2, corresponding to MID_1 and MID_2 in Table 1, respectively.

The parameters of optimal model_1 are $M^* = 0.570 \pm 0.005 M$, $T_{eff} = 11,300 \pm 10 K$, $-\log(MH/M) = 9.15 \pm 0.01$, and $-\log(MHe/M) = 4.94 \pm 0.01$. For optimal model_2, they are $M^* = 0.720 \pm 0.005 M$, $T_{eff} = 11,910 \pm 10 K$, $-\log(MH/M) = 6.11 \pm 0.01$, and $-\log(MHe/M) = 3.09 \pm 0.01$. The σ_{rms} values are 0.06 s and 0.04 s for optimal model_1 and model_2, respectively. The half-height and full width of the reciprocal of σ_{rms} are used to calculate parameter errors. We note that when using initial, medium, and fine step sizes, the fitting error is very close to the corresponding step size. The last two columns of Table 2 show the fitting errors obtained with fine step sizes.

In Table 2, we see that both $-\log(M_{env}/M^*)$ values are very similar. However, the other five global parameters for optimal model_1 differ significantly from those of optimal model_2, highlighting the critical role of mode identification in model fitting. Taking XHe as an example, it is 0.32 ± 0.01 for optimal model_1

and 0.75 ± 0.01 for optimal model_2, indicating a carbon-dominated envelope for optimal model_1 and a helium-dominated envelope for optimal model_2. The six XO parameters for optimal model_1 are similar to those for optimal model_2. According to optimal model_1, TIC 231277791 is likely a relatively low-mass, cool DAV star with a very thin hydrogen atmosphere. Meanwhile, optimal model_2 suggests it is a relatively massive, hotter DAV star with a moderately thick hydrogen atmosphere.

Table 3 presents detailed fitting results. For optimal model_2, the absolute values in the last column are 0.05 s, with $\sigma_{rms} = 0.04$ s. For optimal model_1, there are two larger fitting errors of 0.06 s and 0.13 s in the fourth column with $\sigma_{rms} = 0.06$ s. However, both solutions are of the same order of magnitude. We adopt optimal model_2 for our analysis.

Figure 1 [Figure 1: see original paper] shows the sensitivity of the eight parameters for optimal model_2. In each panel, we vary one parameter along the abscissa while fixing the others to the values in the last column of Table 2. The smallest σ_{rms} value in each panel is 0.04 s, with the minima corresponding to the values in Table 2's last column.

Figure 2 [Figure 2: see original paper] displays the fitting error σ_{rms} between mass and effective temperature. The color scale represents σ_{rms} values. Both Figure 2(a) (fitting MID_1) and Figure 2(b) (fitting MID_2) show results from 14,271 DAV star models. The optimal model lies near $(0.570 M, 11,300 K)$ in Figure 2(a) and near $(0.720 M, 11,910 K)$ in Figure 2(b), confirming that optimal model_1 is indeed a low-mass, cool DAV star while optimal model_2 is a massive, hot DAV star.

Figure 3 [Figure 3: see original paper] shows the fitting error σ_{rms} between hydrogen atmosphere mass and helium layer mass. In Figure 3(a), the $-\log(MH/M)$ range is $6.50-10.00$ with a step of 0.01 , and the $-\log(MHe/M)$ range is $4.40-5.40$ with a step of 0.01 . In Figure 3(b), the $-\log(MH/M)$ range is $5.51-10.01$ with a step of 0.02 , and the $-\log(MHe/M)$ range is $2.61-3.51$ with a step of 0.02 . Figures 3(a) and (b) contain 35,451 and 10,396 DAV star models, respectively. Optimal model_1 has a thin hydrogen atmosphere and likely exhibits strong mode trapping effects.

Figure 4 [Figure 4: see original paper] shows the compositional profiles and corresponding Brunt-Väisälä frequencies for the two optimal models. A white dwarf has a degenerate core surrounded by shells of different chemical elements. In Figure 4(b), corresponding to the last column of Table 2, the central oxygen abundance h_1 is 0.72 , the envelope mass is 1.90 ($-\log(M_{env}/M)$), the helium abundance (X_{He}) is 0.75 , the helium layer mass ($-\log(M_{He}/M)$) is 3.09 , and the hydrogen atmosphere ($-\log(MH/M)$) is 6.11 . The gradient in the transition zone of elements in the lower panel produces spikes in the upper panel. The number, height, and width of these spikes strongly influence the overall structure of stellar pulsation spectra (Althaus et al. 2010a). In Figure 4(a), a small discontinuity is visible around $-\log(1 - Mr/M) = 5$ in the helium layer. This

small discontinuity is a numerical artifact previously reported (Bischoff-Kim 2024) that affects the period spectrum at the level of a tenth of a second in the fitness parameter (Kim 2007).

According to asymptotic theory for g-modes, modes with the same n and consecutive k have an asymptotic period spacing, while trapped modes have smaller period spacings due to their insertion between normal modes (Brassard et al. 1992). Additionally, trapped modes typically have smaller oscillation kinetic energy. Figure 5 [Figure 5: see original paper] shows the period spacing and oscillation kinetic energy (K.E.) versus pulsation period for optimal model_1. The red dotted lines represent the observed periods in MID_1. Modes f06 and f08 are identified as trapped modes in Figure 5. For optimal model_2, no suspected trapped modes were found.

3.2. Asteroseismological Distance

The asteroseismological distance can be calculated using the luminosity of the optimal fitting model (see, e.g., Bognár et al. 2023), allowing comparison with the Gaia distance. Optimal model_2 has a luminosity of $\log(L/L_{\odot}) = -2.666$. The bolometric magnitude of TIC 231277791 can be calculated using the solar bolometric magnitude $M_{\text{bol},\odot} = 4.74$ (Cox 2000) and the modified Torres formula $M_{\text{bol}} = M_{\text{bol},\odot} - 2.5 \times \log(L/L_{\odot})$ (Torres 2010). This yields $M_{\text{bol}} = 11.405$ for optimal model_2. The bolometric correction (BC) values for DAV star models at $T_{\text{eff}} = 11,000$ K and $12,000$ K are -0.441 mag and -0.611 mag in the V band, respectively (Bergeron et al. 1995). Through interpolation, we obtain $BC = -0.596$ mag for optimal model_2 ($T_{\text{eff}} = 11,910$ K). The absolute visual magnitude is $M_v = M_{\text{bol}} - BC(V) = 11.405 - (-0.596) = 12.001$. The apparent visual magnitude of TIC 231277791 is $m_v = 16.406$ mag (Gaia Collaboration 2022). Using the distance modulus formula $m_v - M_v = 5 \log d - 5$, we calculate a distance of 76.04 ± 0.09 pc (parallax 13.15 ± 0.02 mas) for optimal model_2. The distance error arises from the luminosity error caused by parameter uncertainties in Table 2. The Gaia distance for TIC 231277791 is 81.19 ± 0.26 pc (parallax 12.32 ± 0.04 mas; Gaia Collaboration 2022). The optimal model_2 distance differs from the Gaia distance by 6.3%.

Optimal model_1 has a luminosity of $\log(L/L_{\odot}) = -2.622$ and $T_{\text{eff}} = 11,300$ K. Using the same method, we obtain an asteroseismological distance of 83.91 ± 0.48 pc (parallax 11.92 ± 0.07 mas), which differs from the Gaia distance by 3.4%. Vincent et al. (2024) reported $\log(L/L_{\odot}) = -2.626$ and $T_{\text{eff}} = 11,466$ K for TIC 231277791, yielding a distance of 77.78 pc (parallax 12.86 mas), which differs from the Gaia distance by 4.2%. Comparing the distances from our optimal models with the Gaia distance, optimal model_1 provides a better match. However, optimal model_2 gives a closer distance than Gaia because more massive stars are smaller and therefore must be closer to Earth.

Results

Table 4 summarizes previous spectroscopic and asteroseismological studies of TIC 231277791, along with our optimal fitting models. Jiménez-Esteban et al. (2018) (ID 1) used Gaia Data Release 2 to identify 73,221 WDs within 100 pc, obtaining $M^* = 0.633 \pm 0.054 M_\odot$, $T_{\text{eff}} = 11,750 \text{ K}$, and $\log g = 8.050 \pm 0.031$ for TIC 231277791. Gentile Fusillo et al. (2019, 2021) (ID 2, 3) reported 260,000 and 359,000 high-confidence WDs and derived stellar parameters for this target. Using Gaia DR3, Jiménez-Esteban et al. (2023) (ID 4) constructed a complete sample of 12,718 WDs within 100 pc and obtained stellar parameters, while Vincent et al. (2024) (ID 5) created a catalog of 100,000 high-quality WDs and measured parameters for TIC 231277791. For ID 6, Romero et al. (2022) performed an asteroseismological analysis using fully evolutionary models, obtaining $M^* = 0.570 M_\odot$, $T_{\text{eff}} = 11,300 \text{ K}$, $-\log(\text{MH}/M^*) = 5.45$, and $\sigma_{\text{rms}} = 0.88 \text{ s}$ for their best-fitting model. IDs 7 and 8 correspond to our optimal model_1 and optimal model_2, respectively.

The stellar mass from spectroscopic work (IDs 1–5) ranges from 0.612 to 0.653 M_\odot , with T_{eff} ranging from 11,275 to 11,750 K. The M^* and T_{eff} values for model ID 7 are identical to those of model ID 6. The M^* values for IDs 6 and 7 are slightly lower than those for IDs 1–5, while the M^* for ID 8 is slightly higher. The T_{eff} values for IDs 6 and 7 lie at the cool end of the range for IDs 1–5, while the T_{eff} for ID 8 lies at the hot end. Model ID 7 has a thin hydrogen atmosphere, while models IDs 6 and 8 have relatively thick hydrogen atmospheres. The fitting errors for IDs 7 and 8 are reduced by at least 93% compared to ID 6.

4. Discussion and Conclusions

This study presents an asteroseismological analysis of the DAV star TIC 231277791. Based on 10 detected independent modes reported by Romero et al. (2022), we performed detailed mode identifications and obtained two reliable mode identification schemes (MID_1 and MID_2). We derived a rotation period of $41.64 \pm 2.73 \text{ hr}$ for TIC 231277791 based on the identified triplets and quintuplets. Using the WD evolution code WDEC (2018, v16), we evolved a large sample of DAV star models (7,558,272) and used the theoretical modes to fit the observed modes from MID_1 and MID_2. The explored grid parameters and the two optimal fitting models are presented in Table 2.

For optimal model_1, the parameters are $M^* = 0.570 \pm 0.005 M_\odot$, $T_{\text{eff}} = 11,300 \pm 10 \text{ K}$, $-\log(\text{MH}/M) = 9.15 \pm 0.01$, $-\log(\text{MHe}/M) = 4.94 \pm 0.01$, and $\sigma_{\text{rms}} = 0.06 \text{ s}$. This model has a very thin hydrogen atmosphere, and two observed modes (f06 and f08) are identified as trapped modes. Based on optimal model_1, the calculated asteroseismological distance is $83.91 \pm 0.48 \text{ pc}$, slightly farther than the Gaia distance ($81.19 \pm 0.26 \text{ pc}$). For optimal model_2, the parameters are $M^* = 0.720 \pm 0.005 M_\odot$, $T_{\text{eff}} = 11,910 \pm 10 \text{ K}$, $-\log(\text{MH}/M) = 6.11 \pm 0.01$, $-\log(\text{MHe}/M) = 3.09 \pm 0.01$, and $\sigma_{\text{rms}} = 0.04 \text{ s}$.

The asteroseismological distance based on optimal model_2 is 76.04 ± 0.09 pc, slightly closer than the Gaia distance. The fitting errors for our optimal models are reduced by at least 93% compared to Romero et al. (2022).

The central oxygen abundances for optimal model_1 and optimal model_2 are 0.71 and 0.72, respectively, consistent with existing theories of stellar structure and evolution (Salaris et al. 2010; Althaus et al. 2010a). As WDs represent the final stage of stellar evolution, the central oxygen abundance is influenced by the structure and evolution of their progenitor stars. Asteroseismological studies of WDs offer opportunities to explore additional physical information about their progenitors. We must conduct asteroseismological research on more WDs from the ongoing TESS mission and the upcoming PLATO mission (Rauer et al. 2014).

Acknowledgments

This work is supported by the International Centre of Supernovae, Yunnan Key Laboratory (No. 202302AN36000101) and the Yunnan Province Youth Talent Project (2019-182).

ORCID iDs

Y. H. Chen <https://orcid.org/0000-0001-8343-3052>

M. Y. Tang <https://orcid.org/0000-0001-9160-2944>

References

- Althaus, L. G., Córscico, A. H., Bischoff-Kim, A., et al. 2010a, *ApJ*, 717, 897
Althaus, L. G., Córscico, A. H., Isern, J., et al. 2010b, *A&ARv*, 18, 471
Bergeron, P., Wesemael, F., & Beauchamp, A. 1995, *ApJ*, 449, 258
Bischoff-Kim, A. 2024, *ApJ*, 974, 183
Bischoff-Kim, A., & Montgomery, M. H. 2018, *AJ*, 155, 187
Bognár, Z., & Sódor, Á. 2024, *A&A*, 684, A76
Bognár, Z., Sódor, A., I. R., C., & Kawaler, S. D. 2023, *A&A*, 674, A204
Bóhm, K. H., & Cassinelli, J. 1971, *A&A*, 12, 21
Borucki, W. J., Koch, D., Basri, G., et al. 2010, *Sci*, 327, 977
Brassard, P., Fontaine, G., Wesemael, F., & Hansen, C. J. 1992, *ApJS*, 80, 369
Brickhill, A. J. 1991, *MNRAS*, 251, 673
Brickhill, A. F. 1975, *MNRAS*, 170, 405
Chen, Y. H. 2022, *ApJ*, 934, 32
Córscico, A. H. 2020, *FrASS*, 7, 47
Córscico, A. H. 2022, *BAAA*, 63, 48
Córscico, A. H., Althaus, L. G., Miller Bertolami, M. M., & Kepler, S. O. 2019, *A&ARv*, 27, 7
Cox, A. N. 2000, *Allen's Astrophysical Quantities* (Berlin: Springer)
Dolez, N., & Vauclair, G. 1981, *A&A*, 102, 375
Duan, R. M., Zong, W., Fu, J. N., et al. 2021, *ApJ*, 922, 2

- Gaia Collaboration 2022, *yCat*, I/355
- Gentile Fusillo, N. P., Tremblay, P. E., Cukanovaite, E., et al. 2021, *MNRAS*, 508, 3877
- Gentile Fusillo, N. P., Tremblay, P. E., Gänsicke, B. T., et al. 2019, *MNRAS*, 482, 4570
- Giammichele, N., Charpinet, S., & Brassard, P. 2022, *FrASS*, 9, 879045
- Giammichele, N., Charpinet, S., Fontaine, G., et al. 2018, *Nat*, 554, 73
- Gianninas, A., Bergeron, P., & Ruiz, M. T. 2011, *ApJ*, 743, 138
- Goldreich, P., & Wu, Y. 1999, *ApJ*, 511, 904
- Guo, J., Chen, Y., Wang, X., et al. 2023, *MNRAS*, 523, 1591
- Guo, J., Chen, Y., Yang, Y., et al. 2024, *MNRAS*, 528, 5242
- Hermes, J. J., Gänsicke, B. T., Kawaler, S. D., et al. 2017, *ApJS*, 232, 23
- Howell, S. B., Sobek, C., Haas, M., et al. 2014, *PASP*, 126, 398
- Jiménez-Esteban, F. M., Torres, S., Rebassa-Mansergas, A., et al. 2018, *MNRAS*, 480, 4505
- Jiménez-Esteban, F. M., Torres, S., Rebassa-Mansergas, A., et al. 2023, *MNRAS*, 518, 5106
- Kepler, S. O., Koester, D., Pelisoli, I., et al. 2021, *MNRAS*, 507, 4646
- Kim, A. 2007, PhD thesis, Univ. of Texas
- Kutter, G. S., & Savedoff, M. P. 1969, *ApJ*, 156, 1021
- Lamb, D. Q., & Van Horn, H. M. 1975, *ApJ*, 200, 306
- Landolt, A. U. 1968, *ApJ*, 153, 151
- Nather, R. E., Winget, D. E., Clemens, J. C., et al. 1990, *ApJ*, 361, 309
- Paxton, B., Bildsten, L., Dotter, A., et al. 2011, *ApJS*, 192, 3
- Rauer, H., Catala, C., Aerts, C., et al. 2014, *ExA*, 38, 249
- Ricker, G. R., Winn, J. N., Vanderspek, R., Latham, D. W., Bakos, G., et al. 2015, *JATIS*, 1, 014003
- Romero, A. D., Córscico, A. H., Castanheira, B. G., et al. 2017, *ApJ*, 851, 60
- Romero, A. D., Kepler, S. O., da Rosa, G. O., & Hermes, J. J. 2024, *arXiv:2407.07260v1*
- Romero, A. D., Kepler, S. O., Hermes, J. J., et al. 2022, *MNRAS*, 511, 1574
- Salaris, M., Cassisi, S., Pietrinferni, A., et al. 2010, *ApJ*, 716, 1241
- Saumon, D., Blouin, S., & Tremblay, P. E. 2022, *PhR*, 988, 1S
- Torres, G. 2010, *AJ*, 140, 1158
- Unno, W., Osaki, Y., Ando, H., Saio, H., & Shibahashi, H. 1989, *Nonradial Oscillations of Stars* (2nd ed.; Tokyo: Univ. Tokyo Press)
- Vincent, O., Barstow, M. A., Jordan, S., et al. 2024, *A&A*, 682, 5
- Winget, D. E., & Kepler, S. O. 2008, *ARA&A*, 46, 157
- Winget, D. E., van Horn, H. M., & Hansen, C. J. 1981, *ApJL*, 245, L33
- Winget, D. E., van Horn, H. M., Tassoul, M., et al. 1982, *ApJL*, 252, L65
- Wood, M. A. 1990, PhD thesis, The Univ. Texas at Austin
- Yang, Y. H., Chen, Y. H., & Tang, M. Y. 2023, *MNRAS*, 522, 6094
- Zong, W., Charpinet, S., Vauclair, G., Giammichele, N., & Van Grootel, V. 2016, *A&A*, 585, A22

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.