Pulsation Analysis of High-Amplitude δ Scuti Stars with TESS

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Abstract

In this work, the pulsation analysis is performed on 83 high-amplitude δ Scuti stars (HADS), which have been observed by the Transiting Exoplanet Survey Satellite. The results show that 49 of these HADS show single-mode pulsation, 27 of them show radial double-modes pulsation (in which 22 of them pulsate with the fundamental and first overtone modes and five of them pulsate with the first and second overtone modes), and seven of them show radial triple-modes pulsation (three of which are newly confirmed triple-mode HADS). The histogram of the fundamental periods and the ratios between the fundamental and first overtone periods show bimodal structures, which might be caused by the stellar evolution in this specific phase. Most of the radial triple-mode HADS have a fundamental amplitude of 41–54 mmag, and 50% of them have similar amplitudes of the fundamental and first overtone pulsation modes. All these hints require further confirmation not only in observations with more HADS samples, but also in theoretical models with suitable treatments of stellar evolution and pulsation.

Full Text

Preamble

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Pulsation Analysis of High-Amplitude δ Scuti Stars with TESS

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Abstract

In this work, we perform pulsation analysis on 83 high-amplitude δ Scuti stars (HADS) observed by the Transiting Exoplanet Survey Satellite. The results show that 49 of these HADS exhibit single-mode pulsation, 27 show radial double-mode pulsation (22 pulsating in the fundamental and first overtone modes, and five pulsating in the first and second overtone modes), and seven show radial triple-mode pulsation (three of which are newly confirmed triple-mode HADS). The histogram of the fundamental periods and the ratios between the fundamental and first overtone periods exhibit bimodal structures, which might be caused by stellar evolution in this specific phase. Most radial triple-mode HADS have a fundamental amplitude of 41–54 mmag, and 50% of them have similar amplitudes for the fundamental and first overtone pulsation modes. All these hints require further confirmation not only through observations with more HADS samples, but also through theoretical models with suitable treatments of stellar evolution and pulsation.

Key words: stars: variables: δ Scuti – stars: oscillations (including pulsations) – stars: evolution

1. Introduction

δ Scuti stars are a classical type of short-period pulsating variable stars, with periods ranging from 15 minutes to 8 hours and spectral classes A-F. In the Hertzsprung–Russell (H-R) diagram, they are located on the main sequence (MS), pre-MS, or post-MS evolutionary stage at the bottom of the classical Cepheid instability strip and are self-excited by the mechanism due to the partial ionization of helium in the outer layers (Breger 2000; Kallinger et al. 2008; Guenther et al. 2009; Handler 2009; Uytterhoeven et al. 2011; Holdsworth et al. 2014; Steindl et al. 2022). Most of them pulsate in radial and non-radial p-modes (Zong et al. 2015), and some also show non-radial g-modes in the low-frequency region simultaneously (hybrid pulsators; see, e.g., Breger & Beichbuchner 1996; Bradley et al. 2015; Yang et al. 2021).

High-amplitude δ Scuti stars (hereafter HADS) are a subclass of δ Scuti stars that have relatively larger amplitudes ($\Delta V > 0.1$ mag) and slower rotations (v sin i < 30 km s^{-1}) in most cases. However, as HADS samples have accumulated, these classical criteria have become less clear (see, e.g., Balona et al. 2012). Most HADS pulsate in single or double radial pulsation modes (Niu et al. 2013; Alton 2019; Bowman et al. 2021; Alton 2022c, 2022; Daszyńska-Daszkiewicz et al. 2022), and some have three radial pulsation modes (Wils et al. 2008; Niu & Xue 2022) or even some non-radial pulsation modes (Poretti et al. 2011; Xue & Niu 2020).

From the perspective of stellar evolution theory, the period variation of a single star has different observed linear period variation rates at different evolutionary stages. As a result, the period variation rate could be an important criterion for determining the evolutionary stage of a star. Based on times of maximum light spanning decades, some HADS can be considered normal stars evolving into a special evolutionary stage, which can be precisely determined according to asteroseismology self-consistently (see, e.g., Niu et al. 2017; Xue et al. 2018, 2022). These results show that HADS should be located in the post-MS evolutionary stage. However, some works show that certain HADS can also be located in the terminal-age main sequence (TAMS) or even MS (see, e.g., Bowman et al. 2021; Sun et al. 2021; Lv et al. 2022; Yang et al. 2022), although the observed period variations are inconsistent with (always significantly greater than) the theoretical model predictions in these works.

In recent years, a large number of HADS have been monitored by the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015), whose continuous photometric data enable us to study their pulsation properties statistically.

2. Methods

We collected 10,731 HADS from the International Variable Star Index (VSX), which were then cross-matched with the TESS input catalog. Finally, we obtained 83 HADS (most with 2-minute cadence flux measurements, except some triple-mode HADS) from the MAST Portal, which were processed by the TESS Science Processing Operations Center (SPOC; Jenkins et al. 2016). After converting the normalized fluxes to magnitudes using the TESS magnitude and removing long-term trends in each Sector, we selected the light curves from one Sector (with the smallest standard deviation among all Sectors) for each of the 83 HADS to perform the pre-whitening process.

In the pre-whitening process, we used the software Period04 (Lenz & Breger 2005) to perform Fourier transformations of the light curves, searching for significant peaks in the frequency spectra from 0 to 150 cd^{-1} until no significant peaks remained (S/N > 5.6; Zong et al. 2018). After removing alias frequencies considering the resolution and gaps of the data sets, we obtained the significant frequencies and their amplitudes for each HADS. Each significant frequency was then identified as either an independent frequency or a harmonic/combination of independent frequencies. Finally, we obtained all independent frequencies (and their amplitudes) for each HADS.

These independent frequencies were identified as belonging to radial pulsation modes based on the following period ratios (Stellingwerf 1979): 0.787, 0.632, 0.525, where P_0, P_1, P_2, and P_3 are considered the periods of the fundamental, first overtone, second overtone, and third overtone pulsation modes, respectively. In this work, we strictly follow these relations to perform the identification. Independent frequencies that did not follow these relations were considered to belong to non-radial pulsation modes, which are not the focus of this work. For convenience, the fundamental mode, first overtone mode, and second overtone mode are abbreviated as F, 1O, and 2O, respectively.

3. Results

Among the 83 HADS, we find 49 single-mode HADS, 27 radial double-mode HADS (22 with F and 1O pulsation and five with 1O and 2O pulsations), and seven radial triple-mode HADS.

3.1. Single-mode HADS

In Table 1, we list the single-mode HADS with their periods and amplitudes. In the following statistical analysis, all these single-mode HADS are assumed to be pulsating in their fundamental modes, although this may not be correct in all cases and requires further research based on additional stellar information. An interesting work by Pietrukowicz et al. (2020) finds that the shapes of light curves differ between single-mode fundamental and first overtone δ Scuti stars, but this needs further verification and requires clear quantitative criteria for application.

3.2. Double-mode HADS

In Table 2, we list the 27 radial double-mode HADS with their periods and amplitudes, together with the period and amplitude ratios of the double modes. Of particular interest, five HADS pulsate in the 1O and 2O modes (V0488 Gem is a newly confirmed such star), and five HADS have larger amplitudes in the 1O mode than in the F mode, as denoted in Table 2. The origins of these differences should be related to pulsation mode selection mechanisms and warrant in-depth study in the future.

3.3. Triple-mode HADS

In Table 3, we list the seven radial triple-mode HADS with their periods and amplitudes, together with the ratios of periods and amplitudes of different pulsation modes. We also note that three HADS have larger amplitudes in the 1O mode than in the F mode, which might be related to the same phenomenon observed in double-mode HADS.

Up to now, only 15 HADS have been confirmed to pulsate in the first three radial modes (the fundamental mode plus the first and second overtones) in the galaxy: V829 Aql (Handler et al. 1998), GSC 762-110 (DO CMi) (Wils et al. 2008), GSC 03 144-595 (Mow et al. 2016), GSC 08 928-01300 (Yang et al. 2021), V761 Peg (Kazarovets et al. 2020), two cases from Khruslov (2014) (V0803 Aur and V1647 Sco), four cases from the OGLE project (OGLE-GD-DSCT-0021, OGLE-GD-DSCT-0033, OGLE-GD-DSCT-0048, and OGLE-GD-DSCT-0049), and four cases from Khruslov (2022) (GSC2.3 NBY9001324, GSC2.3 NAVT000282, GSC2.3 S5SR001526, and GSC2.3 S4NM025687). Additionally, two triple-mode HADS have been confirmed in the Large Magellanic Cloud (OGLE-LMC-DSCT-0927 and OGLE-LMC-DSCT-2345) (Poleski et al. 2010). These stars exhibit different pulsating properties compared to other HADS, which would help us understand the selection mechanism of pulsation modes more deeply (Niu & Xue 2022).

In this work, three radial triple-mode HADS are newly confirmed: ASAS J094303-1707.3, V1384 Tau, and V1393 Cen. Their light curves and frequency spectra are shown in Figures 1, 2, and 3, respectively. The continuous photometric data provide us with an opportunity to study their nature in the near future.

4. Discussions and Conclusions

Although the sample size is not large, the statistical analysis of pulsation properties for all 83 HADS in Tables 1, 2, and 3 provides some hints about the different origins of the three types.

Figure 4 shows the distribution of P_0 (period of fundamental pulsation mode) for 78 HADS (excluding radial double-mode HADS pulsating with 1O and 2O). We can see that most P_0 values are concentrated in the range of 0.08 to 0.13 days. In detail, there is a small peak at about 0.2 days, which might be related to two possible evolutionary stages of HADS (MS and post-MS).

Figure 5 shows the distribution of A_0 (amplitude of the fundamental pulsation mode) for the 78 HADS (excluding radial double-mode HADS pulsating with 1O and 2O). We can see that most A_0 values are concentrated in the range of 30–130 mmag. The distribution decreases slowly when $A_0 > 130$ mmag while dropping sharply when $A_0 < 30$ mmag (which might be caused by the selection criterion of the HADS samples). All triple-mode HADS have A_0 in the range of 30–80 mmag. If we consider the particularity of GSC 08 928-01300 (a δ Scuti and γ Dor hybrid star; Yang et al. 2021), all other triple-mode HADS have A_0 values from about 41 to 54 mmag. The low amplitude of these HADS can be explained by the fact that more pulsation modes must share the driving energy in the ionization zones, while their concentrated distribution might be a feature of this type of star rather than a coincidence, which needs more samples to confirm.

Figure 6 shows the distribution of P_1/P_0 (period ratio of the first overtone to the fundamental pulsation mode) for 29 HADS (excluding single-mode HADS and double-mode HADS pulsating with 1O and 2O). The distribution for double-mode HADS shows an obvious bimodal structure, while that for triple-mode HADS shows a relatively smooth distribution from about 0.763 to 0.778.

Figure 7 shows the distribution of A_1/A_0 (amplitude ratio of the first overtone to the fundamental pulsation mode) for the 29 HADS (excluding single-mode HADS and double-mode HADS pulsating with 1O and 2O). We can see that most A_1/A_0 values of double-mode HADS are concentrated in the range of about 0 to 0.5. What is interesting is that over 60% of triple-mode HADS have A_1/A_0 values around 1.0 (from about 0.8 to 1.2), which could be ascribed to coupling between the fundamental and first overtone modes in these stars. For example, in the triple-mode HADS KIC 6382916 (GSC 03 144-595), the three pulsation modes are related by the resonance relationship $2f_1 + \Delta\omega = f_0 + f_2$ (where $\Delta\omega$ is the rotation frequency of the star), which couples the fundamental and first overtone modes together (Niu & Xue 2022).

In Figure 8, we plot the Petersen diagram of the 29 HADS (which have fundamental and first overtone pulsation modes, excluding single-mode HADS and double-mode HADS pulsating with 1O and 2O), together with evolutionary tracks of single stars calculated by MESA (Paxton et al. 2011, 2013, 2015, 2018, 2019) and GYRE (Townsend & Teitler 2013; Townsend et al. 2018; Goldstein & Townsend 2020), with solar element abundances: X = 0.7438, Y = 0.2423, and Z = 0.0139 (Asplund et al. 2021); the mixing-length parameter: $\alpha\{MLT\}$ *= 1.89 (Niu et al. 2017); and convective overshooting (Herwig 2000) whose exponential parameter depends on stellar mass M (in solar masses):* $f\{\mathrm{ov}\}$ = (0.13M - 0.098)/9.0 (Magic et al. 2010) from MS to post-MS with masses from 1.5 to 2.5 M in steps of 0.1 M . As a comparison, the evolutionary tracks are also plotted in the H-R diagram. The period change rate of the fundamental mode (which can be treated as a marker of the stellar evolutionary rate of the star) is also plotted in different evolutionary regions: 10^{-8} yr^{-1} < $|P/P_0|$ < 10^{-6} yr^{-1}, and $|P/P_0| > 10^{-6}$ yr^{-1}. In each evolutionary track, the round symbol corresponds to the overall contraction phase after MS (commonly known as the "hook" in the H-R diagram), which is a quite rapid evolutionary phase in the range from MS to post-MS (Aerts et al. 2010). What is interesting is that these most rapidly evolving states in each evolutionary track start when P_1/P_0 0.77, which is clearly represented in the Petersen diagram of Figure 8. As a result, if we assume that HADS are normal stars evolving in the MS to post-MS phase, the distribution of their P_1/P_0 would have a gap at about 0.77 and show a bimodal structure, which is consistent with the result shown in Figure 6. This gives us a hint that the pulsation properties of HADS might be related to their evolutionary phases, which should be tested and confirmed with more samples in the future.

Although the evolutionary tracks are simply constructed based on solar element abundances, tracks with different element abundances have similar round evolutionary phases (even though they will have overall shifts). If we combine all these tracks together, there still exists a most rapidly evolving state in the Petersen diagram around P_1/P_0 0.77.

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