A wavelet analysis of photometric variability in *Kepler* white dwarf stars

S. R. de Lira, J. P. Bravo, I. C. Leão, A. D. da Costa, B. L. Canto Martins, D. B. de Freitas and J. R. De Medeiros

1 Universidade Federal do Rio Grande do Norte, Departamento de Física Teórica e Experimental, 59072-970 Natal, RN, Brazil
2 Instituto Federal de Educação, Ciência e Tecnologia do Rio Grande do Norte, Natal, RN 59015-000, Brazil
3 Universidade da Integração Internacional da Lusofonia Afro-Brasileira, Redenção, CE 62790-000, Brazil
5 Universidade Federal do Ceará, Departamento de Física, Campus do Pici, Fortaleza, CE 60455-900, Brazil

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

This work brings a wavelet analysis for 14 *Kepler* white dwarf stars, in order to confirm their photometric variability behavior and to search for periodicities in these targets. From the observed *Kepler* light curves we obtained the wavelet local and global power spectra. Through this procedure, one can perform an analysis in time-frequency domain rich in details, and so to obtain a new perspective on the time evolution of the periodicities present in these stars. We identified a photometric variability behavior in ten white dwarfs, corresponding to period variations of ∼ 2 h to 18 days: among these stars, three are new candidates and seven, earlier identified from other studies, are confirmed.

Key words: stars: white dwarfs – methods: data analysis – techniques: photometric

1 INTRODUCTION

The observations of the space missions *Kepler* and *CoRoT* are revolutionizing our understanding of stellar variability and generating new insights in the correlation between photometric variability and rotation of main sequence stars (e.g. Davenport 2017; Leão et al. 2015; Paz-Chinchón et al. 2015; McQuillan et al. 2014; De Medeiros et al. 2013; Nielsen et al. 2013; Walkowicz & Basri 2013) and beyond the main sequence (e.g. Costa et al. 2015; van Saders & Pinsonneault 2013; De Medeiros et al. 2013; Mosser et al. 2012). These works have shown that rotation is a major constraint on the study of the net angular momentum evolution as well as on the angular momentum transport from core to surface and expanding envelope. In addition, the normalcy of Sun rotation with respect to the main sequence stars with surface physical parameters close to the solar values (Leão et al. 2015; de Freitas 2013) and bimodality in the rotation period distribution for main sequence stars (Davenport 2017; McQuillan et al. 2014) have also emerged from data acquired by the referred space missions.

The observation of photometric modulation has also a unique potential to probe for rotation in white dwarfs (hereafter WD), one of the few remaining traces to the physics of the formation process of WD (Kawaler 2015, 2003). Such a procedure is more easily applied to magnetic white dwarfs, which comprise approximately 20 percent of white dwarf stars presently reported in the literature (e.g. Kepler et al. 2013; Kawka et al. 2007). Typically, the observed rotation period for these stars ranges from less than one hour to a few days (e.g. Kawaler 2015; Brinkworth et al. 2013; Kawka et al. 2007). Nevertheless, photometric modulation in normal white dwarfs can also be revealed by surface dynamo activity, producing localized star-spots (e.g. Kawaler 2015).

Finally, asteroseismology analysis, based on high photometric precision, can be used for the measurements of the rotation period of white dwarfs, showing the appropriate range of effective temperature in which they undergo non-radial g-mode pulsations.

Maoz et al. (2015) have conducted a Fast Fourier Transform analysis of *Kepler* light curves (hereafter LCs) in 14 WD, searching for photometric variability. Those authors detected periodic signals ranging from 2 hours to 10 days for 7 among the 14 targets they analyzed. These signals were detected in both short and long cadence data LCs from *Kepler* Mission. In the present work, we perform a time-frequency analysis of the same *Kepler* WD datasets studied by Maoz et al. (2015) in the interest to point out the spectral components, and to follow their time evolution which leads to short- and long-lived signatures formation that could be
linked to the WD rotation or activity. For this purpose, since the continuous wavelet transform (WT) is a powerful mathematical tool for non-stationary signals, we used a 6th order Morlet wavelet (Torrence & Compo 1998) to obtain the energy distribution of each LC computed as a local wavelet spectrum, mapping short- and long-term features.

This paper is organized as follows. Section 2 presents our stellar sample and the methods used for this analysis. Section 3 brings the primary results, in which the periods detected from the wavelet method are analysed and compared with those obtained by Maoz et al. (2015). Finally, our conclusions are provided in Section 4.

## 2 SAMPLE SELECTION AND LC ANALYSIS

NASA *Kepler* mission provides LCs in 18 runs (also known as quarters) with standard treatment as Simple Aperture Photometry (SAP) data and with a more refined treatment, in which instrumental effects were removed, as Pre-search Data Conditioning (PDC) (Stumpe et al. 2012; Smith et al. 2012). For our purposes, we have chosen 14 WD with long (30 minutes) and short (1 minute) cadence LCs retrieved from the *Kepler* Data Archive\(^1\). Those targets were previously studied by Östensen et al. (2011, 2010) searching for pulsation among compact objects, and by Maoz et al. (2015) focusing on photometric variations using the FFT.

As underlined by Maoz et al. (2015), their analysis made use of Public Releases 14 – 21 of the long cadence data and Public Release 21 of the short cadence, downloaded from the *Kepler* mission archive. However, it seems that no additional treatment of the LCs was performed by the authors.

The detection threshold for periodicity varies from star-to-star, depending on its brightness, the number of quarters of observations, and the final cleaning of the LCs. To avoid possible distortions in the spectral wavelet maps, and consequently, changes in the power spectra, an additional treatment as outliers removal and instrumental trend corrections was performed in the PDC LCs (e.g. Paz-Chinchón et al. 2015). The single long-term LC was obtained by assembling the available quarters for each object, based on the procedure of Bányai et al. (2013). The map signatures are then well defined, inducing to more reliable variability periodicities.

Wavlet power spectra were analysed based on procedures described by Bravo et al. (2014). The local map is defined as the signal energy distribution in time and frequency, while the global power spectrum is computed from the time integration of the wavelet map. Examples of these are displayed in the Results section. The WT application and the variability analysis was performed for each quarter of the whole sample, as well as for merged LCs in short- and long-cadence modes. Since WD time series present some gaps, the wavelet map was obtained individually for each set of continuous data. Thus, the global spectrum was produced by considering the weighted average by time span of these parts (Costa et al. 2015) for the targets KIC 4829241, KIC 5769827, KIC 6669882, KIC 6862653, KIC 8682822, KIC 10420021, KIC 11604781 and KIC 11822535. For the referred stars, the data treatment is related to long cadence data set. The objects of our sample are listed in Table 1, including their spectral type, effective temperature, \(T_{\text{eff}}\), surface gravity, \(\log g\), and surface gravity, \(\log g\), (e.g. Hallakoun et al. 2018; Doyle et al. 2017; Östensen et al. 2011); the periodicities computed by Maoz et al. (2015) using the FFT and those obtained using our wavelet procedure.

Furthermoe, we have applied the FFT in our data af-

### Table 1. White dwarfs parameters, including photometric periodic variations computed via wavelet technique.

| KIC      | Spectral type | \(K_p\) (mag) | \(T_{\text{eff}}\) (kK) | \(\log g\) (cm s\(^{-2}\)) | Period (days) | Quarters\(^a\) | Wavelet Variability Periods (days) |
|----------|---------------|---------------|--------------------------|-----------------------------|---------------|----------------|----------------------------------|
|          | Non-periodic (Maoz et al. 2015) |              |                          |                             |               |                |                                  |
| 3427482  | DA            | 17.3          | -                        | -                           | -             | 1               | -                  |
| 4829241  | DA            | 15.8          | 9.5                      | 8.0                         | -             | 2-13            | 16.04              |
| 7129927  | composite DA+DA | 16.6          | 9.5                      | 8.3                         | -             | 3,5,6           | -                  |
| 9139775  | DA            | 17.9          | 24.6                     | 8.6                         | -             | 2               | -                  |
| 10198116 | DA            | 16.4          | 13.5                     | 8.0                         | -             | 4-6             | -                  |
| 10420021 | DA            | 16.2          | 12.8                     | 7.8                         | -             | 2,5,6,8,10      | 11.70              |
| 11822535 | DA            | 14.8          | 36.0                     | 7.9                         | -             | 2-13            | 13.83              |

\(^a\) Periods obtained by Maoz et al. (2015)

\(^b\) Quarters of long cadence available in *Kepler* public data and analyzed in this work.

\(^1\) [http://archive.stsci.edu/kepler/](http://archive.stsci.edu/kepler/)
3 RESULTS AND DISCUSSION

Considering that the observed rotation periods in white dwarfs range from less than one hour to a few days (Kawaler 2015), in the present work we are mostly searching for short periodicities. Our wavelet procedure confirms the periodic modulation found by Maoz et al. (2015) for the stars KIC 5769827, KIC 6669882, KIC 6862653, KIC 8682822, KIC 11337598 and KIC 11604781, with periodicities similar or close to the values reported by those authors, as illustrated by their wavelet maps in Figures 1 to 3. Nevertheless, for the WD KIC 11514682 we found a period of 17.59 days, in contrast with Maoz et al. (2015) who computed a 9.89 days period. Among the seven WD stars classified by Maoz et al. (2015) as non-periodic, our wavelet analysis reveals unambiguous periodicities for three of them, KIC 4829241, KIC 10420021 and KIC 11822535, with 16.04 days, 11.70 days and 13.83 days, respectively. The computed wavelet periodicities, along with those from Maoz et al. (2015), are listed in Table 1.

The results obtained using the long-cadence data are in agreement with those found making use of short-cadence data. However, for better viewing of the variability signature in the WD wavelet maps, and hence a clear identification of periodicities, we given priority to display long-cadence datasets. Thus, the wavelet periods in Table 1, also displayed in the respective wavelet global spectra, are related...
to the Kepler long-cadence mode. One exception is the WD KIC 11337598, for which variability is better defined in the wavelet spectra using short-cadence data.

Let us underline that, except for KIC 8682822 and KIC 11822535, the level of persistence of the periodicity in the wavelet maps of the analysed stars is larger than 50%, a fairly significant fraction of the entire data set. For KIC 8682822 and KIC 11822535 the fraction persistence is about 5% and 40%, respectively. In the following we discuss a few particular features emerging from our wavelet analysis, in particular for those stars with photometric variability revealed in the present study.

3.1 KIC 11337598

Ostensen et al. (2011) detected a Balmer line broadening in the spectrum of KIC 11337598, suggesting the possibility that this WD is a rapid rotator with a $v \sin i = 1500$ km s$^{-1}$. The fit used by those authors corresponds to a rotational period of about 40 s or 0.000463 days. Moreover, Maoz et al. (2015) suggested a period of 0.09 days as the variability period for KIC 11337598. In Figure 2 (lower panel), our wavelet analysis reveals three dominant periods, $P_1 = 0.93$ days, $P_2 = 2.13$ days and $P_1 = 0.09$ days. The period $P_2$ is persistent over the entire time span, corresponding to the main wavelet period, in agreement with Maoz et al. (2015). $P_1$ is also persistent, and probably it is a P3 multiple period related to rotation. It should be noted that $P_1$ is exactly 2000 times the 40-second periodicity found by Ostensen et al. (2011). Therefore, we consider here both $P_1$ and $P_2$ linked to the WD rotation, while $P_2$ is a plausible aliasing period.

3.2 KIC 11514682

For this star the wavelet analysis reveals two periodicities, in contrast with the 9.89 days found by Maoz et al. (2015). The wavelet map displayed in the upper panel of Figure 4 shows a predominant period of 40.42 days and a secondary one at 17.59 days. These two periods are confirmed in the Lomb-Scargle periodogram displayed in the lower panel of Figure 4. The periods of 17.59 days and 40.42 days have approximately a 1:2 correspondence, respectively. This suggests that the first one is more likely a physical period and the latter one is a possible alias.

3.3 KIC 4829241, KIC 10420021 and KIC 11822535

The stars KIC 4829241, KIC 10420021 and KIC 11822535 were classified as non-periodic by Maoz et al. (2015). Instead, our study suggests a periodic or quasi-periodic modulation well describing a variability signature in the wavelet representations. We attribute to this variability periodicities ranging between 11 and 16 days, which is reasonable for WD (e.g. Kawaler 2015; Valeev et al. 2017; Braker et al. 2017). In fact, these periodicities are more persistent in KIC 4829241 and KIC 10420021 than in KIC 11822535, even though also noticeable in the latter star. We do not expect to find magnetic cool spots signatures for KIC 4829241 and KIC 11822535 considering their high $T_{\text{eff}}$ and their log g values (Tremblay et al. 2015). However, a transient signature for KIC 10420021 is conceivable in view of its $T_{\text{eff}}$ and log g being close to the limit value (Tremblay et al. 2015) to still envisage the presence of a convection zone at the WD surface.

Combining the surface gravities and the effective temperatures, derived spectroscopically by Hallakoun et al. (2018), with evolutionary grids (Benvenuto & Althaus 1999), we are able to estimate the mass of these three WDs. KIC 4829241 is a WD of mass $\sim 0.45$–$0.80$ $M_\odot$. The Lomb-Scargle periodogram for this WD shows a period of 16.68 days with an amplitude of 286 ppm, as indicated by the letter A in the upper-right panel of Figure 5. Following Maoz et al. (2015), given its mass, rotation combined with an accretion of gas from the interstellar medium (ISM) and the material carried on the magnetic poles generating hotspots, with an accretion luminosity of $\Delta L_{\text{acc}} \sim 1.4 \times 10^{30}$ erg s$^{-1}$, could explain the periodic modulation. Figure 5 (upper-left panel) displays the wavelet analysis, from which we noticed a long-lasting periodicity of 16.04 days over the time observation. With a lower amplitude, we also found a 40-day period which could be considered as a possible aliasing period. The 16-day period characterizes the WD photometric modulation since it...
left panel of Figure 5, is very similar to that of KIC 4829241. However, for this star, the main period of 13.83 days describes short quasi-periodic variations over the entire time span with lower amplitude. In accordance, a period of 13.56 days corresponds to the main peak of the respective Lomb-Scargle periodogram (Figure 5, lower-right panel) with a small amplitude of 74.3 ppm. As the effective temperature of this WD is higher than 30 kK, the quasi-periodic variability observed in the wavelet map could not be associated with magnetic spots, but it is possible to have a photometric modulation due to the rotation. This modulation could result from WD rotation plus magnetic dichroism or UV line absorption plus optical fluorescence.

**4 CONCLUSIONS**

We have carried out a wavelet analysis of the variability behavior of 14 stars observed by Kepler mission, previously analyzed by Maoz et al. (2015) using Fast Fourier Transform approach. We confirm the variability for all the 7 stars classified as periodic by those authors. Nevertheless, for one WD, KIC 11514682, we have found different periodicities. Let us underline that the variable star KIC 6862653 early classified as a WD, turned out to be a carbon-rich helium-dominated subdwarf Hallakoun et al. (2018). We also identified noticeable variability for 3 WD stars reported by Maoz et al. (2015) as non-periodic. The stars KIC 4829241, KIC 10420021 and KIC 11822535, present wavelet maps revealing clear signature of periodicities, ranging approximately from 11 to 16 days. These are then placed within the list of WD with periodic modulations, while for KIC 3427482, KIC 7129927, KIC 9139775 and KIC 10198116 we confirm their non-periodic behavior.

The 10 stars here studied present different features in their time-frequency representations. For KIC 5769827 and KIC 116047812 a particular semi-regular colour-filled contour, lasting all along their time span, leads to assume the rotation modulation as the most probable agent of such local map signature. As the KIC 116047812 effective temperature is about 9000 K, it is very likely that the observed rotation modulation is combined with cool magnetic spots. Otherwise, the maps of KIC 6669827 and KIC 11337598 reveal a short-term variability which is hardly hidden only by visual inspection of the data. The wavelet procedure helps on the identification of such short periodicities, which define a variability modulation characterized by their persistence, despite their low amplitude, along the time span. The 5-day periodicity found for the KIC 5862822 WD is considered to be less reliable because it only appears during almost 20 days of the total time span of 360 days. It was necessary to cut the entire light curve in small time intervals and apply the wavelet treatment in each dataset to pick up short timescales.

The time-frequency behaviors for KIC 11514682, 4829241 and 11822535 are very similar. The main peaks in the wavelet global spectra ranging from 13 to 18 days describe a semi-regular track probably associated to the WD variability. Other periods higher than 11 days are in those cases considered as aliasing of the most predominant period. Finally, KIC 10420021 classified as a DA-type WD by Østensen et al. (2011) presents expected conditions for cool
magnetic spots, in view of its effective temperature value close to the threshold limit value for which their atmospheres are expected to be fully radiative. This is noticeable in its wavelet analysis, for which we found two main periodicities of 11.70 and 5.46 days.

As underlined, the wavelet procedure offers a unique possibility for LC analysis because we can map short- and long-term features from the energy distribution of each LC computed as a local wavelet spectrum. In the present study, in addition to an enlarged treatment of the LCs, performed to avoid possible distortions in the spectral wavelet maps and changes in the power spectra, our wavelet approach was able to reveal new variability traces in the analyzed stellar sample.

**ACKNOWLEDGEMENTS**

Research activities of the observational astronomy board at the Federal University of Rio Grande do Norte are supported by continuous grants from the Brazilian funding agencies CNPq, and FAPERN and by the INCT-INEspaço. SRdeL acknowledges CAPES graduate fellowships. JPB and ADC acknowledge a postdoctoral fellowship from the Brazilian agency CNPq (Science Without Borders program, Grant No. 207393/2014-1). DBdeF acknowledges financial support from the Brazilian agency CNPq-PQ2 (grant No. 306007/2015-0). We also thank the reviewer, Prof. S. O. Kepler, for very useful comments to the original manuscript. This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission Directorate.

The data presented in this paper were obtained from the...
Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

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