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DETECTION OF NEW PULSATIONS IN THE roAp STAR HD 177765

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Introduction

The rapidly oscillating Ap (roAp) stars were first identified by Kurtz (1982). They show high-overtone ($n > 15$) low-degree ($\ell \leq 2$) non-radial modes, with periods between about 5-23 min. In most cases, pulsations are thought to be driven by the κ-mechanism acting in the H I ionisation zone, with evidence that turbulent pressure may be the driving mechanism in a subset of the stars (Cunha et al. 2013). Due to the intrinsic nature of the roAp stars, they are an ideal class of pulsator to study the interaction between pulsations, rotation, chemical stratification and strong global magnetic fields. To date, there are 61 known roAp stars (see Smalley et al. 2016).

HD 177765 (J2000 α=19$^{\rm h}$07$^{\rm m}$09$\overset{\rm s}{.}$78, δ=−26°19′54$\overset{\prime\prime}{.}$5; $V = 9.15$; $T_{\rm eff} = 8000$ K, $\log g = 3.8$, Alentiev et al. 2012) was shown to be a roAp star by Alentiev et al. (2012) through the analysis of high-resolution spectra obtained with VLT/UVES over a period of 66 min. Previous attempts to identify pulsations in photometric data have failed (e.g. Martinez & Kurtz 1994; Holdsworth 2015) due to the inherent low-amplitude of the variability ($7 - 150\,{\rm m\,s^{-1}}$; Alentiev et al. 2012). However, with the precision afforded by the *Kepler* space telescope, we are able to confirm the spectroscopic observations, and identify two further pulsation frequencies in this star.

Observations and Data Reduction

HD 177765 was observed during Campaign 7 of the K2 mission in long cadence (LC) mode (through proposals GO7030 & GO7061). Observations cover a period of 81.32 d (2015 October - 2015 December) and consist of 3720 data points. Due to the systematics in the raw K2 data, data processed by the pipeline of Vanderburg & Johnson (2014) was used for the analysis. The top panel of Figure 1 shows the pipeline processed light curve. As can be seen, there are some instrumental artefacts remaining in the light curve at the start of the observations; these data points were disregarded from the analysis. We also removed data points which were obvious outliers from the mean light curve. The resultant light curve consists of 3614 data points.

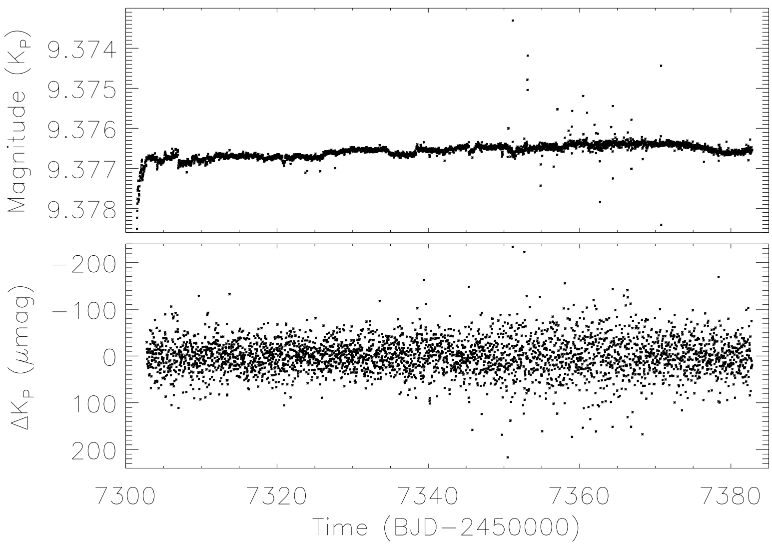

Figure 1. Top panel: K2 light curve reduced with the Vanderburg & Johnson (2014) pipeline. Bottom panel: the prewhitened light curve which was used for the pulsation analysis.

To be able to attain the best signal-to-noise ratio for the pulsation frequencies, we prewhitened the final light curve to remove all low-frequency signals, to a maximum of $10\,\mathrm{d}^{-1}$, which have an amplitude of $2.5\,\mu$mag or greater (the approximate noise level surrounding the pulsations). There is a significant frequency gap between the prewhitened region and the pulsations such that this process does not affect the astrophysical signal. The result of this process is shown in the bottom panel of Figure 1.

Analysis

Although HD 177765 was observed in LC mode, there is no ambiguity in differentiating between an alias peak and a true peak as the principal pulsation frequency is known from spectroscopic observations. We therefore assume that the two newly identified peaks are in the same frequency range, as is seen in other multifrequency roAp stars. Further to this, the peaks are well defined; alias peaks show a 'ragged' structure as a result of Nyquist-frequency crossings, thus implying ν_2 and ν_3 are the true pulsation frequencies as this is not the case. Figure 2 shows the periodogram of the light curve where the true pulsations are found. Note that the amplitudes presented are suppressed due to undersampling of the pulsations, which are above the LC Nyquist frequency.

Analysis of the pulsations was conducted following the methodology of Kurtz (1985), with the results of a non-linear least-squares fit to the three frequencies shown in Table 1. There are no rotationally split sidelobes associated with any of the identified peaks, which are expected with the oblique pulsator model (Kurtz 1982; Bigot & Kurtz 2011). However, this is not surprising for HD 177765 due to the expected long rotation period of the star. Mathys et al. (1997) measured a constant mean magnetic field modulus for the star over two years of observations, suggesting the rotation period of the star is much longer than their time base.

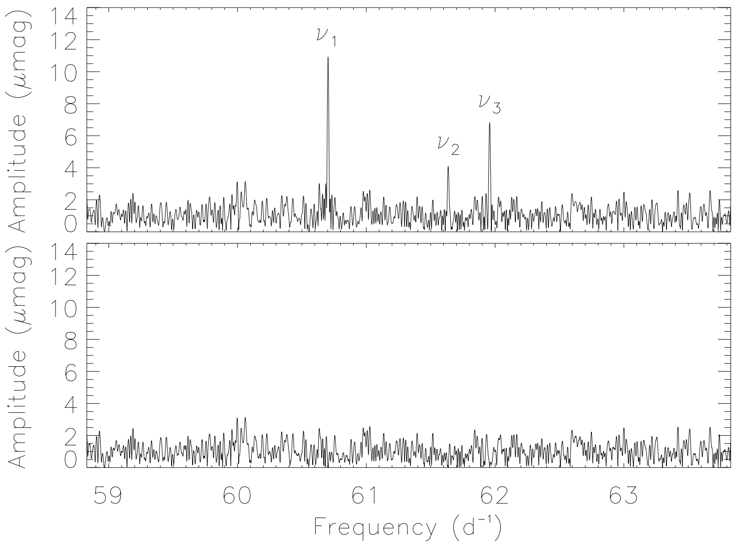

Figure 2. Top panel: periodogram of the K2 data showing the three identified frequencies, as listed in Table 1. Bottom panel: periodogram of the same data after the three identified peaks are removed showing no further significant peaks, and confirming the peaks to be the correct frequencies.

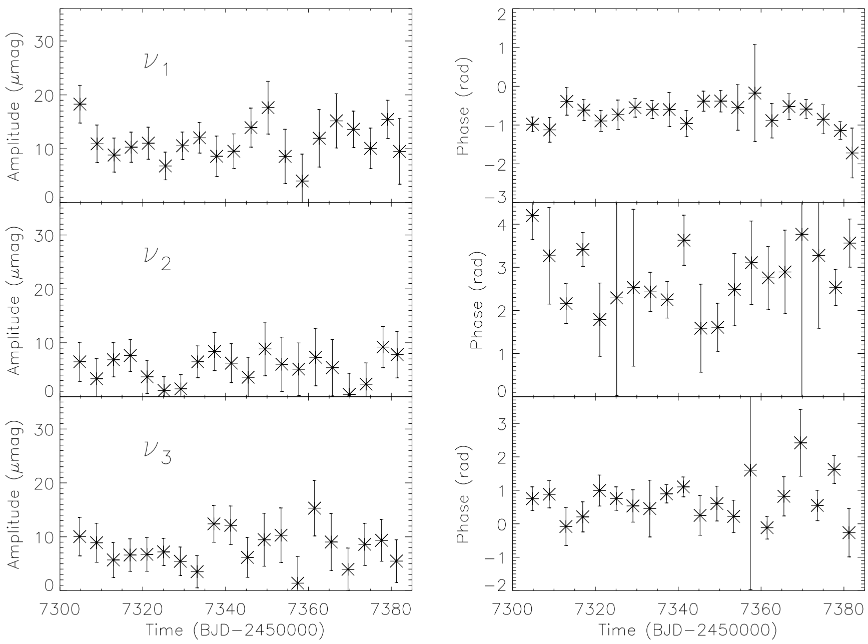

Figure 3. Left column: pulsation amplitude as a function of time for each identified mode. Right column: pulsation phase as a function of time for each identified mode. There is no trend in either parameter, indicating a long rotation period and stable pulsations.

Table 1. The results of a non-linear least-squares fit to the K2 light curve. The zero-point for the phases is BJD−245 7342.7892.

ID	Frequency (d^{-1})	Amplitude (μmag)	Phase (rad)
ν_1	60.7029 ± 0.0005	11.0 ± 0.8	-2.69 ± 0.08
ν_2	61.6362 ± 0.0013	4.2 ± 0.8	1.35 ± 0.20
ν_3	61.9580 ± 0.0009	6.8 ± 0.8	2.36 ± 0.12

To test the stability of the pulsation modes, we divided the data into sections of 250 pulsation cycles (for each mode separately) and computed the amplitude and phase of the pulsation. This number of pulsation cycles allowed us to well resolve ν_2 and ν_3. None of the pulsation modes show a variation in amplitude or phase, as shown in Figure 3. This is consistent with the long rotation period as the amplitude is not modulated with rotation, nor does the phase change at quadrature (cf. figure 15 of Holdsworth et al. (2016) for examples of amplitude and phase modulations). Finally, there is no long-term drift in the phase that would indicate frequency variability, as phase and frequency are coupled.

To perform an asteroseismic analysis on HD 177765 requires knowledge of the large frequency separation, $\Delta\nu$, which varies between $\sim 6.9\,\mathrm{d}^{-1}$ for main-sequence A stars (for modes of (n, ℓ) and $(n+1, \ell)$), and $\sim 3.5\,\mathrm{d}^{-1}$ for slightly evolved stars (Heller & Kawaler 1988; Shibahashi & Saio 1985). Through the analysis of their spectra, Alentiev et al. (2012) derive a luminosity of $\log L/\mathrm{L}_\odot = 1.15$, and thus expect a large separation of $\Delta\nu \sim 4.3\,\mathrm{d}^{-1}$ for HD 177765. However, the separations of the pulsations presented here are: $\nu_2 - \nu_1 = 0.933 \pm 0.002\,\mathrm{d}^{-1}$, $\nu_3 - \nu_1 = 1.255 \pm 0.001\,\mathrm{d}^{-1}$, and $\nu_3 - \nu_2 = 0.321 \pm 0.002\,\mathrm{d}^{-1}$. The frequency difference between these values and those expected are too large for any of the frequency separations to be considered to be $\Delta\nu$.

The newly identified peaks are not indicative of rotation as the peaks are not equally split and do not agree with the results of Mathys et al. (1997) mentioned above.

There is the possibility, however, that these newly detected pulsations are of different ℓ values. Kurtz, Elkin & Mathys (2006) argued for a new type of variability in the upper atmospheres of the roAp stars. Through VLT/UVES observations, they found eight out of nine of their target stars showed radial velocity variations at frequencies not seen in photometric data. One of their hypotheses was higher ℓ pulsations high in the atmosphere which are averaged out in photometric observations of the continuum. It is plausible that *Kepler* observations have the precision to detect these higher degree modes. Further high-resolution, time-resoled spectra, over a significant time-base, are required for HD 177765 to resolve the peaks and confirm this theory.

Conclusions

For the first time, we have shown HD 177765 to be a multiperiodic roAp star. Analysis of the K2 photometric light curve has allowed us to identify the principal frequency to a much higher precision than was obtained previously. Two further pulsation frequencies have been identified above the noise in the periodogram, the first detection of these frequencies. The lack of rotational sidelobes to the pulsations, as expected by the oblique pulsator model, shows this star has a rotation period longer than 81 d, a result consistent with the literature. The frequency difference between the modes is not expected to be the large frequency separation required for an asteroseismic analysis of HD 177765.

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