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Asteroseismology of hot subdwarf B stars observed with TESS: discovery of two new gravity mode pulsating stars

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Abstract

TIC 033834484 and TIC 309658435 are long-period pulsating subdwarf B stars, which were observed extensively (675 and 621 days, respectively) by the Transiting Exoplanet Survey Satellite (TESS). The high-precision photometric light curve reveals the presence of more than 40 pulsation modes including both stars. All the oscillation frequencies that we found are associated with gravity (g)-mode pulsations, with frequencies spanning from $\sim$80 μHz (2 500 s) to $\sim$400 μHz (12 000 s). We utilize the asteroseismic tools including asymptotic period spacings and rotational frequency multiplets in order to identify the pulsational modes. We found dipole ($l = 1$) mode sequences for both targets and calculate the mean period spacing of dipole modes ($\Delta P_{l=1}$), which allows us to identify the modes. Frequency multiplets provide a rotation period of $\sim$64 d for TIC 033834484. From follow-up ground-based spectroscopy, we find that TIC 033834484 has an effective temperature of 24 210 K (140), a surface gravity of log g/cms^{-2} = 5.28 (03) and TIC 309658435 has an effective temperature of 25 910 K (150), a surface gravity of log g/cms^{-2} = 5.48 (03).

Keywords: asteroseismology — stars: oscillations (including pulsations) — stars: interiors — stars: evolution — stars: horizontal-branch — stars: subdwarfs — Stars: individual: TIC 033834484, TIC 309658435

1. Introduction

One of the major progresses in our understanding of sdB stars was initiated by Kilkenny et al. (1997) discovering rapid pulsations in hot sdBs known as V361 Hya stars (often referred to as short-period sdBV stars). The V361 Hya stars show multiperiodic pulsations with periods spanning from 60 s to 800 s. Green et al. (2003) discovered the long-period sdB pulsators known as V1093 Her stars. These stars show brightness variations with periods up to a few hours and have amplitudes smaller than 0.1 per cent of their mean brightness. In the first group, the pulsational modes correspond to low-degree, low-order pressure (p)-modes while in the second group, the pulsational modes correspond to low-degree, medium- to high-order gravity (g)-modes. Some sdB pulsators showing both g- and p-modes have been discovered among the two described families of pulsating sdB stars. These stars are referred to as hybrid sdB pulsating stars. These modes are excited by a classical κ-mechanism due to the accumulation of the iron group elements (mostly iron itself), in the Z-bump region (Charpinet et al., 1996, 1997; Fontaine et al., 2003). The authors also showed that radiative levitation is a key physical process to enhance the abundances of iron group elements in order to be able to excite the pulsational modes.

With the advance of high precision (~ 0.02 μHz) and high duty cycle (> 90 %) photometric monitoring from space, unprecedented asteroseismic measurements and tools have become available for sdB pulsators. The non-radial oscillations observed in pulsating sdBs offer a unique way to probe these stars resolving their pulsation geometry, which is described by three quantized numbers: l (modal degree) defines total surface nodes, n (radial order) characterizes radial nodes from core to the surface and m (azimuthal order) describes surface nodes which pass through the pulsation axis.

For almost all the sdBVs observed from space, the asymptotic period sequences for g-mode pulsations have been successfully applied, especially for dipole and quadrupole modes, as more than 60% of the periodicities are associated with these modes (Reed et al., 2011). The asymptotic approximation can be perfectly applied for homogeneous stars. However, sdB stars are stratified and diffusion processes (gravitational settling and radiative levitation) contribute significantly to compositional discontinuities, which disturb the pulsational modes and could break the sequences. This effect was also seen in a few sdBV stars observed with Kepler (Uzundag et al., 2017). Furthermore, when the compositional discontinuities become stronger at the transition zones, some modes are trapped, and this effect was also seen in a few sdBV stars observed with Kepler.

Another asteroseismic tool, rotational multiplets, is useful to identify the pulsation modes as well as to determine the rotation period of the core and the surface of sdBVs. Single sdB stars tend to have a much longer rotation period from 16 d to 289 d (review by Charpinet et al. 2018, see also Silvotti and Németh 2022). While sdBs in binaries have shorter rotation period between 2.42 h and 14.16 d (Charpinet et al., 2018).

We are still discovering new sdBVs thanks to NASA's latest Transiting Exoplanet Survey Satellite (TESS), which is dedicated to high-precision photometric monitoring of stars from space. Thus far, TESS has monitored thousand of sdB stars with 2-min and 20-sec cadence during 56 sectors. The stars at high latitude region, close to the ecliptic caps, have been observed continuously (CVZ) and several sdBs were found in this zone. In this work, we present the analysis of two new discoveries of hot subdwarf B pulsating stars. TIC 033834484 and TIC 309658435, were observed by TESS during the first and third year in the southern ecliptic hemisphere. We obtained a low-resolution spectrum of each target and applied the model atmosphere models in order to derive the fundamental parameters of the stars. We performed the frequency analysis and detailed seismic mode identification for both targets.

2. Spectroscopy

Intermediate-resolution spectra (R = 3500) of TIC 033834484 and TIC 309658435 were collected during three half-nights of observation between 2015 January 28 and February 22 at Las Campanas Observatory, with the IMACS spectrograph at the focus of the Baade 6.5 m telescope. The instrument was used at f/4 in longslit mode, and the 0".75-wide slit was employed. The 1200−17.5 grating was tilted by an angle of $16^o.8$ to cover the spectral range 3660-5250 Å on the CCD. Figure 1 shows the IMACS spectra together with their best-fit TLUSTY/XTGRID models. The determined spectroscopic parameters demonstrate that TIC 033834484 has $T_{\rm eff} = 24210(\pm 140)$ (K) and $\log g = 5.28(\pm 0.03)$ (cm s^{-2}) while TIC 309658435 has $T_{\rm eff} = 25910(\pm 150)$ (K) and $\log g = 5.47(\pm 0.03)$ (cm s^{-2}). The spectra of both sdB stars are dominated by Balmer-lines and only weak He I lines are seen. Both stars belong to the He-weak sdB spectroscopic group, which overlaps with g-mode sdBV pulsators. The atmospheric parameters are in good agreement with the earlier results by Moni Bidin et al. (2017).

3. Photometric data

TIC 033834484 and TIC 309658435 located in the TESS' CVZ, were observed extensively during 675 and 621 days, respectively. TESS data were examined using both the short-cadence (SC) mode with 2-minute sampling and the ultra-short-cadence (USC) mode with 20-second sampling, allowing us to investigate the frequency range up to the Nyquist frequency at about 25 000 μHz. The Fourier transforms (FT) of the light curves were computed to examine the periodicities present in the data, aiming at identifying the frequency of all pulsation modes, along with their phase and amplitude. We fitted each frequency that appears above the 0.1% false alarm probability (FAP) using a nonlinear least square (NLLS) algorithm as described in (Uzundag et al., 2021). We identified 23 pulsational frequencies for TIC 033834484 spanning from $\sim$2500 s to $\sim$12 000 s, while we extracted 10 pulsational frequencies for TIC 309658435 ranging from $\sim$90 s to $\sim$11 500 s. In Fig. 2, we depict the FT of TIC 033834484 (top panel) and TIC 309658435 (bottom panel) in period domain.

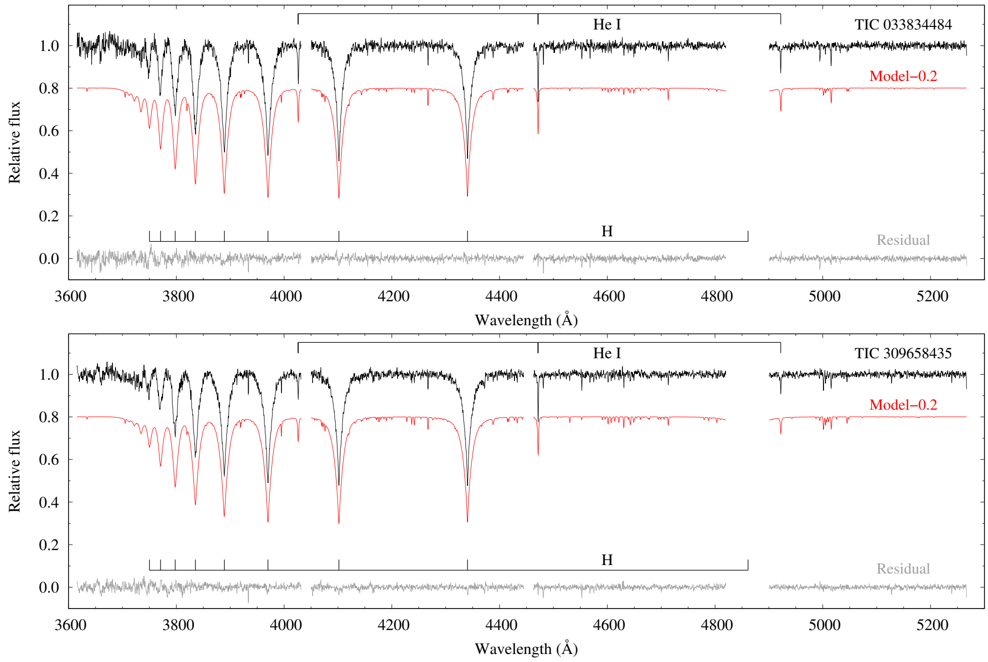

Figure 1: Optical spectra of the two new pulsating hot subdwarf B pulsating stars (black lines). Overplotted are the best-fit atmospheric models (red lines). Identifications of Balmer-lines and weak He I lines are marked.

4. Asteroseismology

4.1. Rotational multiplets

In rotating stars, the pulsation frequencies are split into $2l+1$ azimuthal components due to rotation, revealing equally spaced multiplets of $2l+1$ components. This $2l+1$ configuration can be resolved with high-precision photometry if the star has no strong magnetic field and the rotational period is not longer than the duration of the observation. Also, in order to detect rotationally split modes, the rotational axis has to be aligned with the pulsation axis, otherwise the pulsation frequencies are split into nine components for $l = 1$ mode (Silvotti and Németh, 2022, and references therein). Lastly, the inclination angle has to be different from 0 ($i \neq 0$).

The following equation gives the rotation period ($P_{\rm rot}$) in terms of frequency splitting $\Delta\nu_{n,l,m}$.

$$\nu_{n,l,m} = \nu_{n,l,0} + \Delta\nu_{n,l,m} = \nu_{n,l,0} + m\frac{1-C_{n,l}}{P_{\rm rot}}, \quad (1)$$

where $C_{n,l}$ is the Ledoux constant (Ledoux, 1951), which, in the asymptotic limit, depends on the modal degree as $C_{n,l} = 1/l(l+1)$. For dipole and quadrupole modes therefore we get $C_{n,1} \sim 0.5$ and $C_{n,2} \sim 0.17$, respectively.

For TIC 033834484, we were able to determine a frequency splitting of $\sim$0.0905 μHz (Fig. 2), and therefore this star appears to be another slow-rotating single sdB pulsating star with a rotation period of $\sim$64 days.

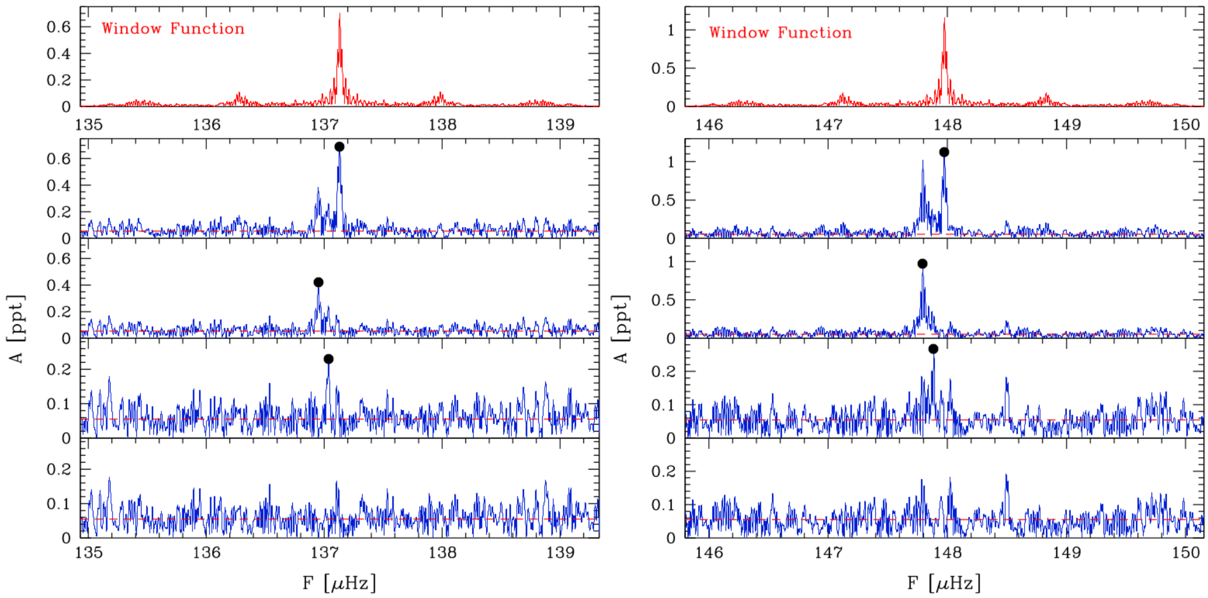

Figure 2: FT of TIC 033834484 showing the region around the frequency triplets near 137 μHz (left panel) and 148 μHz (right panel). From top to bottom we show the window function, the original FT, and the FT of the residuals after subtracting each sequence of frequencies. A black dot represents each prewhitened peak.

TIC 309658435 does not show any multiplets suggesting that it has either a very slow rotation period (longer than ~600 days) or a pole-on orientation of the pulsation axis, or the side components are not driven.

4.2. Asymptotic period spacing

In the asymptotic limit of stellar pulsations, i.e., for large radial orders ($k \gg \ell$), g-modes of consecutive radial order in sdBs are approximately uniformly spaced in period (Tassoul, 1980). The asymptotic period spacing is given by $P_{\ell,n} = \Delta P_0/\sqrt{\ell(\ell+1)}n + \varepsilon_l$, where ΔP_0 is the asymptotic period spacing for g-modes, which is defined as $\Delta P_0 \propto [\int_{r_1}^{r_2} \frac{|N|}{r} dr]^{-1}$, N being the Brunt-Väisälä frequency, the critical frequency of nonradial g-modes (Tassoul, 1980), and ε_l is a constant (Unno et al., 1989). The pulsation spectrum is displayed in units of period in Fig. 3 with the expected locations of the $\ell = 1$ modes for even period spacing indicated. We derived the mean period spacing of dipole modes ($\Delta P_{l=1}$) and found $263.84^{+0.8}_{-1.4}$ s for TIC 033834484, $257.06^{+1.5}_{-1.4}$ s for TIC 309658435. We used a bootstrap resampling analysis as described by Uzundag et al. (2021) in order to propagate the errors in the mean period spacing obtained in our analysis.

5. Results and conclusions

We presented the discovery of two new long-period sdB pulsating stars TIC 033834484 and TIC 309658435. The long dataset allows us to achieve a high frequency resolution of ~0.02

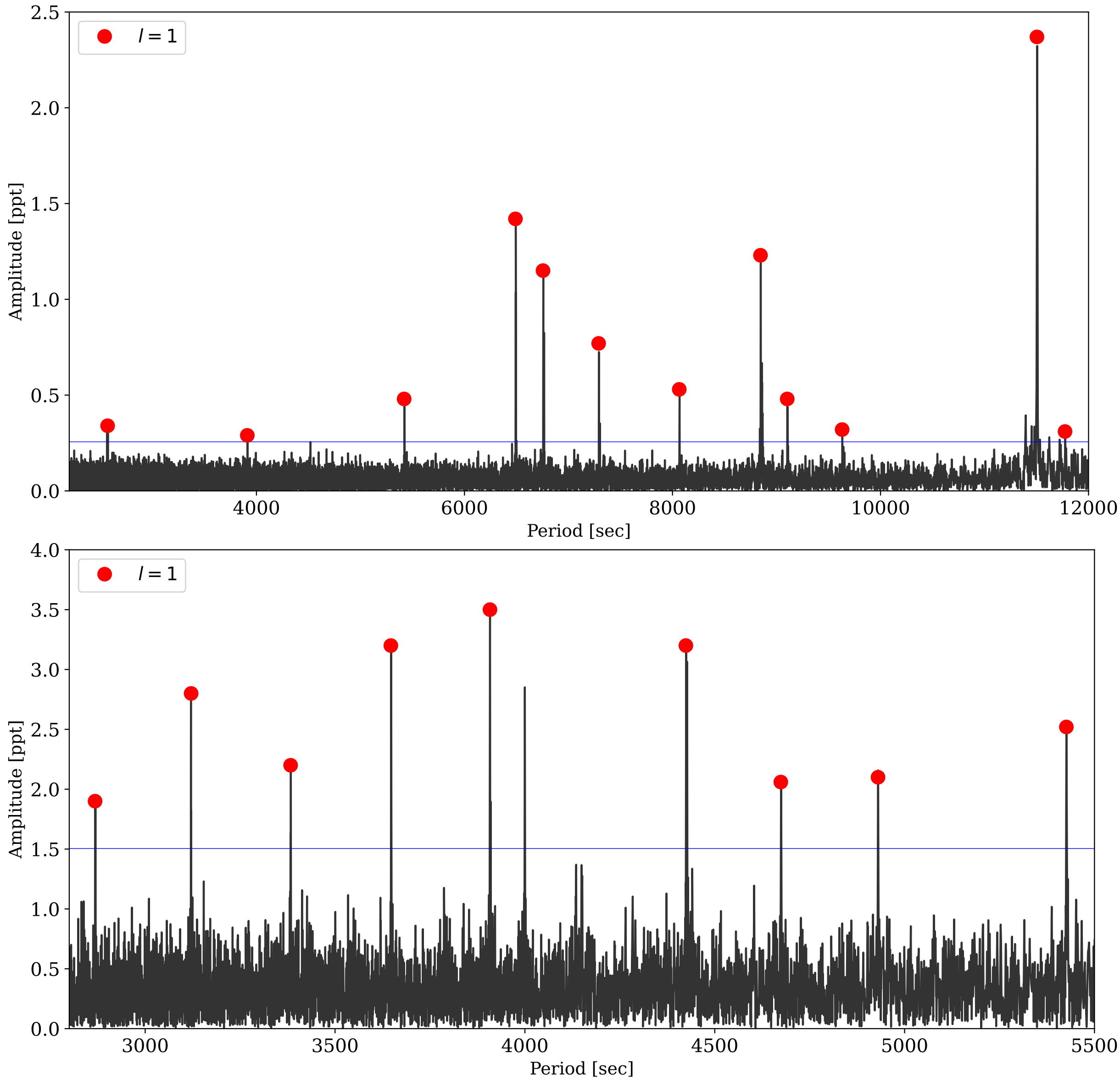

Figure 3: Pulsation spectrum of TIC 033834484 (top panel) and TIC 309658435 (bottom panel) in the period space with the red dots indicating the expected locations of $\ell = 1$ modes from the asymptotic pulsation theory. The horizontal blue lines show the confidence level of 0.1% FAP.

μHz and study the temporal stability of the pulsations, as well as to reveal the rotation period of TIC 033834484. We derived the atmospheric parameters for both stars by fitting synthetic models to the spectra. We investigated the potential variability of the two new sdBVs by examining their short and ultra-short-cadence observations obtained with TESS. Our investigation of the detected frequencies reveals:

- 12 dipole ($l = 1$) modes for TIC 033834484 with the relative radial order between 20 and 44 and mean period spacing of dipole modes ($\Delta P_{l=1}$) = $263.84^{+0.8}_{-1.4}$ s.
- 9 dipole modes for TIC 309658435 with the relative radial order between 11 and 21 and mean period spacing of dipole modes ($\Delta P_{l=1}$) = $257.06^{+1.5}_{-1.4}$ s.
- Rotational triplets for TIC 033834484 with $\Delta\nu_{l=1}$ of $\sim$0.0905 μHz, corresponding to a stellar rotation period of about 64 days, making thi star another slowly rotating single pulsating sdB among ten others (Silvotti and Németh, 2022).

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Further Information

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Author contributions

M.U. and R.S. and A.S.B. carried out the light curve analyses as well as frequency solutions. P.N. performed the atmospheric analysis. The text was written by M.U. All authors contributed to the discussion and interpretation of the results and commented on the written draft of the paper.

Conflicts of interest

The authors declare no conflict of interest.

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