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High-speed colourimetry of the subdwarf B star SDSS J171722.08+58055.8 with ULTRACAM*

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ABSTRACT

We present high-speed multicolour photometry of the faint V 361 Hya star SDSS J171722.08+58055.8 ($B \simeq 16.7$), which was recently discovered to be a pulsating subdwarf B star. The data were obtained during two consecutive nights in 2004 August using the three-channel photometer ULTRACAM attached to the 4.2-m William Herschel Telescope. The data have a total time-span of 1.11 d and consist of two groups spanning roughly 2.5 h each. The adopted integration time was 10 s. We confirm the star to be oscillating and we refine the dominant frequency to 6.960 ± 0.022 mHz. A second new oscillation frequency of 7.267 ± 0.025 mHz is discovered, having a well-covered beat period of 0.9 h with the dominant one. Both modes have amplitudes that are significant in all three colours at a level $>5\sigma$ and show, within the measurement accuracy, the same phase in all three colours. We attempted mode identification for the two modes from their amplitude ratios but did not obtain conclusive results due to the too-large uncertainties in the observed ratios.

Key words: stars: individual: SDSS J171722.08+58055.8 – stars: oscillations – subdwarfs – stars: variables: other.

1 INTRODUCTION

Asteroseismology of hot subdwarf B stars (hereafter termed sdB stars) has received a lot of attention ever since the theoretical prediction of κ-driven oscillations (Charpinet et al. 1996) and the almost simultaneous and independent observational discovery of oscillations in some such stars in 1997 (see Kilkenny 2002, for an overview of the discovery history). The reason is that precise determination of their fundamental parameters (in particular, their total and surface envelope mass and stratification) in principle should be possible through modelling of their observed oscillation properties (e.g. Brassard et al. 2001, for a pioneering study). This would lead to important diagnostic values to test the current uncertain evolutionary scenarios for sdB stars (e.g. Han et al. 2003, and references therein).

To date, 33 sdB stars with p-mode oscillations (the so-called V 361 Hya stars) are known. Detailed modelling efforts are available for only a few of them: PG 0014+067 (Brassard et al. 2001; Charpinet et al. 2005a), PG 1219+534 (Charpinet et al. 2005b) and Feige 48 (Charpinet et al. 2005c). Other much less-extensive studies have also been presented by Kilkenny et al. (2003) for PG 1336 − 018 and by Reed et al. (2004) for Feige 48. These modelling efforts either result from matching the observed frequencies with those from theoretical predictions (usually using equal weighting), or assume some modes to have a particular spherical degree from the abscence or presence of rotational splitting for these particular frequencies. The value of a seismic model stands or falls with the correct mode identification and with the uniqueness of the model. Since we do not have any strong clue about the mode selection mechanism in these stars, a great need for empirical mode identification, that is, identification obtained independently of the details of period-matching exercises, emerges.

Empirical mode identification can be achieved in essentially two ways: from amplitude ratios and/or phase differences from multicolour photometry (e.g. Dupret et al. 2003, and references therein for main-sequence stars; Jeffery et al. 2004; Randall et al. 2005, for applications to sdB stars in the adiabatic and non-adiabatic description, respectively) or from line-profile variations in high-resolution spectroscopic data (e.g. Aerts & Eyer 2000, for a review). The latter application still lacks for V 361 Hya stars because of the stringent constraints on temporal and spatial resolution for the rapid

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oscillations in such faint stars. Time-resolved spectroscopy was achieved for some V 361 Hya stars (Jeffery & Pollacco 2000; O'Toole et al. 2000, 2002) but its interpretation has been limited to velocities so far.

The method of photometric amplitudes has been applied to three V 361 Hya stars until now: KPD 2109+4401 and HS 0039+4302 (Koen 1998; Jeffery et al. 2004) and PG 0014+067 (Jeffery et al. 2005). In none of these cases were unambiguous identifications achieved because the degree dependence of the amplitude ratios is generally quite weak for sdB stars, particularly for low-degree modes with $l = 0$, 1 and 2 (see, Ramachandran, Jeffery & Townsend 2004; Randall et al. 2005). However, in some instances, useful restrictions on the degree of some oscillation modes have been derived. For instance, Jeffery et al. (2005) have suggested, on the basis of ULTRACAM photometry, that the $l = 3$ identification proposed by Brassard et al. (2001) for one of the main modes observed in PG 0014+067 may be erroneous. In view of this, and to unravel the mode selection in general, one should aim to get multicolour photometry for as many of the V 361 Hya stars as possible, to guide future modelling efforts.

The current paper provides colour amplitude ratios for a fourth V 361 Hya star. SDSS J171722.08+58055.8 (hereafter abbreviated as SDSS 1717) is an sdB star of B magnitude 16.7. Solheim et al. (2004) recently discovered one oscillation frequency in SDSS 1717 from white-light data gathered with the Nordic Optical Telescope during three consecutive nights in 2002. These data revealed a frequency of 7.03 mHz and a variable amplitude ranging from 4.4 to 6.2 mmag. The authors indicated that the amplitude modulation is probably a reflection of multimode beating, but their data did not allow the derivation of more than one oscillation frequency. As far as we know, no follow-up study to this discovery campaign was performed for this faint V 361 Hya member besides the one that we present here. Preliminary results of our analysis were presented in Aerts et al. (2006).

2 OBSERVATIONS

In their recent study, Jeffery et al. (2005) reported on the outcome of a 6 n ULTRACAM run with the 4.2-m William Herschel Telescope (WHT) dedicated to the sdB star PG 0014+067 performed in 2004 August. ULTRACAM is a three-channel CCD photometer specifically designed for fast photometry programmes (Dhillon et al. in preparation). The main target of this campaign was not yet visible during the first 2.5 h of each of these nights and several secondary science targets were observed. In this way, we recorded the three-colour light curve (Sloan u', g' and r' filters) of SDSS 1717 ($\alpha_{2000} = 17:17:22.0$, $\delta_{2000} = +58:05:59$) and several comparison stars among which C2–C6 (see Fig. 1) during two blocks of 2.5 h on two consecutive nights. We adopted an integration time of 10 s which samples the dominant 140-s pulsation well.

The reduction of the data frames was performed in the same manner as for PG 0014+067, which was already described in much detail in Jeffery et al. (2005). We hence refer the reader to that paper for information. Different comparison stars C2–C6 were considered to compute the differential magnitudes in each of the channels. It turned out that C3 and C4 were too bright, while C5 was too faint. Several other stars (not indicated in Fig. 1 for clarity) were also considered. In the end, we used C2 and C6 to construct the final differential light curves, C6 being the only star with a count rate higher than the target in u'. However, the final results of the frequency analysis are independent of the different choices of the unsaturated comparison stars. The brightness relative to the target

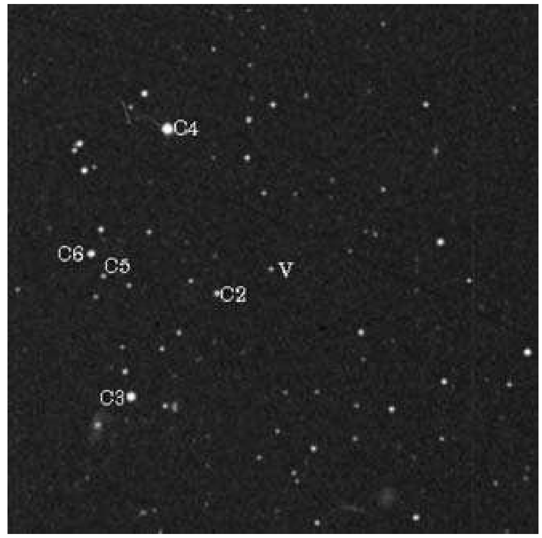

Figure 1. Chart on which SDSS 1717 is indicated as V while the comparison stars are denoted C2–C6. The final light curves were obtained by using C2 and C6.

in u', g' and r' (in magnitudes) amounts to $\delta u' = +0.88, \delta g' = -0.76, \delta r' = -1.51$ for C2 and $\delta u' = -0.60, \delta g' = -2.04, \delta r' = -2.75$ for C6.

The differential light curves we publish here were made by adding the counts of comparison stars C2 and C6 before for the u' and g' channel, and by considering only C2 for the r' channel. C6 introduced jumps in r' due to saturation so we limited to the counts of C2 for that channel. The obtained oscillation amplitudes have a higher precision in this way compared to using only one of the comparisons for each of the u' and g' channels.

The data were normalized to give a mean zero level in each light curve in two methods: (1) by subtracting the average differential magnitude for each of the two nights and (2) by subtracting a second-degree polynomial fit to the data for the two nights. The former normalization does not remove trends in the nightly variation (that may be due to the star, to the atmospheric conditions or to the instrument), while the latter does. The data were subsequently also cleaned by removing all points lying above or below 5σ. Both the normalization methods led to the same oscillation frequencies in each of the three light curves. We here provide the results only for method 2, which leads to slightly smaller uncertainties on the amplitudes of the oscillations.

The differential light curves [V − (C2+C6) for u' and g', and V − C2 for r'] for the first night are shown in Fig. 2. A beat pattern is readily seen in the g' light curve, pointing towards multiperiodicity as already suspected by Solheim et al. (2004). The final light curves contain 1807 data points for each of the three u', g' and r' filters and have a standard deviation of 16.6, 7.9 and 8.0 mmag, respectively.

3 FREQUENCY ANALYSIS

We performed frequency analysis by computing the Lomb–Scargle periodogram (Scargle 1982) over the frequency range [0, 14] mHz in steps of 0.1 μHz, which is largely sufficient for our data set. Indeed, in the absense of aliasing, the frequency accuracy is determined by the total time-span, the number of observations, the amplitude of the variation and the standard deviation of the noise (e.g. Cuypers

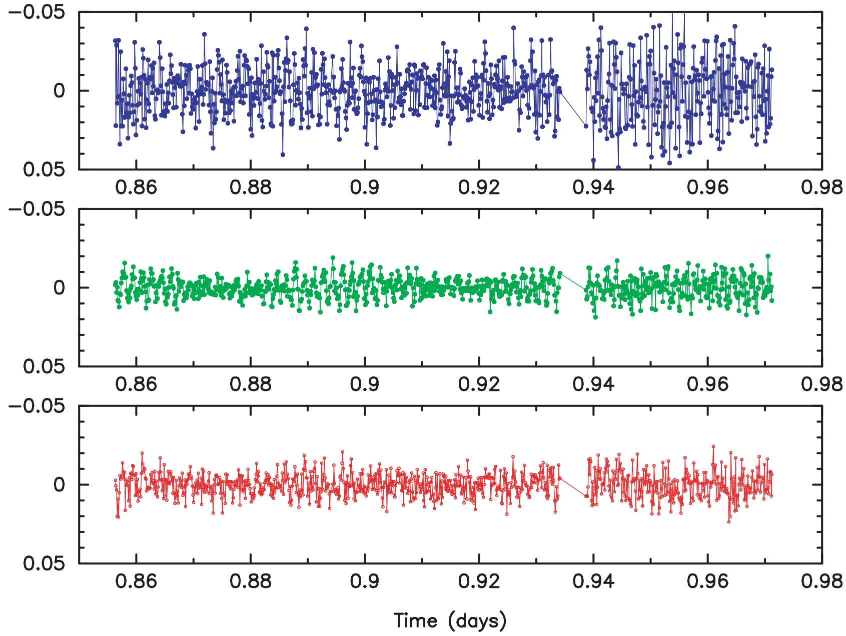

Figure 2. ULTRACAM light curves for SDSS 1717 on 2004 August 24. The differential light curves: V − (C2+C6) for u' (top panel) and g' (middle panel), and V − C2 for r' (bottom panel) are shown. In the online version, the data are coloured blue, green and red from top to bottom panel.

1987; Montgomery & O'Donoghue 1999). The latter is only known after the pre-whitening process but will in any case be lower than the original standard deviation in each of the light curves, while the amplitude of the dominant mode was estimated to be near 5 mmag by Solheim et al. (2004). Our first estimate of the frequency accuracy of the dominant mode obtained from a single night of data is hence 5 μHz. We will compute a more realistic error estimate, taking into account the aliasing for each of the frequencies, further on.

The Lomb–Scargle periodograms for the u', g' and r' light curves of V − (C2+C6) after different stages of pre-whitening are shown in Fig. 3 for the region [4, 10] mHz and point towards one dominant frequency of $f_1 = 6.960$ mHz with amplitudes of 5.8 ± 0.8, 5.0 ± 0.3 and 3.7 ± 0.4 mmag for u', g' and r', respectively. In order to obtain a safe frequency error we first computed the Montgomery & O'Donoghue (1999) formula using only the first night of data, so that aliasing does not interfere. This leads to $\simeq$4 μHz. To this, we added the larger uncertainty stemming from the alias confusion encountered when deriving the frequency from the whole data set. This uncertainty was estimated from the frequencies derived for the g' and r' light curves of the two nights separately (ignoring the results for u' as the noise level in this filter is much higher). This leads to a frequency uncertainty due to aliasing of 18 μHz. We thus finally adopt $f_1 = 6.960 \pm 0.022$ mHz as a conservative error estimate. This result for f_1 is entirely compatible with the one found by Solheim et al. (2004). No phase difference occurs for this frequency among the three colour curves to the level of precision we achieve, which amounts to 11°. This is in line with theoretical expectations.

After pre-whitening with f_1, we find a new second very significant frequency in all three residual light curves (see Fig. 3). The error estimates are obtained in the same way as explained above: $f_2 = 7.267 \pm 0.025$ mHz. This frequency has amplitudes 3.8 ± 0.7, 2.8 ± 0.3 and 2.0 ± 0.3 mmag in u', g' and r', respectively. Again, the residual light curves for this frequency are in phase with each other to the obtained accuracy of 22°. The beat period between these two oscillations amounts to 0.9 h and is covered during each of the two nights, for which the data span about 2.5 h (see also Fig. 4).

The periodograms following the second pre-whitening stage reveal no further significant frequencies (see Fig. 3 for g', we omit the plots for u' and r' for brevity). For comparison, we also show the periodogram of the g' light curve of C2–C6 in the bottom panel of Fig. 3. It is clear that we have reached the noise level for V − (C2+C6) after pre-whitening with f_1 and f_2. This same conclusion is reached in all three colours. The average amplitude of the periodograms over the range [17, 23] mHz was taken as a good estimate for the variance σ, and amounts to 0.70, 0.28 and 0.28 mmag for u', g' and r', respectively. The dashed lines in Fig. 3 indicate the 4σ level. Any frequency peak with a height above that level corresponds to a true intrinsic frequency at a 99.9 per cent confidence level according to Kuschnig et al. (1997).

A segment of the g' light curve, with the fit for f_1 and f_2 superimposed on the data, is shown in Fig. 4. The g' light curve of C2–C6 is also shown for comparison. The standard deviations of the residual light curves of V − (C2+C6) after pre-whitening with f_1 and f_2 amount to 15.9, 6.8 and 7.4 mmag for u', g' and r', respectively.

4 MODE IDENTIFICATION

Aerts et al. (2006) have presented a preliminary analysis of the amplitude ratios of the main mode in an attempt to identify or at least constrain its degree value. They compared qualitatively in their fig. 3, the observed amplitude ratios u'/g' and g'/r' with predictions coming from a representative sdB model computed by Ramachandran et al. (2004), and found an intriguing apparent mismatch between observations and theory. As possible explanations, the authors speculated that non-adiabatic effects – neglected in the approach of Ramachandran et al. (2004) – could play an important role, and/or that unresolved beating could affect the observed amplitude ratios and make them deviate from the theoretical predictions.

We propose here a more quantitative approach based on the method put forward recently by Randall et al. (2005). This method

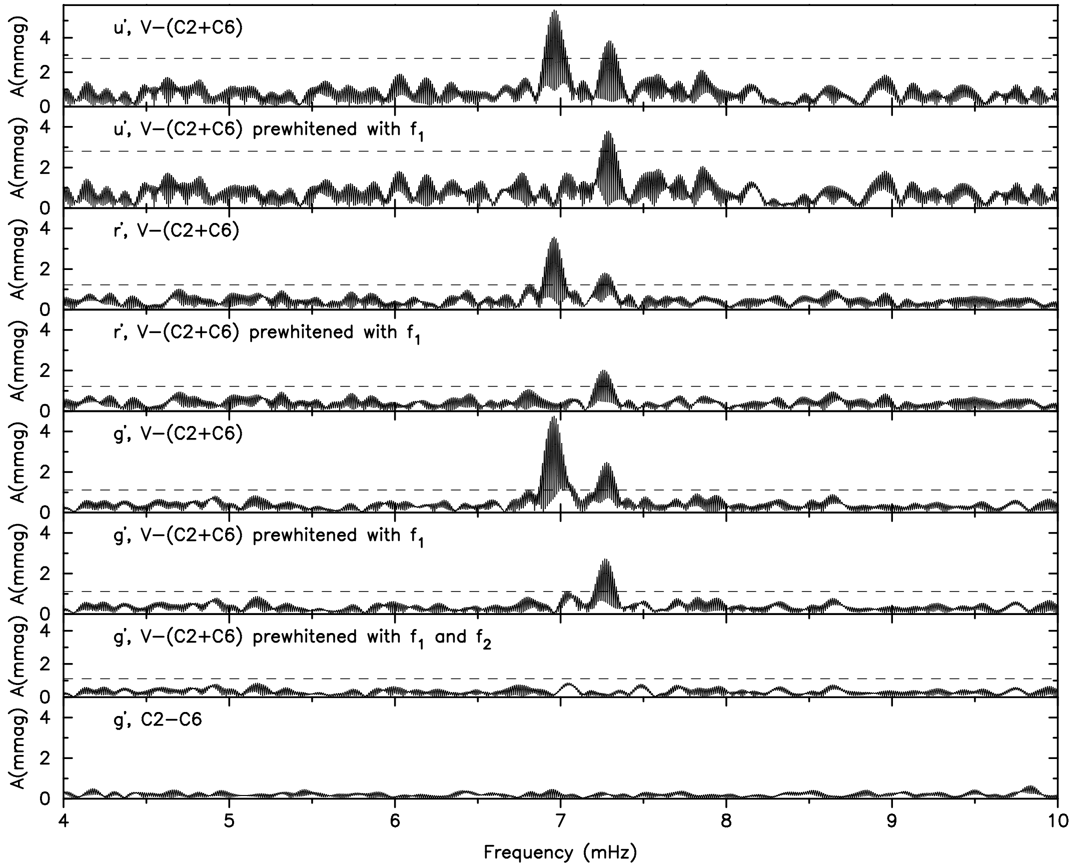

Figure 3. Top seven panels: Lomb–Scargle periodograms for V − (C2+C6) at the indicated stages of pre-whitening for the u', r' and g' filters. The dashed line indicates the 4σ level determined within the interval [17, 23] mHz after pre-whitening with f_1 and f_2. The lower panel shows the Lomb–Scargle periodogram for C2–C6 in g'.

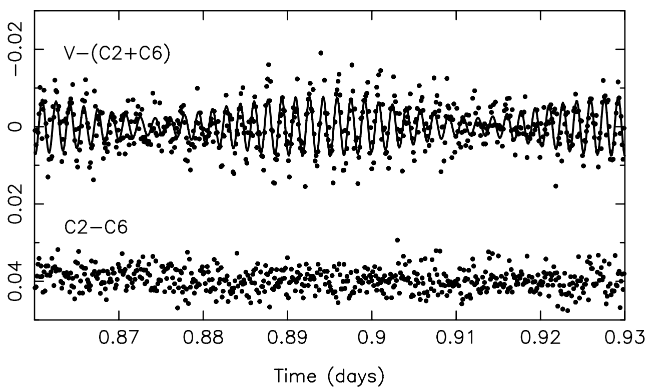

Figure 4. Observed g' light curve of V − (C2+C6) (dots, upper part) and a biperiodic sinusoidal least-squares fit with the frequencies f_1 and f_2 fixed superimposed as a full line. For comparison, the g' light curve of C2–C6 is also shown (dots, lower part).

incorporates a full non-adiabatic description of the atmospheric layers in the computations of theoretical pulsation observables. As in main-sequence stars (e.g. Dupret et al. 2003), such description is found to be quite significant in sdB stars as well. In particular, while the predicted phase shifts between various bandpasses remain quite small – they would be identically zero in the adiabatic approximation – Randall et al. (2005) found that amplitude ratios cannot, in that approximation, be computed with enough accuracy for quantitative studies. Furthermore, they found that the amplitude ratios do depend sensitively on the atmospheric parameters of the target, so for the purpose of our present need, we specifically computed a detailed model atmosphere appropriate for SDSS 1717. For that goal, we adopted the values of the atmospheric parameters given by Solheim et al. (2004) for SDSS 1717, namely, $\log g = 5.70$ and $T_{\rm eff} = 34\,500$ K. Following Randall et al. (2005), we thus calculated the pulsational amplitudes expected from the u', g' and r' photometry for degree indices from $l = 0$ to 5 for a model specific to our target star. Note that, in the Randall et al. approach (see also Ramachandran et al. 2004), the use of a perturbed model atmosphere automatically incorporates the wavelength dependence of the limb darkening, so that approximate parametrized limb darkening coefficients – as used in most other multicolour photometry studies – are not needed. The interested reader will find more details on this approach in that paper.

We next contrasted the predicted multicolour amplitudes with those observed using a χ^2 minimization routine following Fontaine et al. (1996). For every degree index l, the theoretical amplitudes $a_{\rm theo}$ in each of the three bandpasses i are multiplied by a free scaling factor f_l, chosen in such a way as to minimize

$$\chi^2 = \sum_{i=1}^{3} \left(\frac{f_l a^i_{\rm theo} - a^i_{\rm obs}}{\sigma^i} \right)^2, \qquad (1)$$

where $a^i{}_{\rm obs}$ is the amplitude observed in a given waveband and σ^i is the error on the measurement. We thus do not use the standard

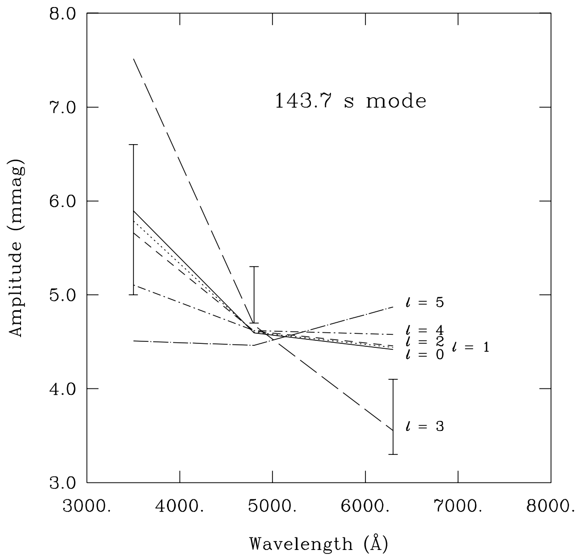

Figure 5. Fits to the u', g' and r' pulsational amplitudes observed for the 6.960-mHz mode of SDSS 1717. The predicted amplitude–wavelength behaviours of modes with $l = 0$–5 have been fitted to the observed values using a least-squares procedure.

normalization of all amplitudes to one particular waveband. Our approach is a more objective way of determining the overall quality of a match per l-value, since the data from all bandpasses are weighted evenly.

The results of this operation for the 6.960-mHz mode are shown in Fig. 5, while those for the 7.267-mHz mode are shown in Fig. 6. It is immediately apparent that none of the fits is particularly good, except perhaps for the $l = 3$ solution for the 7.267-mHz mode. Even in this case, however, the quality of the fit is not necessarily overwhelming because the relatively large uncertainties on the observed amplitudes strongly suggest that mode discrimination can be difficult here.

Following Randall et al. (2005), this can be put on a quantitative basis by explicitly computing the quality-of-fit Q (see Press et al. 1986) for each solution illustrated in Figs 5 and 6. The quantity Q

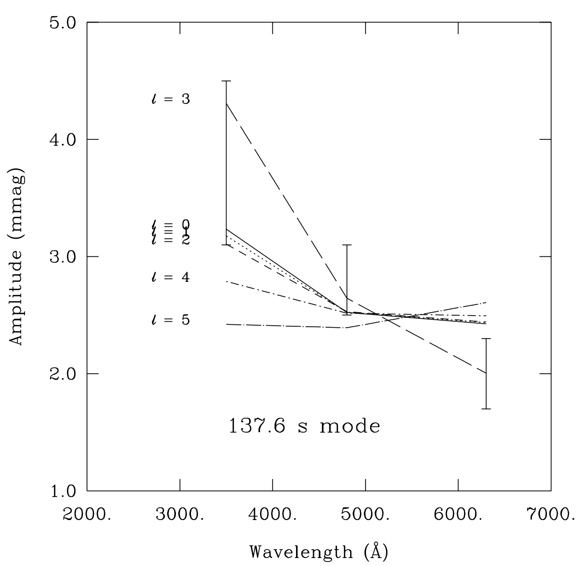

Figure 6. Similar to Fig. 5, but for the 7.267-mHz mode.

depends on the value of χ^2 for each solution and the number of degrees of freedom (three fitted points minus the free parameter f_l gives two degrees of freedom in the present case). Adopting the canonical notion suggested by Press et al. (1986) that a fit is acceptable if its quality-of-fit $Q > 0.001$, we then find that all modes considered here for the 7.267-mHz mode are formally acceptable, while only the solution with $l = 5$ can be excluded for the 6.960 mHz. We thus find that mode discrimination is not possible here on the basis of our present observations of SDSS 1717. The culprits are the large uncertainties on the colour amplitudes.

We note that we carried out another analysis using a similar model but by forcing the adiabatic approximation. Not surprisingly, we found no qualitative differences (if anything the fits are degraded somewhat), and mode discrimination is not possible. This shows that non-adiabatic effects are not at the heart of the situation described by Aerts et al. (2006) for SDSS 1717. Simply put, our quantitative investigation has revealed that our signal-to-noise ratio was unfortunately not large enough for mode identification.

5 CONCLUSIONS

We have presented high-speed multicolour photometry from ULTRACAM at WHT of the faint V 361 Hya star SDSS 1717, which was only recently discovered to be an oscillating sdB star. Besides the known frequency of 6.960 ± 0.022 mHz, we found a second new one of 7.267 ± 0.025 mHz in our data, which show a clear beat pattern. The frequency separation of ≃0.3 mHz suggests that these two frequencies are not due to consecutive overtones of central multiplet peaks belonging to the same low degree l. Indeed, such modes have typically a spacing of ∼1 mHz (Charpinet et al. 2002). The light curves are in phase in the three colours for both frequencies. The theoretically predicted amplitude ratios were computed for the case of SDSS 1717 and compared with the observations. The errors of the amplitude ratios are too large to identify the modes of this star.

Large search campaigns for new V 361 Hya members have been ongoing ever since the discovery of the prototype by several teams and have led to a number of 33 class members at the time of writing (Kilkenny 2002, and references therein, and since then Bonanno et al. 2003; Solheim et al. 2004, among others). At the same time, several multisite campaigns were performed for specific targets (PG 1605+072: Kilkenny et al. 1999; HS 2201+2610: Silvotti et al. 2002; PG 1047+003: Kilkenny et al. 2002; PG 1336 − 018: Kilkenny et al. 2003). All these studies are based on white-light fast photometry and do not allow empirical mode identification.

The stability computations for the V 361 Hya stars (Charpinet et al. 1996, 1997), as for any non-radially oscillating star, are limited to the linear approximation and hence do not predict the amplitudes of the modes. Also, we do not know the mode selection mechanism. From the examples mentioned above, it is in any case clear that a large diversity in the number of excited modes and in frequency patterns occur for different members of the class, despite the fact that the stars are situated in only a very narrow domain of the Hertzsprung–Russell diagram. These shortcomings in our knowledge imply limitations for the seismic tuning of such stars in terms of the uniqueness of the obtained model. The only way to make progress in this respect seems to be to increase the number of case studies with accurate empirical mode identification. Comparison of the quality of the amplitude ratios for the four V 361 Hya stars for which an attempt of mode identification has been made (see Jeffery et al. 2006, for an overview) make it clear that the greatest progress will be achieved by limiting future multicolour campaigns to the brightest members among the V 361 Hya class.

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