Nine months of monitoring of a V777-Her pulsator with the Kepler spacecraft

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Abstract. The V777 Her pulsator KIC 8626021 has been observed continuously by the Kepler space telescope for nine months. Two new independent pulsation modes are detected in the extended dataset, which both match the predicted sequence of $\ell = 2$ modes. We demonstrate the photometric stability of the main pulsation modes and discuss the prospect of measuring period changes within the context of the extended Kepler mission.

Introduction

The Kepler spacecraft is monitoring a 105 deg$^2$ field in the Cygnus–Lyrae region, primarily to detect transiting planets (Borucki et al. 2011). In the first four quarters of the Kepler Mission, a survey for pulsating stars was made, and a total of 113 compact-pulsator candidates were checked for variability (Østensen et al. 2010a, 2010b). The survey was extremely successful with respect to subdwarf-B (sdB) pulsators, with discoveries including one clear V361-Hya pulsator (Kawaler et al. 2010b), a total of thirteen V1093-Her stars (Reed et al. 2010; Kawaler et al. 2010a; Baran et al. 2011), including a spectacular sdB+dM eclipsing binary in which the hot primary shows an exceptionally rich pulsation spectrum (Østensen et al. 2010a). However, not a single pulsating white dwarf was found during the survey phase. As the Kepler Guest Observer programme permits monitoring of interesting targets in one month or longer slots, we started searching among the faint rejects from our original survey sample, where the $K_p = 18.46$ mag KIC 8626021 was found. The first 1-month dataset of this V777-Her pulsator was obtained in the second month of quarter 7 of the Kepler Mission (Q7.2), and the Fourier transform (FT) revealed eleven peaks, of which nine forms triplets with even splittings of 3.3 $\mu$Hz, corresponding to a rotation period of 1.7 d when assuming that the modes have degree $\ell = 1$. For further details about the search and the Q7.2 dataset, please see the discovery paper; Østensen et al. (2011a).

An asteroseismic solution for KIC 8626021 was presented by Bischoff-Kim & Østensen (2011), where all the modes could be well matched by a structural model only if the target is significantly hotter than the spectroscopic estimate made in the discovery paper. Since the spectrum had a rather low signal-to-noise ratio, and DB stars are notoriously difficult to get reliable temperatures for, a higher temperature is not controversial. A further asteroseismic study by Córsico et al. (2012) corroborates the high temperature solution.
Table 1. Frequencies detected in the Q10+11+12 dataset.

| ID | Frequency | Period | Type       | $\ell, k$ |
|----|-----------|--------|------------|----------|
| $f_1$ | 4309.89 | 232.02 | Triplet, $\delta f = 3.3\,\mu$Hz | 1,4 |
| $f_2$ | 5070.05 | 197.11 | Triplet, $\delta f = 3.3\,\mu$Hz | 1,3 |
| $f_3$ | 3681.87 | 271.60 | Triplet, $\delta f = 3.3\,\mu$Hz | 1,5 |
| $f_4$ | 3294.22 | 305.56 | Single peak | 1,6 |
| $f_5$ | 2658.85 | 376.10 | Single peak | 1.8 or 2,15 |
| $f_6$ | 6965.29 | 143.57 | Single peak | 2,4 |
| $f_7$ | 4398.37 | 227.36 | Single peak | 2,8 |

The 9-month dataset

*Kepler* quarters Q10, Q11 and Q12 covers BJD 2455739.83 to 2456015.03, giving a full span of 275.2 days, which corresponds to a frequency resolution of $\sim 0.04\,\mu$Hz. The dataset contains 389,195 60-s measurements, or 386,863 after sigma clipping. The eight monthly data-downlink gaps are 0.74 to 1.06 d in duration, and 0.87 d on average, which is too short to produce significant monthly aliases in the Fourier spectrum. Since the target is so faint, only $\sim 250\,e^\text{−}$/s are collected, corresponding to $\sim 15,000$ counts per short cadence measurement. In signal-to-noise terms we get only $S/N = 30$ (Q10), 32 (Q11), and 28 (Q12). Still, with 43,000 consecutive measurements per month, this is sufficient to bring down the mean Fourier amplitude level to $\sim 0.25\,\text{mma}$ in a month of data, and to just below 0.1 mma in the 9-month dataset (Fig. 1).

Running Fourier spectra were made by clipping the full Q10+11+12 dataset into chunks of up to 14 d length and taking the FT of each. When displayed as a grey-scale plot as in Fig. 2 it is easy to see that some of the peaks such as the central component of the $f_1$ triplet variable amplitudes. Other peaks, such as the longest-frequency component of the $f_1$ and $f_2$ triplets, show no significant amplitude variability over the course of the nine-month run.

New frequencies

In addition to the five independent modes seen in Q7.2, two new ones are detected in the 9-month dataset, that were below the 4-$\sigma$ detection limit in the discovery run. These are labeled $f_6$ and $f_7$ in Table[1] and Figures[1] and[2]. On closer inspection, $f_6$ is present in Q7.2 with a slightly higher amplitude than in the 9-month dataset, but 0.85 mma is only 3.5 $\sigma$ in Q7.2, well below our preferred detection limit of 4 $\sigma$. $f_7$ is below the 3-$\sigma$ level in Q7.2. In the 9-month FT, $f_6$ has $S/N = 8.13$ and $f_7$ has $S/N = 8.48$. That the two new frequencies are real and stable pulsation modes of the star is immediately clear from the running FT. While well below the detection limit in individual FTs, their steady recurrence at the same frequency betrays their presence.

The spacing for $\ell = 1$ modes derived in the discovery paper was $\Delta P_1 = 35.7\,\text{s}$. Since $\Delta P_1/\Delta P_2 = \sqrt{3}$ for $g$-modes in the asymptotic limit, one can assume an $\ell = 2$ spacing of $\Delta P_2 = 20.6\,\text{s}$. In the discovery paper $f_5$ was identified as $\ell = 1, k = 8$, whereas in [Bischoff-Kim & Østensen (2011)] it was found to be a closer match to $\ell = 2, k = 15$. Assuming the latter, one can tentatively assign $f_6$ as $\ell = 2, k = 4$, and $f_7$ as $\ell = 2, k = 8$. 
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Figure 1. Fourier spectrum of KIC 8626021 based on the full Q10+11+12 dataset. The 7 independent modes are marked as $f_1$ to $f_7$, see Table 1. Artifacts produced by the long cadence cycle ($f_{lc} = 566.423 \mu\text{Hz}$) are also marked.

This is very encouraging as the number of free parameters in the asteroseismic models had to be kept small with only the original five independent modes to work from. Adding two more independent modes, allows the models to be substantially improved.
Figure 2. Running Fourier spectra of KIC 8626021 produced by clipping the full Q10+11+12 light curve into chunks of up to 14 d length and taking the FT of each. Time in BJD + 2400000 is given on the left-hand axis and Kepler Mission months are indicated on the right-hand side. Horizontal lines mark the monthly Earth downlink interruptions.
Conclusions

A faint V777-Her pulsator was found in the Kepler field, and observed for one month during Q7, and monitored continuously from Q10 onwards. The ongoing observations have revealed that some of the strongest modes are almost perfectly stable in time, and that low-amplitude modes come and go. Further monitoring should therefore reveal more independent modes, thereby providing further constraints on the asteroseismic models.

With the current mission extension, we have the opportunity to get more than five years of near-continuous monitoring, provided the spacecraft maintains its excellent performance. With such a time-base, we have a unique opportunity to detect period changes ($\dot{P}$) due to the changes in interior structure as the white dwarf cools.

The rate of period change in a white dwarf has so far only been measured in the ZZ-Ceti pulsator, RY LMi, for which Kepler et al. (2005) found $\dot{P} = (3.57 \pm 0.82) \times 10^{-15}$ s/s based on 31 years of monitoring. At the high-$T_{\text{eff}}$ end of the V777-Her instability strip the cooling is completely dominated by plasmon neutrino emission (Winget et al. 2004), and is predicted to be a hundred times faster than for the DAVs due to the neutrino contribution. The measurement of an evolutionary $P$ is therefore quite possible within the time-frame of the extended Kepler Mission, as currently scheduled to go on until the end of 2016.

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