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AT LAST—A V777 HER PULSATOR IN THE KEPLER FIELD

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ABSTRACT

We present the discovery of the first—and so far the only—pulsating white dwarf star located in the field of view of the Kepler spacecraft. During our ongoing effort to search for compact pulsator candidates that can benefit from the near-continuous coverage of Kepler, we recently identified a faint DB star from spectroscopy obtained with the William Herschel Telescope. After establishing its physical parameters to be $T_{\text{eff}} = 24,950$ K and $\log g = 7.91$ dex, placing it right in the middle of the V777 Her instability strip, we immediately submitted the target for follow-up space observations. The Kepler light curve reveals a pulsation spectrum consisting of five modes that follow a sequence roughly equally spaced in period with a mean spacing of 37 s. The three strongest modes show a triplet structure with a mean splitting of 3.3 $\mu$Hz. We conclude that this object is a V777 Her pulsator with a mass of $\sim 0.56 M_\odot$ and very similar to the class prototype.

Key words: stars: individual (GALEX J192904.6+444708) – stars: oscillations – stars: variables: general – white dwarfs

Online-only material: color figures

1. INTRODUCTION

The Kepler spacecraft is now in its third year of photometric monitoring of a 105 deg$^2$ field in the Cygnus–Lyrae region. Its primary mission is to detect transiting planets, and 1235 planetary candidates with transit-like signatures were detected orbiting 997 host stars in the first 4.5 months of operations alone (Borucki et al. 2011). As a byproduct of the planet hunt, high-quality photometric data of variable stars are obtained, an incredibly valuable input for the study of binary stars (Prša et al. 2011) and asteroseismology (Gilliland et al. 2010). In the first four quarters of the Kepler Mission, a survey for pulsating stars was undertaken by the Kepler Asteroseismic Science Consortium (KASC), and a total of 113 compact pulsator candidates were checked for variability using Kepler short cadence (SC; 58.8 s) exposures (Østensen et al. 2010b, 2011). The survey was extremely successful with respect to sdB pulsators, with discoveries including one clear V361 Hya pulsator (Kawaler et al. 2010b), a total of 11 V1093 Her stars (Reed et al. 2010; Kawaler et al. 2010a; Baran et al. 2011), and one spectacular sdB+dM eclipsing binary in which the hot primary shows an exceptionally rich pulsation spectrum (Østensen et al. 2010a). But even the surprisingly lucky discovery of a rare AM CVn type of cataclysmic variable (Fontaine et al. 2011) could not compensate for the fact that not a single one of the 17 white dwarfs in the sample turned out to be pulsating. This was unfortunate, but not entirely surprising as the spectroscopic identification was only made after the sample was constructed and submitted for Kepler observations, and the conclusion was that none of the candidates were actually residing inside any of the white dwarf instability strips (Østensen et al. 2011).

Since their discovery, the pulsating white dwarfs have been the kingpins of the emerging field of stellar asteroseismology. The degenerate nature of the white dwarf stars ensures that their interiors are relatively simple to model to a meaningful precision. The work of Winget et al. (1991), analyzing more than 260 hr of photometry from the third Whole Earth Telescope campaign on the pulsating DO white dwarf GW Vir, was seminal to the field of asteroseismology as it was the first time stellar pulsations had been used to establish the mass and interior structure of a star. Since then, asteroseismology has been applied to practically all stellar classes across the H–R diagram (Aerts et al. 2010). Asteroseismology of white dwarf stars is still breaking new ground by challenging theoretical models with respect to cooling rates, crystallization effects, equations of state, the physics of Type Ia supernovae, and more. For details on white dwarf physics and asteroseismology of the various pulsator types, see the recent reviews by Winget & Kepler (2008), Fontaine & Brassard (2008), and Althaus et al. (2010).

2. TARGET SELECTION

By 2010 June it had become clear that there were no white dwarf pulsators contained in the KASC compact pulsator sample. In order to avoid losing the enormous potential for white dwarf asteroseismology offered by the Kepler Mission, we made a renewed effort to identify white dwarf pulsators in the Kepler field by obtaining spectroscopy of a number of targets that were not contained in the first sample. We included all the potential targets that had been excluded from the initial sample for reasons of crowding or faintness, and added further targets from proper motion surveys and additional UV photometry from the GALEX satellite (Martin et al. 2005) released to MAST on 2010 June 15. This last sample contained 18 stars, of which we managed to get spectroscopy of 13 with the ISIS spectrograph on the William Herschel Telescope (WHT) during a run from...
July 2 to 5. We used the spectroscopic model grids of Koester (2010), which uses a mixing length prescription of ML2/α = 0.6 for DA models and 1.25 for DB models. The observed spectra were fitted to these models with the classic χ² minimization procedure of Bergeron et al. (1992).

From the sample, we selected two objects as likely white dwarf pulsators on account of their derived parameters. The first was a ZZ Ceti candidate, GALEX J191040.9+442515, which we identified with a target from the Kepler input catalog, KIC 08420780 (KP = 18.12). With $T_{\text{eff}} = 10,650 \pm 100$ K and $\log g = 7.99 \pm 0.05$ dex, it sits just off the red edge of the ZZ Ceti instability strip. The quoted errors on the physical parameters are just the formal fitting errors relative to the models, and systematic errors from, e.g., instrumental effects can be substantially larger than these, but are hard to quantify. Hoping that the truth was on the lucky side of our error bars, we targeted this object for follow-up. Anyway, it was our best ZZ Ceti pulsator candidate.

The second candidate was GALEX J192904.6+444708, which we identified with a target from the Kepler input catalog, KIC 8626021 (KP = 18.46). The spectrum clearly shows the extremely broadened helium lines characteristic of a DB white dwarf, and our fitting procedure produced the parameters

$$T_{\text{eff}} = 24,950 \pm 750 \text{ K}$$

and

$$\log g = 7.91 \pm 0.07 \text{ dex}$$

The observed spectrum and best-fit model is shown in Figure 1. For the plot, the spectrum was scaled with an instrumental response correction function determined by using a hot sdO star as a standard, in order to get the slope roughly correct. The slope was also dereddened by $E(B-V) = 0.05$, which is much less than the extinction provided by the Schlegel et al. (1998) dust value, $E(B-V) = 0.1633$, indicating that the white dwarf is located in front of the bulk of the dust detected in the region. Note that the model fitting procedure does not depend on the slope correction, as it determines its own continuum points in the wings of each line used in the fit. The only discrepancy with the model is around 3900 Å, which corresponds to the point where the instrumental response correction function starts to rapidly fall off.

The GALEX DR6 entry for this star lists it with FUV = 17.76(3), NUV = 17.92(1), and the Kepler Input Catalog provides some photometry: $g = 18.508$, $r = 18.405$, and $i = 18.442$. The uncertainty on such faint stars in the KIC is probably quite large. The USNO catalog provides photographic magnitudes, $B = 18.33$ and $R = 18.46$, which suggest a blue color, more typical for a single DB.

In spite of these two targets being fainter than any of the targets in the KASC survey, our experience with that data set made us confident that Kepler would be able to obtain useful photometry in SC mode. Thus, immediately after establishing their spectroscopic parameters, we submitted these objects for one month of Kepler DDT8 observations through the Guest Observer office. We also had the opportunity to check both targets for obvious photometric pulsations during a second run at the WHT a few months later. The ZZ Ceti candidate did not reveal any significant pulsations, but the V777 Her candidate immediately revealed a very promising light curve.

3. GROUND-BASED PHOTOMETRY

A 2 hr photometry run of GALEX J192904.6+444708 was obtained on 2010 August 30 with the recently installed ACAM spectrograph and imager at the WHT, using the Sloan $g$ filter. The light curve and its Fourier Transform (FT) are shown in Figure 2, and clearly reveal a pulsation mode with a period of 232 s and an additional weaker peak around 270 s with some possible residual pulsation power hidden in the noise at the 2 mma level. The noise in the FT is around 1 mma, so the second peak is close to the 4σ detection level.

The EEV 2k × 4k detector was windowed to 2k × 0.5k in order to reduce the readout time to 6 s. With a 30 s integration time the cycle time was 36 s, which corresponds to a Nyquist
frequency of $f_{\text{Nyq}} \approx 13900 \mu$Hz. There are no significant peaks in the high frequency range above the Nyquist frequency of Kepler SC data (8500 $\mu$Hz), so we do not need to worry about short-period pulsations reflected around $f_{\text{Nyq}}$. The light curve shown in Figure 2 was extracted on-site with the Real Time Photometry program (RTP; see Østensen et al. 2001). The data set is too short to perform any meaningful analysis of the pulsation properties, but its high signal-to-noise ratio (S/N) serves to clearly demonstrate the pulsational nature of the target. In the next section, we present the 1 month Kepler light curve of this pulsator, which due to the absence of significant gaps gives an unprecedented spectral window. In spite of a rather low S/N, the resulting FT is superior to any obtained from ground-based photometry.

4. FREQUENCY ANALYSIS OF KEPLER PHOTOMETRY

During Q7, Kepler performed SC observations of KIC 8420780 in the first month (Q7.1), and KIC 8626021 in the second month (Q7.2). The data were downloaded from the MAST archive.10 The Kepler data were processed in the same way as the KASC survey targets described in Østensen et al. (2010b, 2011).

The FT of KIC 8420780 reveals no clear pulsations. The highest peak is found at 3919.6 $\mu$Hz with an amplitude of 0.58 mma, which corresponds to 4.07 times the mean FT level. No significant peaks are found in the frequency range above this value. The mean level of the amplitude spectrum is 0.245 mma, so the 4 $\sigma$ detection level is just below 4 $\mu$Hz. As mentioned in Østensen et al. (2010b, 2011), many Kepler targets have been found to exhibit peaks in the FT up to 4.1 $\sigma$, and we do not consider these as significant detections.

The run on KIC 8626021 appears much more interesting. Kepler observations commenced on 2010 October 24 at UTC 12:54:26 and ended on 2010 November 22 at UTC 17:40:54. The data set consists of 42,760 measurements, which were reduced to 42,350 after detrending and clipping at 4 $\sigma_k$ (with $\sigma_k$ being the rms variance of the light curve). The light curve is too noisy to show obvious pulsations, but due to the large number of data points and excellent data coverage, the FT easily reveals a detailed pulsation spectrum. The upper panel of Figure 3 shows the peak amplitude spectrum of the data set, revealing five pulsation modes from the white dwarf labeled $f_1$ to $f_5$, as well as two artifact peaks associated with harmonics of the long cadence cycle of the Kepler photometer (labeled 8$f_{LC}$ and 9$f_{LC}$ in the figure). The mean level of the amplitude spectrum is 0.245 mma, so the 4$\sigma$ detection level is just below 1 mma. The lower panels of Figure 3 show zoomed-in views of the five detected frequencies, three of which appear to show a triplet structure. The splitting of the triplets is found to be 3.3 $\mu$Hz $\approx 0.3$ cpd, which corresponds to a rotational period of $P_{\text{rot}} \approx 1.7$ days for g-modes (see Aerts et al. 2010, Equation (3.359)), when using the asymptotic limit for $C_{n\ell} \approx 1/(\ell(\ell+1))$ and assuming $\ell = 1$.

The detected peaks are listed in Table 1, with $f_1$ to $f_5$ indicating the five detected modes, and subscripts + and − indicating the lower and higher frequency components of the triplets. The

![Figure 2](https://example.com/figure2.png)

Figure 2. WHT discovery light curve of GALEX J192904.6+444708 (top left) and its FT (bottom left). In the right panel, a 2’ × 2’ section of the first image reveals that the target is well separated from the other objects in the vicinity, so that there is no reason for concern about significant contamination within the large pixels of the Kepler photometer. According to the KIC, the nearest neighbor is an 18th magnitude star 17 arcsec away.

(A color version of this figure is available in the online journal.)

**Table 1**

<table>
<thead>
<tr>
<th>ID</th>
<th>Frequency ($\mu$Hz)</th>
<th>Period (s)</th>
<th>Amplitude (mma)</th>
<th>Phase (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>4306.52</td>
<td>232.21</td>
<td>4.47</td>
<td>+0.766</td>
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<td>232.02</td>
<td>5.21</td>
<td>+1.938</td>
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<td>4313.35</td>
<td>231.84</td>
<td>3.29</td>
<td>–1.605</td>
</tr>
<tr>
<td>$f_2$</td>
<td>5070.05</td>
<td>197.24</td>
<td>3.20</td>
<td>+1.278</td>
</tr>
<tr>
<td>$f_3$</td>
<td>5073.26</td>
<td>197.11</td>
<td>2.92</td>
<td>–2.874</td>
</tr>
<tr>
<td>$f_4$</td>
<td>5076.38</td>
<td>196.99</td>
<td>1.07</td>
<td>+0.206</td>
</tr>
<tr>
<td>$f_5$</td>
<td>3677.94</td>
<td>271.89</td>
<td>0.96</td>
<td>–1.998</td>
</tr>
<tr>
<td>$f_6$</td>
<td>3681.87</td>
<td>271.60</td>
<td>1.87</td>
<td>–1.920</td>
</tr>
<tr>
<td>$f_7$</td>
<td>3684.98</td>
<td>271.37</td>
<td>1.84</td>
<td>+0.979</td>
</tr>
<tr>
<td>$f_8$</td>
<td>3294.22</td>
<td>303.56</td>
<td>1.29</td>
<td>–3.126</td>
</tr>
<tr>
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<td>2658.85</td>
<td>376.10</td>
<td>1.05</td>
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<td>$f_{1C}$</td>
<td>4531.59</td>
<td>220.67</td>
<td>1.72</td>
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<tr>
<td>$f_{2C}$</td>
<td>5098.01</td>
<td>196.15</td>
<td>3.62</td>
<td>–2.135</td>
</tr>
</tbody>
</table>

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10 NASA’s Multimission Archive at STScI distributes the data from the Kepler Mission at [http://archive.stsci.edu/kepler/](http://archive.stsci.edu/kepler/). The data on KIC 8626021 becomes public on 2012 March 24. Until then, please contact the author for access.
Figure 3. FT of the detrended Kepler Q7.2 light curve of KIC 8626021. Besides the two long-cadence artifacts (labeled $8f_{LC}$ and $9f_{LC}$), five frequencies are detected (labeled $f_1$ to $f_5$) and their structure is shown in the sub-panels. The final panel shows the spectral window of the Kepler data set, as computed for a simple sine with the frequency of $f_1$ and the time stamps of the observed light curve. The overplotted curve (green in the online version) shows the FT after prewhitening of the peaks listed in Table 1, and the straight line marks the 4$\sigma$ ft level. (A color version of this figure is available in the online journal.)

phases given in the last column are in radians relative to the mid-exposure time stamp of the first frame (HJD = 55494.038647). The frequency resolution of the data set is $\sim$0.39 $\mu$Hz and can be taken as the error on the measured frequencies. Examining the list of peaks one easily notices that the period spacings between $f_1$, $f_2$, and $f_3$ are close to 36 s. The spacing between $f_4$ and $f_5$ is 72.5 s, close to twice the spacing between the other peaks. Thus, assuming one missing mode between $f_4$ and $f_5$, one can infer an evenly spaced sequence with an average period spacing of 35.68 s. This is very close to the 38.7 s spacing seen in V777 Her.

5. DISCUSSION AND CONCLUSIONS

A DB white dwarf (GALEX J192904.6+444708 = KIC 8626021) was identified from spectroscopy to reside in the middle of the V777 Her instability strip (see Figure 4). Its mass can be inferred to be $0.56 \pm 0.03 M_\odot$ from the evolutionary tracks by Althaus et al. (2009). A short photometric follow-up run established that significant pulsations are present in this object, making it a new member of the V777 Her family of pulsating DB white dwarfs. Follow-up observations with the Kepler spacecraft have confirmed a typical V777 Her pulsation spectrum, which appears to show a sequence of $\ell = 1$ triplets. The observed period spacings between the modes are similar to those of V777 Her itself, and compatible with the $\ell = 1$ sequences of model frequencies with radial overtones of $k = 2, 3, 4, 5, \text{and} 7$ for $0.6 M_\odot$ models from Bradley et al. (1993).

V777 Her pulsators are known to display strong changes in the excitation level of the modes, where the pulsation amplitudes can vary by a factor five or more. V777 Her itself is also known to shift the distribution of amplitudes significantly among its excited modes (Provencal et al. 2009). In extreme cases, the pulsation spectrum can undergo a dramatic change known as an sforzando, where it suddenly acquires a single large amplitude pulsation mode (Castanheira et al. 2005), which subsequently fades. There is a good chance that KIC 8626021 will show similar behavior, so extended Kepler observations will not just bring down the noise level in the amplitude spectrum and reveal further low-level excited modes, but will also have a unique opportunity to monitor the processes that lead up to sforzando events and other types of variabilities that characterize these pulsators.
KIC 8626021 is only the 21st V777 Her pulsator known in the literature. DB white dwarfs are in general rare compared to the common DAs, with the DAs outnumbering the DBs ten to one at any magnitude (Eisenstein et al. 2006). Furthermore, the pulsators among the DBs are extremely rare compared to the bulk of the population, which have effective temperatures below 20,000 K (see, e.g., Figure 7 of Winget & Kepler 2008). Thus, it is an extraordinary stroke of luck finding a pulsating DB white dwarf in the relatively constrained field of view of the Kepler spacecraft, especially since this is only the second spectroscopically confirmed DB found therein.

Of the 20 known V777 Her pulsators, only a few have been subjected to the persistent follow-up observations required in order to assess their frequency spectra in any detail. Except for the well-studied prototype, only V1063 Tau and V824 Her have been subject to extensive multi-site campaigns (Handler et al. 2003), and both stars were found to display substantial variations regarding which modes were excited and their total pulsational amplitude. Of those two, V824 Her was found to exhibit roughly equidistant periods with a mean spacing of \( \Delta P \approx 25 \text{s} \). A mean period of 200 s. A mean period of 8.49 \( \text{s} \) was also found from extensive single-site data of SWLMi (Handler et al. 2002), and in both cases the obvious interpretation is that of a sequence of \( g \)-mode pulsations of degree \( \ell = 1 \) in a nominal mass \( \sim 0.6 \, M_\odot \) DB. Most recently, Bischoff-Kim & Metcalfe (2011) presented an asteroseismic solution for QU Tel and tested the observed pulsation spectrum against various core and envelope parameters.

The periods observed in KIC 8626021 are on the short end of the range usually found in these pulsators. Only V824 Her (Winget et al. 1984) and QU Tel (Koen et al. 1995) have been reported to have periods below 200 s. The range 400–800 s seems to be more commonly excited. Judging from the behavior of other pulsators of this class, it is therefore quite likely that we will see modes of higher radial order excited in future Kepler runs. Being able to precisely determine the periods of modes of a wide range of radial orders is extremely important as each mode has a different sensitivity to the interior structure. Determining a detailed asteroseismic profile of the interior structure of KIC 8626021 should therefore become achievable with further monitoring. The target has been scheduled for further Kepler observations from Q10 onwards.

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