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An Analysis of Pulsating Subdwarf B Star EPIC 203948264 Observed During Campaign 2 of *K2*

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Abstract. We present a preliminary analysis of the newly-discovered pulsating subdwarf B (sdB) star EPIC 203948264. The target was observed for 83 days in short cadence mode during Campaign 2 of *K2*, the two-gyro mission of the *Kepler* space telescope. A time-series analysis of the data revealed 22 independent pulsation frequencies in the $g-$mode region ranging from 100 to 600 μHz (0.5 to 2.8 hours). The main method we use to identify pulsation modes is asymptotic period spacing, and we were able to assign all but one of the pulsations to either $\ell = 1$ or $\ell = 2$. The average period spacings of both sequences are 261.34 ± 0.78 s and 151.18 ± 0.34 s, respectively. The pulsation amplitudes range from 0.77 ppt down to the detection limit at 0.212 ppt, and are not stable over the duration of the campaign. We detected one possible low-amplitude, $\ell = 2$, rotationally split multiplet, which allowed us to constrain the rotation period to 46 days or longer. This makes EPIC 203948264 another slowly rotating sdB star.

1 Introduction

The K2 mission is the extension of the very successful *Kepler* mission. With only two remaining gyros, the spacecraft uses solar radiation pressure and regular thruster firings to ensure accurate pointing to within a pixel. Observing fields are restricted to lie along the ecliptic plane, where the spacecraft can observe them for around ∼ 80 days at a time [1].

Despite some limitations of the *K2* mission, the unprecedented photometric data obtained by *Kepler* has enabled asteroseismologists to study pulsating subdwarf B stars (sdB) in great detail. These stars are located on the extreme horizontal branch and consist of helium-rich cores that are surrounded by thin hydrogen envelopes. The processes for stripping off the envelopes are not well understood, but a likely mechanism is binary interaction [2]. After leaving the horizontal branch, their hydrogen shells are too thin to sustain shell fusion and they proceed directly to the white dwarf cooling track. Subdwarf B stars typically have masses around $0.47 M_\odot$, and effective temperatures ranging from 20,000 to 40,000 K [3].

Many sdB stars have been found to exhibit stellar pulsations. The V361 Hya class are short-period, pressure(*p*)-mode pulsators with periods of a few minutes while the V1093 Her class are longer period, gravity (*g*)-mode pulsators with periods of one to a few hours. The V361 Hya stars tend to be hotter, the V1093 Her cooler,

and hybrid pulsators, with both types of pulsations have intermediate temperatures. For a pre-Kepler pulsation review, see Østensen[4].

EPIC 203948264 was observed during Campaign 2 as part of our Guest Observer proposal. We obtained spectroscopy which indicated EPIC 203948264 to be in the $g-$mode instability region and these K2 observations indicate it to be a pulsator. Our goal for EPIC 203948264 was to identify the modes of the detected pulsations using asymptotic period spacings and rotationally induced frequency multiplets. Reed et al. discovered that sdB stars exhibit asymptotic period spacings in the $g-$mode region, with the $\ell = 1$ sequence equally spaced by about 250 s [5]. In addition, rotationally split multiplets have been used to identify the ℓ and m modes of pulsations [e.g. 6, 7]. Stellar rotation lifts the frequency degeneracy and gives rise to frequency multiplets whose splittings follow the relation $\Delta \nu = \Delta m \Omega (1 - C_{n,\ell})$. $\Delta \nu$ represents the shift from the central frequency ($m = 0$), Ω is the rotation frequency of the star, and the Ledoux constant for $g-$modes is given by $C_{n,\ell} \approx 1/[\ell(\ell + 1)]$ [8]. We can determine the Ledoux constant from period spacing and if we can observe and measure the splitting of multiplets, we can calculate the rotation period of the star.

2 The Data

Kepler observed EPIC 203948264 during Campaign 2 of *K2* in short cadence (SC) mode with an integration time of 58.85 seconds. The Kepler Science office does not


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provide processed SC lightcurves and so we have developed our own custom processing pipeline to extract a lightcurve from the pixel files. Our custom method uses centroiding to determine the stellar center which we follow with round apertures of multiple sizes. We choose the aperture which optimizes the signal-to-noise. Similar to the *Kepler*–developed PyKE software [9], we use pixel–brightness correlations to remove flux variations caused by spacecraft-induced motion from the drift and thruster firings. We compare our custom processed data to PyKE extraced data in oder to search for low-level pulsations that are consistent in both methods.

3 The Analysis

Due to pointing adjustments in the beginning of Campaign 2, we processed only 79 days of the 83-day-long observing campaign. The $1/T$ temporal resolution of the data is $0.147\,\mu$Hz, and we calculated a standard deviation of the Fourier spectrum to be 0.049 ppt. To make it statistically unlikely for peaks to be generated by noise, we chose a detection limit of 4.3σ (0.212 ppt) [10]. Based on simulated data, we chose a second detection threshold of 5.2σ (0.256 ppt) [11].
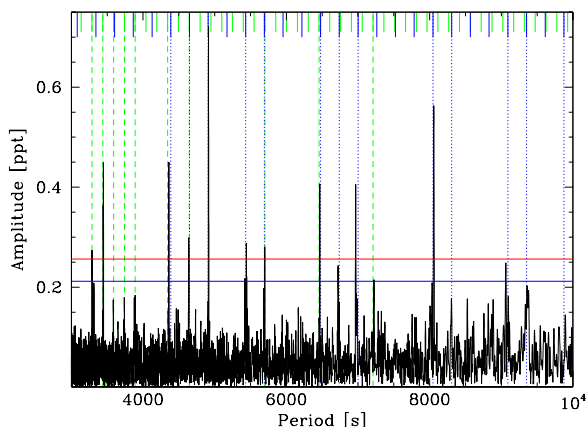
Figure 1: Period transform highlighting the evenly spaced periods in the g–mode region. The short green (blue) lines at the top indicate the asymptic $\ell = 1$ (2) sequence. The dashed lines indicate which periods match the asymptic sequences. The horizontal blue (red) line represents the 4.3σ (5.2σ) detection limit.

We plotted the Fourier spectrum and selected all the peaks above the detection threshold. Figure 1 shows a period transform of the 22 detected pulsations. Their periods range from 1660 to nearly 9900 s (101μ to 602μ Hz). Asymptotic period spacings have been detected in all Kepler-observed sdB g–mode pulsators [5] and they all showed similar spacings of around 250 s for the $\ell = 1$ sequence and 145 s for $\ell = 2$. Once we had our list of detected periods, we started testing for evenly spaced periods using a Kolmogorov-Smirnov (KS) test. This test has been successfully used in sdB stars to indicate common spacings in the pulsation periods. The result of the

KS test revealed two common spacings: 260 s and 150 s. We pick out periods with these separations, assign relative overtones, n, and then do a linear regression fit. The solutions, 261.34 ± 0.78 for the $\ell = 1$ and 151.18 ± 0.34 s for the $\ell = 2$ sequence agree with asymptotic theory, $\prod_{\ell=2} = \prod_{\ell=1} / \sqrt{3}$ [8], and are in agreement with other *Kepler*–observed g–mode pulsators [5]. Using asymptotic period spacings we identified all but one of the pulsations as $\ell = 1$ or $\ell = 2$, with four of them matching both sequences. The unidentified period was the shortest one, which likely does not match the asymptotic criterion of $n \gg \ell$. We also searched for frequency multiplets with the goal of determining the rotation period of the star and identifying ℓ and m modes. In the case of EPIC 203948264, we were only able to find one possible multiplet, an $\ell = 2$ triplet with a splitting of $0.210 \pm 0.004\mu$Hz.
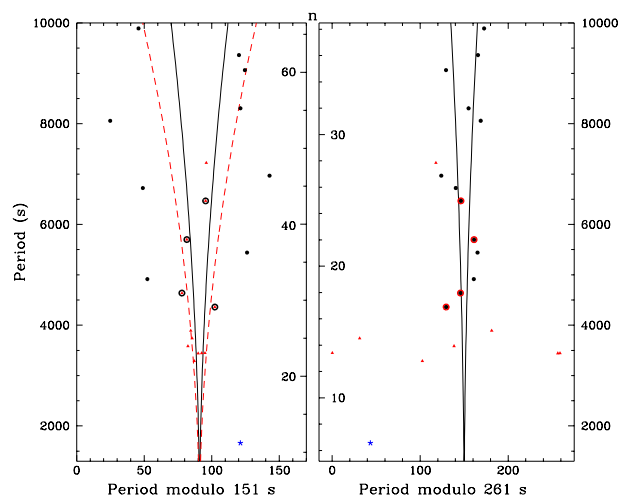
**Figure 2:** Échelle diagram for the $\ell = 2$ (left) and $\ell = 1$ (right) g-modes. Periods found to be $\ell = 1$ ($\ell = 2$) are shown in black (red). Periods that fit both sequences are displayed in both colors, and the unidentified period is shown as a blue star. The curved lines show how frequency splittings translate into period space.

From *Kepler* data, we know that sdB pulsators have amplitudes which can change substantially and show variability in frequency with time. Therefore we use sliding Fourier transforms (SFTs) to investigate the behavior of pulsations in the time domain. For EPIC 203948264, we used data spanning eight days with one day steps, and these are shown in Figure 3 for all regions of variability.

4 Conclusions

From 79 days of K2 data we were able to extract 22 individual pulsations and one possible multiplet. Asymptotic period spacing was used to identify all but one of the pulsations with low-degree ℓ modes. The period transform in Figure 1 shows the pulsations that fall on the $\ell = 1$ and/or $\ell = 2$ sequence. Upon closer inspection one can see that some of the peaks deviate from the sequence lines. However, the deviations are small which implies that the compact, high gravity sdB stars are less stratified
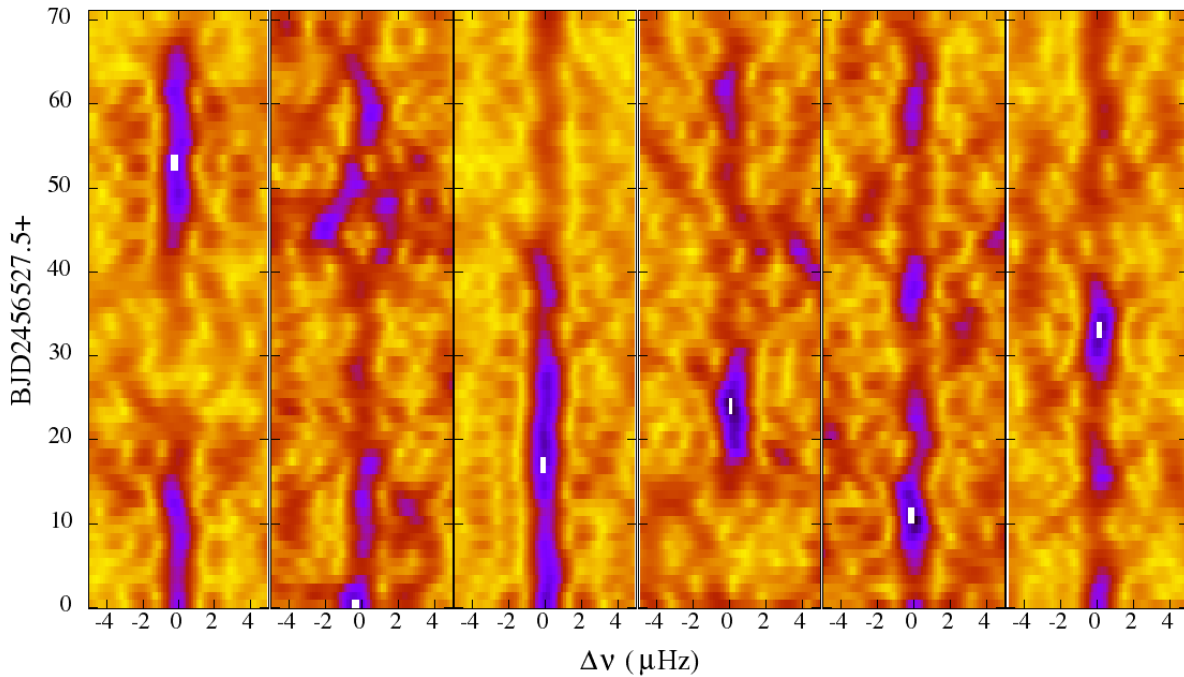
Figure 3: Series of sliding Fourier transforms highlighting the amplitude and frequency variations of six pulsations over time. Note: color indicates the amplitude in terms of σ, but the windows do not follow the same scale.

and more homogeneous than originally considered. The échelle digram (Fig. 2) makes these slight deviation more apparent. The $\ell = 1$ sequence in the right panel of the plot shows a clear "hook" feature, which has been observed in some other sdB pulsators [12, 13]. Models have also shown this feature [14] and it is attributed to a mode trapping feature dependent upon evolution and envelope mass. It will be interesting to calculate échelle digrams for other *Kepler*–observed sdB stars, do an ensemble analysis to correlate this "hook" feature with spectroscopic quantities and to supply additional constraints for models of sdB interiors.

We have identified the only possible multiplet as $\ell = 2$ via asymptotic period spacings. Multiplets are usually related to stellar rotation which lifts the azimuthal degeneracy and gives rise to separations in frequency. If we observe a triplet with $\Delta m = 1$, the rotation period would be 45.9 ± 0.8 days, and if we observe only the outside members of a quintuplet, $\Delta m = 2$, the rotation period would be 91.8 ± 1.5 days. Both rotation periods agree with values measured in other apparently single sdBV stars [15]. An explanation why we do not see more multiplets might be the slow rotation period of the star. Even at the shorter rotation period of about 46 days, $\ell = 1$ multiplets would have a splitting of 0.13μHz, which makes them unresolved from 79 days of data.

Follow-up spectroscopy places EPIC 203948264 in the middle of the $g-$mode instability region (Telting, private communication) and we find it to be a typical Kepler-observed sdB pulsator in that we easily assigned pulsa-

tion modes to the observations. Such constraints will be extremely useful producing models which match the structure defined by the features within the asymptotic sequence. So we add EPIC 203948264 to our list of "solved" sdB pulsators. We note it is one of the few sdB stars showing the "hook" feature (only in the $\ell = 1$ sequence) and our temporal analysis of the pulsations show them to be variable in amplitude, though their frequencies look to be consistent, within the errors. These K2 observations will be invaluable in our understanding of these stars, which represent the cores of all horizontal branch stars. Kepler has proven to be the *only* instrument which provides mode identifications and only through these observations will we be able to obtain an understanding of helium-fusing stars.

Acknowledgements

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