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## Research Article

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# Detection of stellar oscillations in HW Vir

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**Abstract:** We present our analysis of K2 observations of the binary system, HW Vir. We processed the raw Kepler data and used Fourier analysis to search for periodic signals that could be associated with pulsations. We detect the binary frequency and its harmonic and discovered tens of peaks at both low and high frequencies. We interpreted those to be caused by stellar pulsations. Our discovery means we can apply the tools of asteroseismology to the HW Vir system.

**Keywords:** subdwarfs, stars: oscillations (including pulsations)

## 1 Introduction

Stellar pulsations in the subdwarf B stars (sdB) were observationally found in the late 1990s by Kilkenny et al. (1997). At the same time, Charpinet et al. (1997) calculated the first theoretical models and found that the kappa mechanism can be strong enough to drive pulsations in hot subdwarfs. The sdB stars can pulsate in pressure (p) or gravity (g) modes, as well as in both simultaneously. The latter are also known as hybrid sdBV stars and the first member of this class, with plenty of g- and p-modes, was reported by Baran et al. (2005). These discoveries have opened a way to study interiors of hot subdwarfs. Ground-based observations attempted to characterize sdB pulsators (sdBV) while lately, a comparable number [46 to date] have been monitored from space. The latter data are characterized by continuous coverage and very low noise level. These properties make detection of low amplitude pulsations possible.

Some of the hot subdwarfs are in binary systems. Of special interest to us are those binaries with subdwarfs in very close orbits, e.g. HW Vir-type stars. According to our current knowledge, these are binaries consisting of sdB stars as primaries and M dwarfs as secondary components. The orbital periods are close to 3 hours with orbital inclinations close to 90 deg, giving us the chance to observe

very deep eclipses and an irradiation effect. In a few of these systems the primary components show pulsations and they are named NY Vir-type stars, after the prototype.

Our study targets the search for pulsations in the primary component, which according to our current knowledge, is an sdB, though this classification may not be correct. Our second goal was to derive the time shift of the secondary eclipse and constrain the mass of the primary component to uncover its nature. The shift of the secondary eclipse was fully explained by Kaplan (2010). It may appear when the orbit is eccentric, or the components of a binary system are not of equal masses. The latter reason is based on the finite speed of light and is often called a Rømer delay. This delay is a direct measure of the masses of both components and, in the case of HW Vir, is very useful in confirming the canonical mass of the sdB star. The pulsations of sdB stars are very crucial for applying asteroseismology to derive stellar properties, including the total mass, which would be an independent cross check of the Rømer delay.

Analysis of the Rømer delay will be reported elsewhere and with this work we focus on applying asteroseismic techniques to our discovery of pulsations.

## 2 Fourier analysis

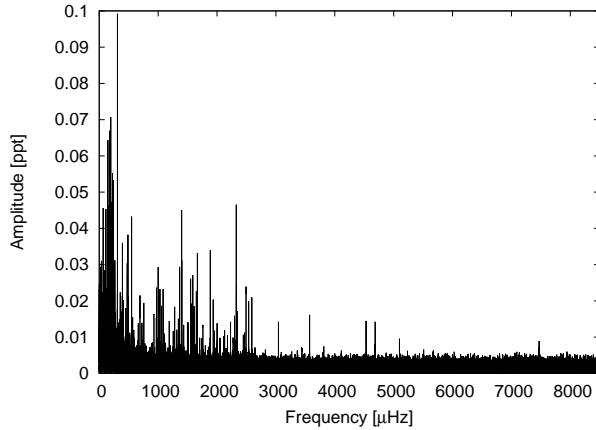
The data were taken with the Kepler spacecraft during the K2 mission Campaign 10 and here we report a preliminary analysis of the short cadence data. As described in Baran et al. (2017), we first extracted the fluxes using IRAF aperture photometry. Next, we de-correlated fluxes to remove the thruster firing artifacts from the data. Finally, we  $4\sigma$  clipped the data and detrended to remove the very long variations which we do not expect are intrinsic to the

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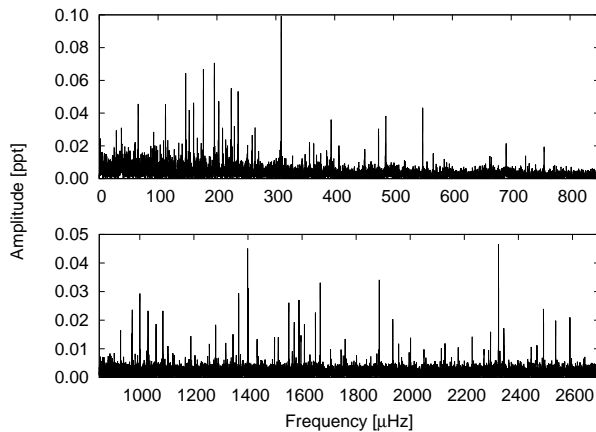
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**Figure 1.** The amplitude spectrum of HW Vir observed during K2 mission Campaign 10.



**Figure 2.** Close-ups of the g-mode (top panel) and p-mode (bottom panel) regions. Note different scales of the vertical axes in two panels.

stars. We also removed the binary frequency and its harmonics using prewhitening. This removal has no significant influence on any other periodic signal that may exist in the data, unless it is located at exactly the same frequencies as those prewhitened. We calculated the amplitude spectrum, which we show in Figure 1. The temporal spectrum is plotted up to the Nyquist frequency. The pulsations have rather low amplitudes with the highest below 0.1 ppt. A few g modes have slightly higher amplitudes than the p modes but on average the amplitudes are comparable. The spectrum looks fairly continuous with a small gap around  $800 \mu\text{Hz}$ , which we assume is the separation between g and p modes. In Figure 2 we show the g- and p-mode regions separately. The region beyond  $2700 \mu\text{Hz}$  is not shown in detail, since it contains only well-separated frequencies which can be seen in Figure 1.

### 3 Multiplets and asymptotic period spacing

For pulsations to constrain models, it is advised, if not a requirement, that the pulsation modes are observationally identified. The identification describes the modal geometry and decreases the number of free parameters, making the calculated models more reliable. The data taken with the Kepler spacecraft are precise enough to allow us to detect rotationally split multiplets (e.g. Baran *et al.* 2012a) and even period spacings, indicative of asymptotic radial overtones (Reed *et al.* 2011). These two features are also very efficient in constraining mode geometries (identifications). Multiplets provide modal degrees, while the period spacings provide both modal degree and relative (to an arbitrary zero-point) radial order. In addition, if trapped modes are detected, these can constrain discontinuities in chemical profiles inside the star.

We searched for multiplets among both g and p modes. The rotation period is directly related to the separations within multiplets. If HW Vir is tidally locked, then, in the absence of non-linear effects, the rotation period of 2.8 hours would create p-mode multiplet splittings near  $100 \mu\text{Hz}$  and  $\ell = 1$  g-modes would be split at roughly half that,  $50 \mu\text{Hz}$ . However, typical rotation periods among sdB stars is about 40 days (e.g. Baran *et al.* 2012b; Østensen *et al.* 2014). Three sdB stars in binaries, with periods of about half a day, have rotation periods of around 10 days (Baran & Winans 2012c) and those are the shortest, well-established rotation periods for sdB stars. We searched for frequency multiplets but did not find any common frequency splittings and no obvious multiplets. The search is likely hampered by the frequency density, with a g- and p-mode median separations of  $7.4$  and  $26.8 \mu\text{Hz}$ , respectively. The lack of consistent multiplet splittings may be the result of non-linear effects caused by a short rotation period. Another explanation for not detecting multiplets could be a pole on orientation of the pulsation axis. However, if the orbital inclination is close to  $90$  deg, we have no reason to expect that the pulsation axis is not aligned with the normal to the orbit. At this point, the rotation period of an HW Vir-type primary has never been derived.

The search for period spacing sequences among g modes also resulted in a null detection. Due to geometric cancellation (Dziembowski 1977), we expect that dipole and quadrupole modes will have higher amplitudes than modes with higher degrees. Therefore, with many peaks in the g-mode region, we anticipated that many would be either  $l = 1$  or  $2$  and those sequences would have been well-established for other sdBV stars to be near 250 and 150 sec,

respectively (Reed *et al.* 2011). However, from our preliminary analysis, we do not find any such sequences. It is possible that the spacing is not uniform over the period range of  $g$  modes, but at present we have no hints of such spacings.

## 4 Summary

We presented our preliminary analyses of K2 data of HW Vir. This is the second such system observed with the Kepler spacecraft. The other system is 2M 1938+4603 (Østensen *et al.* 2010) and those authors found it also to be a pulsator with no obvious multiplets or period spacings. Our conclusion is very much like theirs. Given that the systems are nearly identical, and the same result has been achieved, we expect that the same mechanism is responsible for their amplitude spectra. Such spectra contain no typical multiplets and period spacings as compared to other sdBV stars observed with the Kepler spacecraft. It is possible the pulsations have a completely different nature in HW Vir-type systems.

Menzies & Marang (1986) reported their analysis of HW Vir and their estimation of the mass of the primary component to be  $0.25 M_{\odot}$ . This is half the mass needed for the helium flash to occur, which is necessary for an sdB star. Baran *et al.* (2015) calculated the mass of the primary in 2M 1938+4603 to be below  $0.3 M_{\odot}$ . From the analysis we have done using these K2 observations of HW Vir, we derived the mass to be  $0.25 M_{\odot}$  (details of that analysis will be presented elsewhere), which agrees with Menzies & Marang (1986). If the mass is truly below  $0.3 M_{\odot}$ , the primary component is no longer an sdB star, since such a low mass does not allow for the helium flash to occur, and so the object must be a post red giant branch star on its way to the white dwarf cooling track.

If Menzies & Marang (1986) were right and our estimations of the mass of the primaries in both 2M 1938+4603 and HW Vir are correct, the stars can no longer be considered as sdB stars and so different seismic properties should be expected. Therefore, the application of asteroseismology to HW Vir-type systems is not yet possible, until the nature of the primary star is correctly established.

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