KIC 11911480: the second ZZ Ceti in the Kepler field

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ABSTRACT

We report the discovery of the second pulsating hydrogen-rich (DA) white dwarf in the Kepler field, KIC 11911480. It was selected from the Kepler-INT Survey (KIS) on the basis of its colours and its variable nature was confirmed using ground-based time-series photometry. An atmosphere model fit to an intermediate-resolution spectrum of KIC 11911480 places this DA white dwarf close to the blue edge of the empirical boundaries of the ZZ Ceti instability strip: $T_{\text{eff}} = 12160 \pm 250$ K and $\log g = 7.94 \pm 0.10$. Assuming a mass-radius relation and cooling models for DA white dwarfs, the atmospheric parameters yield: $M_{\text{WD}} = 0.57 \pm 0.06$ M$_\odot$. We also obtained two quarters (Q12 and Q16) of nearly uninterrupted short-cadence Kepler data on this star. We detect a total of six independent pulsation modes with a $\geq 3\sigma$ confidence in its amplitude power spectrum. These pulsations have periods ranging between 172.9 s and 324.5 s, typical of the hotter ZZ Ceti stars. Our preliminary asteroseismic study suggest that KIC 11911480 has a rotation rate of 3.5$\pm$0.5 days.

Key words: stars: pulsating white dwarfs – stars: asteroseismology – stars: WD J192024.90+501721.3 – surveys: Kepler field.

1 INTRODUCTION

Most stars end their lives as white dwarfs (WDs), and hence studying the galactic population of WDs offers insight into the star formation history of the Galaxy. WDs are very diverse and can be found in single or binary systems, and their study is hence central to a global understanding of stellar evolution.

Around 80% of WDs have hydrogen-dominated atmospheres, also known as DA WDs, making them the most commonly found and studied class of WDs (Koester et al. 1979; Bergeron et al. 1992; Giammichele et al. 2012; Kleinman et al. 2013). As WDs cool, they pass through instability strips, exhibiting periodic variations in their mean intensity with amplitudes of up to a few percent. Four classes of pulsating WDs are known, depending on atmospheric composition: the hot pre-WDs (PG 1159 or DOV stars), warm helium-atmosphere WDs (V777 Her or DBV stars, $T_{\text{eff}} \approx 22000 - 29000$ K), cool hydrogen-atmosphere WDs (ZZ Ceti or DAV stars, $T_{\text{eff}} \approx 10900 - 12300$ K), and the carbon-atmosphere WDs (DQV, $T_{\text{eff}} \approx 20000$ K, Dufour et al. 2008; Montgomery et al. 2008). The latter class is the most recently discovered, and there is still a question as to if the variability in DQVs is caused by pulsations or magnetic spots (Dunlap et al. 2013; Lawrie et al. 2013). Pulsating DA WDs have the appropriate temperatures to foster a hydrogen partial ionization zone, which in turn drives global non-radial g-mode pulsations (Robinson et al. 1982; Winget et al. 1991).

While WD parameters are traditionally inferred from model fits to spectra, precision asteroseismology of WDs has the tantalising potential to probe the masses and compositions of their electron-degenerate cores, as well as their non-degenerate envelopes (e.g. Winget & Kepler 2008; Fontaine & Brassard 2008), to determine their internal rotation profiles (Charpinet et al. 2009), to measure weak magnetic fields (Winget et al. 1991), to search for planetary companions via pulse timing variations (Mullally et al. 2008), and to constrain nuclear reaction rates (e.g. $^{12}$C($\alpha$, $\gamma$)$^{16}$O, Metcalfe et al. 2002).

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Only a handful of WDs were known in the NASA Kepler field (Borucki et al. 2010) when it was launched in 2009, and none of them exhibited pulsations (Ostensen et al. 2010, 2011). The recent discoveries of the first V777 Her star (KIC 8626021, Ostensen et al. 2011) and the first ZZ Ceti star (KIC 4552982, Hermes et al. 2011) within the Kepler field represents the dawn of precision space-based WD asteroseismology. ZZ Cetis are known to have pulsation periods ranging from 100 s to 1000 s, which can vary from one end of the instability strip to the other (e.g. Mukadam et al. 2004), although pulsating extremely low-mass (M < 0.25M⊙) WDs have pulsation periods ranging from 1184 – 6235 s (Hermes et al. 2013). The amplitudes of individual pulsation modes in cool ZZ Cetis can vary dramatically on time scales of days to weeks (e.g. G29-38, Kleinman et al. 1994, 1998). This presents a challenge for finding modes with closely-spaced frequencies, such as rotationally split modes, because the beating between such modes appears as an amplitude variation of a single mode in short (e.g. 1 night) time series. This ambiguity can be partially ameliorated with repeated observations from a single site, though gaps between consecutive nights leads to mode aliases. In order to remove aliasing of a single mode in short (e.g. 1 night) time series, we made use of the Kepler spacecraft spread over 15 months. Finally, we present our conclusions in Section 5.

2 TARGET SELECTION

We began our selection of ZZ Ceti candidates using \((U - g, g - r)\) colours from the Kepler-INT Survey (Greiss et al. 2012) see upper panel Fig. 1). KIS is a deep optical survey of the Kepler field, using four broadband filters, \(U, g, r, i\) and one narrowband filter, \(H_o\). All the observations are taken using the Wide Field Camera (WFC) on the 2.5m Isaac Newton Telescope (INT) on the island of La Palma. We narrowed down our selection to candidates in, or close to, the empirical \((T_{eff}, \log g)\) instability strip (Gianninas et al. 2011) projected into \((U - g, g - r)\) space using the cooling models presented in Tremblay & Bergeron (2009). We also make use of the \(H_o\) filter to confidently select DA WDs, as they have broad \(H_o\) absorption lines and therefore stand out as \(H_o\)-deficient object in the \((r - H_o, r - i)\) colour-colour diagram (lower panel of Fig. 1).

In our photometric selection, we found a number of candidates including KIC4552982, the ZZ Ceti star discovered by Hermes et al. (2011). Another star, KIC11911480, showed significant variability from ground-based observations obtained as part of the RATS-Kepler survey (Ramsay et al. 2014) which consists of one hour sequences of 20 s \(g\)-band exposures of objects in the Kepler field using the INT/WFC. The power spectrum of RATS-Kepler data of KIC11911480 revealed short-period variability with a dominant signal at ~290 s. Table 1 gives the coordinates and magnitudes of KIC 4552982 and KIC 11911480.

### Table 1. Coordinates and KIS magnitudes of KIC11911480 and KIC 4552982.

|              | KIC 11911480 | KIC 4552982 |
|--------------|--------------|-------------|
| RA (J2000)   | 19:20:24.90  | 19:16:43.83 |
| Dec (J2000)  | +50:17:21.3  | +39:38:49.7 |
| \(U\)        | 17.701 ± 0.022 | 17.362 ± 0.007 |
| \(g\)        | 18.094 ± 0.015 | 17.755 ± 0.005 |
| \(r\)        | 18.032 ± 0.021 | 17.677 ± 0.007 |
| \(i\)        | 17.969 ± 0.033 | 17.565 ± 0.009 |
| \(H_o\)      | 18.187 ± 0.059 | 17.815 ± 0.018 |
| \(K_p\)      | 17.63 ± 0.05   | 17.85 ± 0.05   |

K\(_p\) corresponds to the magnitude from the Kepler Input Catalog (KIC, Brown et al. 2011).

3 OPTICAL SPECTROSCOPY

On June 7\(^{th}\) 2013, we obtained spectroscopy of KIC11911480 using the double-armed Intermediate Resolution Spectrograph (ISIS) on the William Herschel Telescope (WHT) on the island of La Palma. We observed under 1\(^{st}\) seeing conditions. We used the R600R and R600B gratings, in the ISIS blue and red arms respectively, with a 1\(^{st}\) slit. The blue arm was centred at 4351 Å and the red arm at 6562 Å. The blue spectra covered a total wavelength range from \(\sim3700\) Å to \(\sim5000\) Å, and the red spectra ranged from \(\sim5700\) Å to \(\sim7200\) Å (see Fig. 2). The resolution of the spectrum in the red arm is \(\sim2\) Å and \(\sim1.8\) Å in the blue arm. Three consecutive 20 minute exposures were taken in order to increase the signal-to-noise ratio (S/N) of the average spectrum.

The spectra were de-biased and flat-fielded using the standard STARLINK\(^2\) packages KAPPA, FIGARO and CONVERT. Optimal spectral reduction was then done with PAMELA\(^3\), Copper-argon arc lamp exposures were taken at the start and end of each night for the wavelength calibration of the spectra. We identified around 10 to 15 arc lines in each arm, which we fitted with fourth order polynomials. We observed two standard stars for the flux calibration.

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1 http://www.ing.iac.es/Astronomy/instruments/isis/

2 The STARLINK Software Group homepage website is http://starlink.jach.hawaii.edu/starlink

3 PAMELA was written by T. R. Marsh and can be found in the STARLINK distribution Hawaiik and later releases.
calibration of the spectra: Wolf1346 and Grw+70 5824. We used MOLY\footnote{MOLY was written by T. R. Marsh and is available from http://www.warwick.ac.uk/go/trmarsh/software.} for the wavelength and flux calibration of the extracted 1-D spectra.

We calculate the average spectrum of KIC11911480 using the three spectra obtained from the individual 20 minute exposures and obtain a S/N $\sim 33$ at 4400Å. The normalised Balmer line profiles in the average spectrum were then fitted using the WD models of Koester (2009), following the procedure described in Homeier et al. (1998). For the computation of the models, we used the Stark-broadened Balmer line profiles of Tremblay & Bergeron (2009) and adopted the ML2/$\alpha = 0.8$ prescription for convection. In model atmospheres, convection has been described with the mixing length theory \cite{Bohm-Vitense1958}, and ML2/$\alpha$ ($\alpha$ is the mixing length to pressure scale height ratio) is a parametrisation typically used for WD atmospheres \cite{Tassoul1990}.

In Fig.2\footnote{The cooling models can be found on \url{http://www.astro.umontreal.ca/~bergeron/CoolingModels/}. Also refer to Holberg & Bergeron (2006); Tremblay et al. (2011b); Bergeron et al. (2011) for colour and model calculations.} we show the spectrum and overplot the best model fit, which returned the following parameters for the DA WD: $\text{T}_{\text{eff}} = 13 350 \pm 250 \text{ K}$ and $\log g = 7.96 \pm 0.10$. The uncertainties in the atmospheric parameters were estimated from fitting the three individual 20 min WHT spectra and taking the root mean square. This places KIC11911480 close to the blue edge of the empirical boundaries of the ZZ Ceti instability strip \cite{Gianninas2011}. Using a mass-radius relation and the evolutionary cooling models from Fontaine et al. (2001) with a carbon-oxygen core \cite{Bergeron2001} we obtain a mass estimate of our ZZ Ceti star: $M_{\text{WD}} = 0.58 \pm 0.06 M_{\odot}$. However, we note that this may be a slight overestimate of the true WD mass, as it is now well established that the spectroscopically determined surface gravities, and hence the masses, of WDs with temperatures $\lesssim 13,000 \text{ K}$, are systematically too high (see e.g. Bergeron et al. 1990; Gianninas et al. 2011; Koester et al. 2009 for a discussion). The most likely explanation for this problem is that 1-D mixing length theory does not properly account for the effects of convection on the temperature structure of the atmosphere \cite{Tremblay2011}. For completeness, we adopt the 3-D models corrections of Tremblay et al. (2013) and find $T_{\text{eff}} = 12 160 \pm 250 \text{ K}$ and $\log g = 7.94 \pm 0.10$ corresponding to $M_{\text{WD}} = 0.57 \pm 0.06 M_{\odot}$. The differences in our case are negligibly small and we adopt the corrected values for this study.

Figure 2. Bottom panel: flux-calibrated WHT spectrum of KIC11911480 plotted in grey. Top panel: normalised Balmer profiles were used to determine its atmospheric parameters using 1-D atmospheric models: $\text{T}_{\text{eff}} = 13 350 \pm 250 \text{ K}$ and $\log g = 7.96 \pm 0.10$. The uncertainties in the atmospheric parameters were estimated from fitting the three individual 20 min WHT spectra and taking the root mean square. This places KIC11911480 close to the blue edge of the empirical boundaries of the ZZ Ceti instability strip \cite{Gianninas2011}. Using a mass-radius relation and the evolutionary cooling models from Fontaine et al. (2001) with a carbon-oxygen core \cite{Bergeron2001} we obtain a mass estimate of our ZZ Ceti star: $M_{\text{WD}} = 0.58 \pm 0.06 M_{\odot}$. However, we note that this may be a slight overestimate of the true WD mass, as it is now well established that the spectroscopically determined surface gravities, and hence the masses, of WDs with temperatures $\lesssim 13,000 \text{ K}$, are systematically too high (see e.g. Bergeron et al. 1990; Gianninas et al. 2011; Koester et al. 2009 for a discussion). The most likely explanation for this problem is that 1-D mixing length theory does not properly account for the effects of convection on the temperature structure of the atmosphere \cite{Tremblay2011}. For completeness, we adopt the 3-D models corrections of Tremblay et al. (2013) and find $T_{\text{eff}} = 12 160 \pm 250 \text{ K}$ and $\log g = 7.94 \pm 0.10$ corresponding to $M_{\text{WD}} = 0.57 \pm 0.06 M_{\odot}$. The differences in our case are negligibly small and we adopt the corrected values for this study.
Details on the data handling, processing and releases can be found on the Kepler data analysis website. The Kepler science team. The Kepler-2013. Each observation were taken between January 4th and 29.4 min exposures respectively. The Q12 operates in two modes: short and long cadence observations consisting of 58.89 s and 29.4 min exposures respectively. The Q12 observations were taken between January 4th and March 28th 2012 and Q16 spanned from January 11th to April 8th 2013. Each Kepler quarter corresponds to three months of observations. However, during Q12, a series of coronal mass ejections affected the run by bringing the duty cycle of Q12 down to 88.2%. During Q16, Kepler went into rest mode for 11.3 days, leading to a duty cycle of 84.8% for that quarter. The Kepler light curves, produced using simple aperture photometry and delivered by the Kepler Science Operations Center pipeline, were downloaded from the MAST website. Details on the data handling, processing and releases can be found on the Kepler data analysis website.

We calculate the discrete Fourier Transforms (FT) of each set separately, using the TSA package within MIDAS written by Alex Schwarzenberg-Czerny. We observe optical variability in the Kepler data with periods ranging from 137.1 s to 519.6 s (see Table 2 for more details). These periods are within the expected values for ZZ Ceti stars, which are known to have g-mode pulsations ranging from 100 to 1000 s \citep{fontaine2008}, and match the pulsation periods of other known hot ZZ Ceti stars \citep{mukadam2004}.

4 PRELIMINARY ASTEROSEISMIC STUDY

After confirmation of its pulsating nature, we were awarded Kepler short-cadence mode observations of KIC 11911480 during Quarters 12 and 16 (Q12, Q16). Kepler operates in two modes: short and long cadence observations consisting of 58.89 s and 29.4 min exposures respectively. The Q12 observations were taken between January 4th and March 28th 2012 and Q16 spanned from January 11th to April 8th 2013. Each Kepler quarter corresponds to three months of observations. However, during Q12, a series of coronal mass ejections affected the run by bringing the duty cycle of Q12 down to 88.2%. During Q16, Kepler went into rest mode for 11.3 days, leading to a duty cycle of 84.8% for that quarter. The Kepler light curves, produced using simple aperture photometry and delivered by the Kepler Science Operations Center pipeline, were downloaded from the MAST website. Details on the data handling, processing and releases can be found on the Kepler data analysis website.

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4.1 Significance threshold

We adopted a randomisation technique to determine the detection thresholds for the Kepler light curve. In this process, we bootstrap the Kepler data, keeping the times of the individual observations in place, but randomise the sequence of the fluxes. For each of these randomised light curves we compute the discrete FT as described above and we record the highest amplitude from each of the randomisation. The process of randomising is repeated a large number of times, building up a smooth cumulative distribution of the highest recorded amplitudes (Fig. 3), from which the 3σ threshold is determined, i.e. 99.7% of the highest amplitudes recorded in the randomised light curves fall below that threshold. We found that the 3σ threshold converges after about a thousand randomisations, and, to err on the side of caution, we used 3000 randomisations for the final calculation of the significance thresholds. In the case of each individual quarter, the 3σ thresholds for Q12 is 0.138% and Q16 are 0.130%. Strictly speaking, this threshold only applies to the highest amplitude signal detected in the Kepler light curves, and the entire process would need to be repeated after pre-whitening the Kepler data with the highest amplitude signal, carrying on in an iterative fashion until no signal satisfies the 3σ threshold. However, we have experimented with a Kepler light curve that had all pulsation signals (Table 2) and spurious signals removed, and the resulting 3σ threshold is 0.132% in the case of the Q12 data. It is therefore not significantly different from the one derived from the original Kepler light curve.

Note that this method yields more conservative significant thresholds than the more widely adopted method which uses A as the limit to consider significant peaks, where (A) corresponds to the average amplitude of the amplitude power spectrum (see Section 5.4 of \cite{aerts2010} and references therein). We find that A = 0.113% for the Q12 run, and A = 0.099% for Q16.

4.2 Pulsation modes

In the amplitude power spectra of KIC 11911480 (Fig. 4), we mark the Kepler spurious frequencies taken from the Data Characteristic handbook. These spurious frequencies are multiples of 1/LC period, where LC corresponds to long-cadence exposures of 29.4 min. Additional spurious frequencies, unrelated to the inverse of the LC period, have been detected from the analysis of many early Kepler quarters. Some components in the power spectrum of KIC 11911480 appear and disappear between both quarters and it is clear that the amplitudes of the detected frequencies are generally stronger in Q16 than in Q12 (see Fig. 5). The error on the amplitudes is 0.028%. This large overall amplitude variation between Q12 and Q16 may be explained by the fact that our target was observed with two different custom masks in both quarters.

We calculate the frequencies and amplitudes of each significant peak, using a least-squares sine wave fitting routine at each individually selected peak from the FT. We find seven pulsation modes detected above the 3σ threshold in the Q16 data set, four of which are independent (Table 2). In the Q12 data, we find five pulsations modes above the 3σ threshold, out of which three are independent. The pulsation modes found in Q12 are all detected in Q16 as well. In Table 2, we also add two pulsation periods, f5 and f4 − f1.

\footnote{The Data Characteristic handbook can be downloaded from the following webpage: http://keplerscience.arc.nasa.gov/DataAnalysis.shtml}

Figure 3. Top panel: Distribution of the highest amplitude recorded in 3000 randomised light curves. Bottom panel: Cumulative distribution of the highest amplitudes. The 68.3%, 95.5% and 99.7% detection thresholds are indicated by the dashed vertical lines.
Table 2. Pulsation frequencies of KIC 11911480 from the Q12 and Q16 data. The uncertainties are given in between brackets. \(\Delta f\) corresponds to the frequency spacing between two consecutive frequencies in the table.

|     | P (P\(_{\text{cr}}\)) (s) | f (f\(_{\text{cr}}\)) (\(\mu\)Hz) | A (%) | \(\Delta f\) (\(\mu\)Hz) | P (P\(_{\text{cr}}\)) (s) | f (f\(_{\text{cr}}\)) (\(\mu\)Hz) | A (%) | \(\Delta f\) (\(\mu\)Hz) |
|-----|------------------|-----------------|------|-----------------|------------------|-----------------|------|-----------------|
| Q12 |                 |                 |      |                 | Q16              |                 |      |                 |
| \(f_{1,-}\) | 290.9664 (7)    | 3436.823 (8)    | 0.185 |                 | 290.9675 (3)    | 3436.810 (4)    | 0.439 |                 |
| \(f_{1,o}\)  | 290.8016 (1)    | 3438.770 (1)    | 1.187 | 1.947           | 290.8026 (6)    | 3438.759 (7)    | 2.175 | 1.949           |
| \(f_{1,+}\)  | 290.6322 (4)    | 3440.775 (5)    | 0.368 | 2.005           | 290.6341 (2)    | 3440.753 (3)    | 0.641 | 1.994           |
| \(f_{2,-}\)  | 259.3731 (2)    | 3855.451 (3)    | 0.501 |                 | 259.3738 (1)    | 3855.440 (2)    | 0.997 |                 |
| \(f_{2,o}\)  | 259.2531 (2)    | 3857.235 (3)    | 0.581 | 1.784           | 259.2538 (1)    | 3857.224 (2)    | 0.975 | 1.784           |
| \(f_{2,+}\)  | -               | -               | -    | -               | 259.1352 (3)    | 3858.989 (4)    | 0.391 | 1.764           |
| \(f_{3,-}\)  | 324.529 (1)     | 3081.39 (1)     | 0.169 |                 | 324.5299 (6)    | 3081.381 (5)    | 0.321 |                 |
| \(f_{3,o}\)  | 324.3152 (9)    | 3083.420 (9)    | 0.185 | 2.03            | 324.3175 (6)    | 3083.398 (6)    | 0.278 | 2.017           |
| \(f_{3,+}\)  | 324.1032 (1)    | 3085.44 (2)     | 0.100 | 2.02            | -               | -               | -    | -               |
| \(f_{4,-}\)  | 172.9588 (4)    | 5781.72 (1)     | 0.086 |                 | 172.9015 (3)    | 5783.64 (1)     | 0.149 |                 |
| \(f_{4,o}\)  | 172.9003 (5)    | 5783.68 (1)     | 0.113 | 1.96            | 172.9015 (3)    | 5783.64 (1)     | 0.149 |                 |
| \(f_{5,-}\)  | -               | -               | -    | -               | 202.5687 (6)    | 4936.60 (1)     | 0.118 | 1.98            |
| \(f_{5,+}\)  | -               | -               | -    | -               | 202.4873 (5)    | 4938.58 (1)     | 0.091 | 1.98            |
| 2 \(f_{1,o}\) | 145.4007 (3)    | 6877.54 (1)     | 0.125 |                 | 145.4013 (1)    | 6877.516 (6)    | 0.301 |                 |
| \(f_{1,o} + f_{2,o}\) | 137.0614 (2) | 7296.02 (1)    | 0.158 |                 | 137.0614 (1)    | 7295.999 (7)    | 0.234 |                 |
| \(f_{4,o} - f_{1,o}\) | 426.936 (3)    | 2342.27 (2)     | 0.085 |                 | 426.455 (2)     | 2344.91 (1)     | 0.140 |                 |
| \(f_{4,-} - f_{2,-}\) | 519.600 (4)    | 1924.56 (2)     | 0.078 |                 | -               | -               | -    | -               |
| \(f_{4,o} - f_{2,o}\) | 519.110 (4)    | 1926.37 (1)     | 0.078 | 1.81            | -               | -               | -    | -               |
| \(f_{4,+} - f_{2,+}\) | -              | -               | -    | -               | 518.636 (2)     | 1928.136 (7)    | 0.088 | 1.963           |

* the frequency was detected below 3\(\sigma\)

which are not significantly detected in Q12 but they are very close to the Q16 3\(\sigma\) threshold. Their amplitudes are larger than the 4(A) = 0.099% for Q16. The main reason why we believe the detection of \(f_5\) is because it shows splitting with the same frequency separation as the other significant modes. Also, \(f_4 - f_1\) is a non-linear combination of two significant frequencies. In total, we find that KIC 11911480 has five independent pulsation modes and four combination frequencies. Non-linear combination frequencies are not generated by the same physical mechanism driving the pulsations of the star. Brickhill (1992) showed that these combination frequencies may come from the distortion of the sinusoidal waves associated to the normal modes travelling from the convective to the radiative zone of the star, where the heat transport changes dramatically at the base of the hydrogen ionization zone (see also Wu & Goldreich 1999; Vuille 2000; Wu 2001; Yeates et al. 2005). Their amplitudes can provide information on the physical conditions in the WD convection zone (Montgomery 2005).

Also, we look into the phases of these modes and find that they are coherent enough to produce an O-C diagram over the 15-month Kepler observations but are indicative of a large drift in phase. We will address the analysis of those phase changes in a future paper as this requires a careful treatment of the Q12 and Q16 data obtained with different pixel masks.

We also notice splitting of some of the modes, which are denoted with ‘+’ or ‘−’ signs and placed next to the central component (‘o’) of each pulsation mode in Table 2. Not all components of a multiplet are always detected (see Fig. 5). A full asteroseismic study is beyond the scope of this paper, yet we have attempted to match the observed periods to adiabatic pulsation models with the constraints provided by our spectroscopic mass and temperature determinations. The models of Romero et al. (2012) of a 0.57 M\(_\odot\), 12 101 K WD with a thick (10 M\(_{\text{WD}}\)) hydrogen layer mass are in decent agreement with the observed periods of \(f_1 - f_4\) if these four modes have \(\ell = 1\) and \(k = 1, 2, 3, 5, 2\), respectively. However, this is only qualitative guess at a solution, and a full asteroseismic analysis is required to arrive at a more secure identification of these modes.

4.3 Rotation rate

We see what appears to be multiplet splitting of some modes, which is a direct manifestation of the star’s rotation rate (Fig. 5). In the limit of slow rotation, the difference between the frequency of one mode of indices \(l, k, m\) (\(\sigma_{k,lm}\)) and the frequency in the non-rotating case (\(\sigma_{k,l}\)) is:

\[
\sigma_{k,lm} - \sigma_{k,l} = m(1 - C_{k,l})\Omega
\]  

where \(C_{k,l}\) comes from the Coriolis force term in the momentum equation and \(\Omega\) is the rotation frequency (Winget et al. 1991; Vauclair 1997). Note that this equation is the classical first order expansion. In the asymptotic limit for \(g\)-modes, \(C_{k,l}\) only depends on the degree of the mode.
Figure 4. Amplitude power spectrum of KIC 11911480 from the Q12 (top) and Q16 (bottom) data. The Xs above certain frequencies indicate the Kepler spurious frequencies and the dashed horizontal line corresponds to the 3σ threshold limit. The values noted above each significant frequency corresponds to period (in seconds) of the given pulsation mode.

When a pulsating WD rotates, each mode of degree $l$ can be split into $2l+1$ components. We see splitting into three components in several modes in the power spectrum of KIC 11911480 (see Fig. 5), which likely corresponds to an $\ell = 1$ mode in those cases, leading to $C_{k,l} \simeq 0.5$. The frequency spacing between the split components of the modes is quite consistent, $1.93 \pm 0.10\mu$Hz, suggesting these modes are all of the same spherical degree. This corresponds to a rotation rate of $3.0 \pm 0.2$ days. However, $f_1 - f_4$ (with periods from 172.9 – 324.5 s) are likely low-radial-order and far from the asymptotic limit, so their $C_{k,l}$ values should not be identical, and are not exactly 0.5. If we adopt the $C_{k,l}$ values of the model from Romero et al. (2012) discussed in Section 4.2, we obtain a rotation rate of $3.5 \pm 0.2$ days. To best reflect the systematic uncertainties, we adopt a rotation rate of $3.5 \pm 0.5$ days.

Notably, the small but significant deviations in the observed frequency splittings provide additional asteroseismic information, especially useful for constraining which modes are trapped by composition transition zones (Brassard et al. 1992). The shorter-period $g$-modes have lower radial order, and these splittings are observed to have values of 1.97 $\mu$Hz for $f_1$, 1.77 $\mu$Hz for $f_2$, 2.03 $\mu$Hz for $f_3$, and 1.94 $\mu$Hz for $f_4$.

This value is in agreement with previous rotation frequencies found in ZZ Ceti stars. Fontaine & Brassard (2008) give an overview on pulsating WDs and provide the asteroseismic rotation rates of seven ZZ Ceti stars, spanning from 9 to 55 hours, i.e. 0.4 to 2.3 days. In the case of non-pulsating WDs, the sharp NLTE core of the H\alpha line in their spectra has been used in many studies to measure the projected rotation velocities of the stars (Heber et al. 1997, Koester et al. 1998, Karl et al. 2005). In all cases, the same conclusion was drawn: isolated WDs are generally slow rotators.

5 CONCLUSION

We report on the discovery of the second ZZ Ceti in the Kepler field: KIC 11911480. It was discovered using colour selections from the Kepler-INT Survey and confirmed with ground-based time-series photometry from the RATS-Kepler survey. Follow-up Kepler short-cadence observations during Q12 and Q16 are analysed: five independent pulsation modes, as well as four non-linear combinations, were
detected in the combined power spectrum of KIC 11911480, all ranging from 137.1 s to 519.6 s. The splitting of four of the independent pulsations enable us to estimate the rotation period of the star to be $3.5 \pm 0.5$ days, assuming these are all $\ell = 1$ modes.

An intermediate-resolution spectrum using ISIS on the WHT and DA WD model atmosphere fits returned our ZZ Ceti’s atmospheric parameters: $T_{\text{eff}} = 12160 \pm 250$ K and $\log g = 7.94 \pm 0.10$. This places KIC 11911480 close to the blue edge of the empirical boundaries of the ZZ Cetis instability strip. Using DA WD cooling models and evolutionary tracks, the surface gravity translates to $M_{\text{WD}} = 0.57 \pm 0.06 M_{\odot}$.

Kepler has concluded observations of this hot ZZ Ceti star, massing more than 210,000 frames of this pulsating WD. We encourage follow-up, ground-based observations, which will allow to measure the amplitude of any nonlinear combination frequencies with periods < 120 s, which fall below the Kepler Nyquist frequency. Additionally, ground-based data can extend the time baseline in order to measure the rate of period change of the pulsation modes excited in this ZZ Ceti star.

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Balmer/Lyman lines in the models were calculated with the modified Stark broadening profiles of Tremblay & Berg (2009) kindly made available by the authors.

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