Asteroseismic analysis of subdwarf B variable stars of KIC 10001893 and EPIC 220641886

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Resumen / KIC 10001893 y EPIC 220641886 son estrellas subenanas B pulsantes de tipo V1093 Her. Las mismas han sido observadas por *Kepler* en las misiones nominal y K2, respectivamente. A partir de la amplitud espectral de las estrellas, se puede decir que la mayoría de las frecuencias de sus pulsos se encuentran en modo g. De las frecuencias detectadas, 248 pertenecen al dominio de modo g y 15 dentro del rango de modo p, mostrando la naturaleza híbrida de ambas estrellas. Para identificar el grado de los modos hemos utilizado la herramienta sísmica *asymptotic period spacing*. En nuestro análisis, no hemos podido detectar multipletes rotacionales en ninguna de las dos estrellas, lo cual podría indicar que se encuentran en dirección polar. A la estrella KIC 10001893 le hemos asignado modos dipolares y cuadrupolares, mientras que a la estrella EPIC 220641886 le hemos asignado modos que van desde $l = 1$ hasta $l = 12$, exceptuando los modos $l = 3$ y $l = 11$, que no han sido observados.

Abstract / KIC 10001893 and EPIC 220641886 are V1093 Her type pulsating subdwarf-B stars, which were observed by the *Kepler* spacecraft during nominal and K2 mission respectively. The amplitude spectrum of both stars show similar characteristics that the majority of the pulsation frequencies lay in the gravity g-mode domain. While the g-mode region contains 248 frequencies, the p-mode region contains just 15, altogether indicating the hybrid nature of both stars. We used one of the seismic tools, asymptotic period spacing effectively to identify the modal degree of the majority of the modes. We could not find rotational multiplets for both stars which is likely due to pole-on orientation. We assigned dipole and quadrupole modes for KIC 10001893, while for EPIC 220641886 we defined modal degrees ranging from $l = 1$ to $l = 12$, apart from $l = 3$ and $l = 11$ modes, which are not seen.

Keywords / subdwarfs — stars: oscillations (including pulsations)

1. Introduction

Hot subdwarf stars of spectral class B (sdB) are core helium-burning stars, found both in the disk and halo of our Galaxy. The observed properties locate them in the extreme horizontal branch (EHB) part of the HR diagram. Their effective temperatures range from 20 000 to 40 000 K and surface gravities range from 5.0 $\leq \log g \leq$ 6.2 (in cgs units). They are compact objects with radii typically on the order of 0.2 $R_\odot$ and masses confined to about 0.47 $M_\odot$. These stars have experienced extreme mass-loss at the end of the red giant branch phase, in which nearly entire hydrogen envelope is lost, leaving a helium burning core with a very thin inert hydrogen-rich envelope ($M_{\rm env} < 0.01$ $M_\odot$) unable to ascend the asymptotic giant branch. After depletion of helium in the core, they will become subdwarf O (sdO) stars burning helium in a shell surrounding a C/O core and, eventually, they will end their lives as DAO white dwarfs (Heber, 2016). SdB stars are found to pulsate with short period p-modes known as V361 Hya stars and long period g-modes known as V1093 Her stars. Theoretically, Charpinet et al. (1996) explained excitation mechanism for V361 Hya stars as low-order acoustic modes, while Fontaine et al. (2003) explained the excitation mechanism for V1093 Her stars as high-order g-modes. The short period pulsators have frequencies higher than 2000 μHz, while the long period pulsators have frequencies usually below than 1000 μHz, which makes them quite hard to detect from the ground. The V361 Hya stars are found between 28 000 K and 35 000 K with higher surface gravity $\log g$ and V1093 Her pulsators are somewhat cooler with temperatures ranging from 24 000 K to 30 000 K and lower $logg$. There exist also sdB stars that display both kinds of pulsation modes and referred to as hybrid pulsators (Baran et al., 2005). Their nature as hybrid pulsators, gives an invaluable opportunity to understand both the core and the envelope behavior of the stars. Understanding the interior structure of a pulsator heavily depends on the identification of the pulsation modes; which can be achieved by the analyses of precise photometric data using asteroseismological tools. High-precision *Kepler* photometry allowed us to detect many frequencies that we had never obtained previously. Non-radial pulsations are described by spherical harmonics as radial nodes, surface nodes and azimuthal orders n, l, m respectively. The detection of the frequencies with high resolution is a key point to apply asteroseismological methods such as rotational multiplets and asymptotic period spacing to identify the spherical harmonics. In this paper, we present our analysis of two pulsationally rich long period hybrid sdB stars KIC 10001893 and EPIC 220641886. KIC 10001893 was studied extensively by Baran et al. (2011); Silvotti et al. (2014); Uzundag et al. (2017). The star was observed during the nominal mission of *Kepler* and it yields millions of data points which allow us to characterize pulsation properties of the star. EPIC 220641886 (=HD 4539) is a well known, bright (V = 10.24 mag), sdB star for which g-mode pulsations have been suspected but not confirmed (Schoenaers & Lynas-Gray, 2007). From observations made by the *Kepler* spacecraft during K2 mission, which after failure of the second wheel of *Kepler*, the duty of the mission changed slightly and this makes the data much shorter in comparison with the normal mission of the spacecraft.

Here, using the *Kepler* data, we provide a detailed analysis of KIC 10001893 and EPIC 220641886. Firstly, we have calculated Fourier spectra of the stars. Then, using asteroseismological tools such as asymptotic period spacing and rotational multiplets, we have identified the pulsational modes of both stars. After identification of the pulsational modes, we constructed the échelle diagrams.

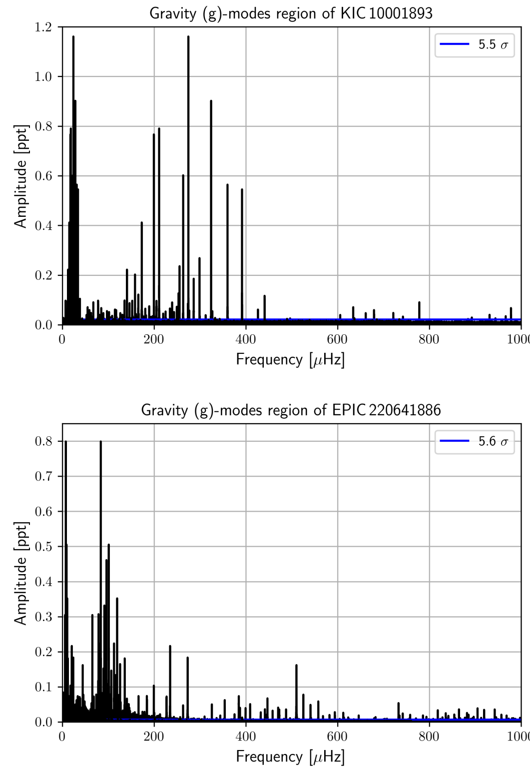

Figure 1: Amplitude spectra of KIC 10001893 and EPIC 220641886, the figures only cover gravity mode regions of the targets.

2. Methods

After we got all available data from the "Barbara A. Mikulski Archive for Space Telescopes" (MAST)*, we started to extract light curves of the objects. We used short-cadence (SC) data allowing for covering the frequency range up to 8495 μHz, and assuring both p- and g-modes regions are covered. Then, in order to identify pulsation frequencies of the targets, we used Fourier technique to calculate the amplitude spectrum of both stars Fig. 1.

2.1. Rotational multiplets

In the presence of stellar rotation, non-radial modes of degree l split into $2\,l+1$ components differing in azimuthal (m) number. In the case of slow rotation, the frequency splitting can be derived from the following equation:

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

where $\Delta\nu_{n,l,m}$ is a rotational splitting, $\mathrm{P_{rot}}$ is a star's rotation period and $C_{n,l}$ is the Ledoux constant (Ledoux, 1951). The method is quite useful both for identification of the pulsation modes and for determining the rotation period of the surface and the core. However, we could not use this method for any of the two stars. The method is strongly dependent of both the inclination of the star and on the frequency resolution. If the stars are pole-on oriented, there is no way to see azimuthal orders on surface of the star and therefore their amplitude spectra. Another dependence is frequency resolution to apply the method, in fact, the frequency resolution is enough for KIC 10001893, the star does not show any tendency amongst frequencies concerning splitting value so it is quite possible that the star is either pole-on oriented or rather slow rotator. However, it is harder to evaluate the amplitude spectra of EPIC 220641886 due to shorter length of the data and thus lower resolution.

*archive.stsci.edu

2.2. Asymptotic period spacing

In order to identify the pulsation modes in the g - mode region, we used asymptotic period spacing. In the asymptotic limit ($n >> l$), consecutive radial overtones are evenly spaced in period Charpinet et al. (2000). For given n and l values, periods of consecutive overtones can be derived from the following equation,

$$\Pi_{l,n} = \frac{\Pi_0}{\sqrt{l(l+1)}}n + \epsilon, \qquad (2)$$

where $\Pi_{l,n}$ is the period spacing, Π_0 and ϵ are constants.

3. Results

We found 110 oscillation frequencies for KIC 10001893 and 153 frequencies for EPIC 220641886. We defined the threshold as 5.4 and 5.6 sigma, respectively, to make sure the signals are produced by the stars intrinsically. The sigma is calculated based on median value of whole range of Fourier spectra. Then, it has been multiply by 5.4 for normal mission of *Kepler* (KIC 10001893) and 5.6 for K2 mission (EPIC 220641886).

3.1. KIC 10001893

The frequency resolution equals 0.0162 μHz as defined by $\Delta f = 1.5/T$, where T is the time coverage of the data. We identified 110 oscillation frequencies including p- and g-modes region. After identification of the frequencies, we have started to search for pulsational modes using asymptotic period spacing. We identified 50 modal degrees among the g-modes, which is more than 49% of the modes. Out of those 50 modes, 32 are dipole modes and 18 are quadrupole modes. Additionally, we calculated échelle diagrams for $l=1$ and 2 and the diagram for dipole modes shows a common feature of a horizontal shift that called as a hook feature (for detail Baran & Winans, 2012; Uzundag et al., 2017).

3.2. EPIC 220641886

We have analysed K2 observations of one of the brightest known sdBs, confirming the previous report by Schoenaers & Lynas-Gray (2007) that EPIC 220641886 is a V1093 Her-type pulsator. We identify more than 150 pulsation frequencies (144 g-modes, 9 p-modes). Although the frequency resolution is 11 times worse than nominal *Kepler* mission, the amplitude spectra of the star displays quite rich content in terms of g-modes. We have identified 10 sequences between $l=1$ and $l=12$, excluding $l=3$ and $l=11$ which are not seen, likely due to cancellation effects. Since the period spacing changes with l (gets lower with increasing l), the identification of the modes seems quite robust, at least up to $l=6$. It is obvious that cancellation effects are important for high-l modes (Dziembowski, 1977), we are able to see them in EPIC 220641886 is simply due to the fact that this star is particularly bright. In addition to that the modes are visible in the échelle diagrams for $1 \leq l \leq 12$ (Silvotti, Uzundag, et al. 2019, in prep). Here, we present the échelle diagrams for dipole and quadrupole modes Fig. 2.

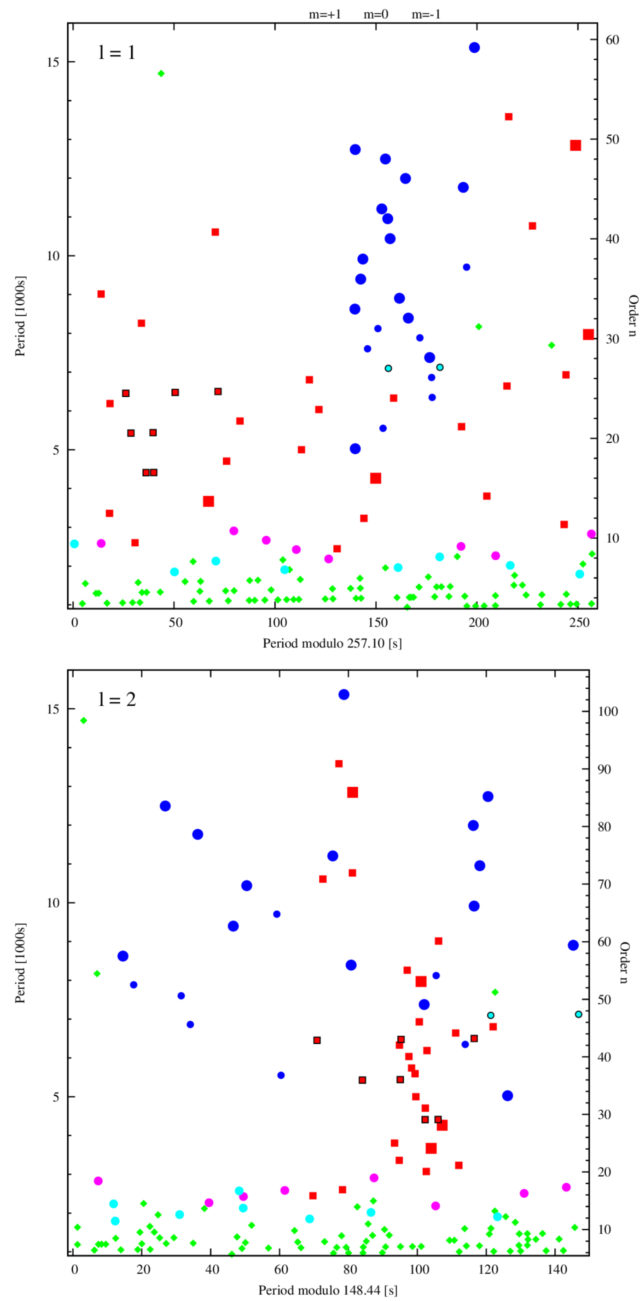

Figure 2: Échelle diagrams of EPIC 220641886 for dipole and quadrupole modes.

4. Conclusion

We have shown our analyses of two long period subdwarf B pulsating stars. Both objects show quite rich contents in terms of g-modes, which are sensitive to the core properties of the stars. In total, we identified 248 g-modes, 15 p-modes in both stars. Both stars are hybrid which can be an important feature to constrain both the core and the envelope parameters. Thanks to uninterrupted observations, the seismic tools are becoming quite useful for pulsating sdB stars, specifically, asymptotic period spacing. Using asymptotic relations, we have identified sequences of near-consecutive modes for degrees ($1 \leq l \leq 2$) for KIC 10001893, ($1 \leq l \leq 12$) for EPIC 220641886 which will be crucial to make future asteroseismic modeling of both stars.

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