The excitation of pulsation modes in rapidly rotating main sequence B-stars

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Abstract. This article summarises the current progress of a project to characterise the internal rotation characteristics of hot, young stars using pulsating members of this group. So far, multi-colour photometry has been collected for 11 stars using the $0.5-\mathrm{m}$ telescope at the Sutherland station of the SAAO on 81 nights during 2013 and 2014. For 6 of these stars, sufficient photometry has been collected to potentially allow the identification of the star's pulsation frequencies and to find the quantum numbers (n, l and m) of the associated pulsation modes. A preliminary frequency analysis was performed on the photometry of one of the stars, HD 81589, which yielded 4 frequencies that are probably due to pulsations of the star. In order to simplify and expedite the reduction and analysis of photometry, a database system was developed along with a set of data reduction and analysis tools that communicate directly with the database. This article reports the results of an initial period analysis of data reduced with these newly developed tools.

1. Introduction

All stars rotate - some quite rapidly, others quite slowly - which causes a breakdown in the spherical symmetry of stars, which (in turn) complicates and reduces the accuracy of stellar models, seeing as most stellar models in use today rely on the assumption of spherical symmetry to simplify the analysis to a manageable level. Stellar rotation also gives rise to various fluid dynamical phenomena, which result in large uncertainties in the rates of stellar evolution and physical stellar parameters in general. Treating rotation consistently in stellar models is unfortunately very difficult and has (until recently) been mostly neglected in studies of the structure and evolution of stars. Good accounts of the scientific problem appear in [1] and in [2].

An intensive observational study of the internal rotation dynamics of stars can therefore provide a wealth of information to support further theoretical work. Asteroseismology is a unique tool for probing stellar interiors - in this context to determine the internal rotation dynamics of stars using the pulsations that are excited deep within the stellar interior. The Beta Cephei class of pulsating stars are ideal for such a study, since they typically exhibit multiple non-spherical pulsation modes and fairly rapid rotation (typically $100-300$ km/s). The rapid rotation makes the frequency spacing between rotationally split pulsation modes sufficiently large to be distinguished in photometry collected over approximately 1 year [3].

Table 1. Stars selected for this study.

Name	RA (J2000.0)	Dec (J2000.0)	Spect. Type	V_{mag}	No. freq[5]
HD 37115	05:35:54	-05:37:42	B7Ve	7.07	2
HD 47416	06:38:51	+07:58:18	B5V	7.80	2
HD 81589	09:24:43	-53:00:43	A3/4	8.90	2
HD 298682	09:49:37	-51:52:21	B0.5 II	9.06	2
HD 303142	10:40:00	-57:32:59	B0 (V)	9.73	2
HD 133823	15:09:55	-65:30:23	B2 IV	9.62	4
CPD -53 6701	15:48:40	-54:14:38	B D	10.37	2
HD 326305	16:52:56	-41:35:08	B0 V	9.97	3
HD 324369	17:48:08	-42:17:12	B1 II	10.00	3
HD 314893	18:01:18	-23:56:43	B3	9.88	3
CPD -31 6271	20:28:20	-31:27:06	B2	10.30	2

Even one strong detection of differential rotation rates would add great value to current theoretical efforts to model internal rotation, as the sample of observationally-detected rotation rates in B stars is very sparse. As there are eleven stars in our sample, we anticipate a strong likelihood of providing very significant results for this purpose. It will be of particular interest to compare pulsationally-determined rotational splitting with the predictions of different theoretical studies, using the spectroscopically-determined photospheric rotation velocities (via spectral line broadening).

Section 2 lists the candidates selected for this study as well as the criteria by which they were selected. Section 3 gives a summary of the observations made to date. Section 4 describes the software systems employed in managing, reducing and analysing the data. Section 5 gives the preliminary results for one of the candidate stars. Section 6 describes the work that needs to be completed during the remainder of this project.

2. Candidates

Over 100 new Beta Cephei pulsating stars have been identified from the All-Sky Automated Survey data - they are listed in [4] and in [5]. Several dozen of these show multiple pulsation modes, which makes them excellent candidates for this study, since the probability of finding two (or more) rotationally split modes is higher for these stars. Since pulsation modes of different order (quantum number n) originate from different depths of the radiative envelope of these stars, finding two rotationally split pulsation modes of different order in one of the candidates enables the determination of the rotation rate at two depths within the star (and similarly for stars with more than two rotationally split modes of different order).

The accessibility through the year of the stars at Sutherland and the apparent magnitude of the stars were also considered. Most of the stars listed by Pigulski & Pojmanski have right ascensions between 7 and 20 hours, making the winter months in Sutherland ideal for observing them.

Eleven stars were selected from the lists of Pigulski & Pojmanski - their details are given in table 1. A magnitude cut-off of $V = 10.5$mag was used, since such bright stars are still easily observed with the $0.5 - \text{m}$ telescope (in terms of centering the star in the photometric aperture and the required integration times in order to obtain a sufficient signal-to-noise ratio) and there are many stars in the lists of Pigulski & Pojmanski that satisfy this criterion.

Table 2. Summary of observations done to date.

Name	No. Obsns	Hours observed	First JD	Last JD	Last-First JD
HD 37115	1243	17.32	2456527	2456621	93.771
HD 47416	202	2.80	2456579	2456621	41.906
HD 81589	2299	47.96	2456407	2456753	346.195
HD 298682	1192	24.14	2456407	2456783	376.101
HD 303142	285	10.40	2456407	2456832	425.020
HD 133823	819	31.23	2456407	2456780	373.004
CPD -53 6701	565	29.49	2456407	2456831	424.053
HD 326305	377	11.38	2456407	2456778	371.186
HD 324369	335	11.09	2456407	2456579	171.662
HD 314893	337	14.81	2456454	2456832	378.003
CPD -31 6271	625	28.43	2456499	2456831	332.158

3. Summary of Observations

The stars listed in section 2 have been observed on 81 nights, resulting in 283 hours of photometry, some of which may be unusable due to environmental conditions (specifically atmospheric transparency variations). A summary of the observations is given in table 2.

Approximately 1000 data points are required in each filter in order to get a sufficient signal-to-noise ratio in the frequency domain and so determine the pulsation frequencies of the star. Furthermore, the time between the first and last observation must be on the order of 1 year in order to get sufficient resolution in the frequency domain. So far there are 3 stars that match these criteria: HD 81589, HD 298682 and HD 133823.

In addition to the photometry collected to date, one spectrum has been recorded for each of HD 81589 and HD 298682 using the Cassegrain spectrograph on the $1.9 - \mathrm{m}$ telescope in Sutherland. Spectra for the remaining stars will be collected during an observing run scheduled on the $1.9 - \mathrm{m}$ telescope during quarter 3 of 2014. All the candidates that are accessible by the Southern African Large Telescope during the current semester have also been added to the queue to be observed with SALT using the Robert Stobie Spectrograph.

4. Database System and Associated Software Tools

Software tools were developed to upload the data to the database from the text-based file format produced by the photometer control software on the $0.5-\mathrm{m}$ telescope, to calculate the geocentric and heliocentric Julian days of the observations, to calculate and apply the dark current and dead time corrections, to perform the sky background subtraction and finally to calculate the corrections to the colour equations (most notably the coefficients of air-mass dependent terms) from the standard star measurements on a particular night and apply them to the data in order to obtain a standardised magnitude for each datum.

Naturally, these new software tools had to be vetted by comparing the results to the results given by established data reduction software or tabulated data. The entire vetting procedure was quite lengthy and meticulous and so falls beyond the scope of this document, figure 1 shows the differences between the results produced by the new software tools developed as part of this project with those of the XReduce software package that is currently used at the SAAO to reduce photometry.

Figure 1 shows a comparison of the new software developed as part of this project with the standard reduction software in use at the SAAO. The fact that all the corresponding points in

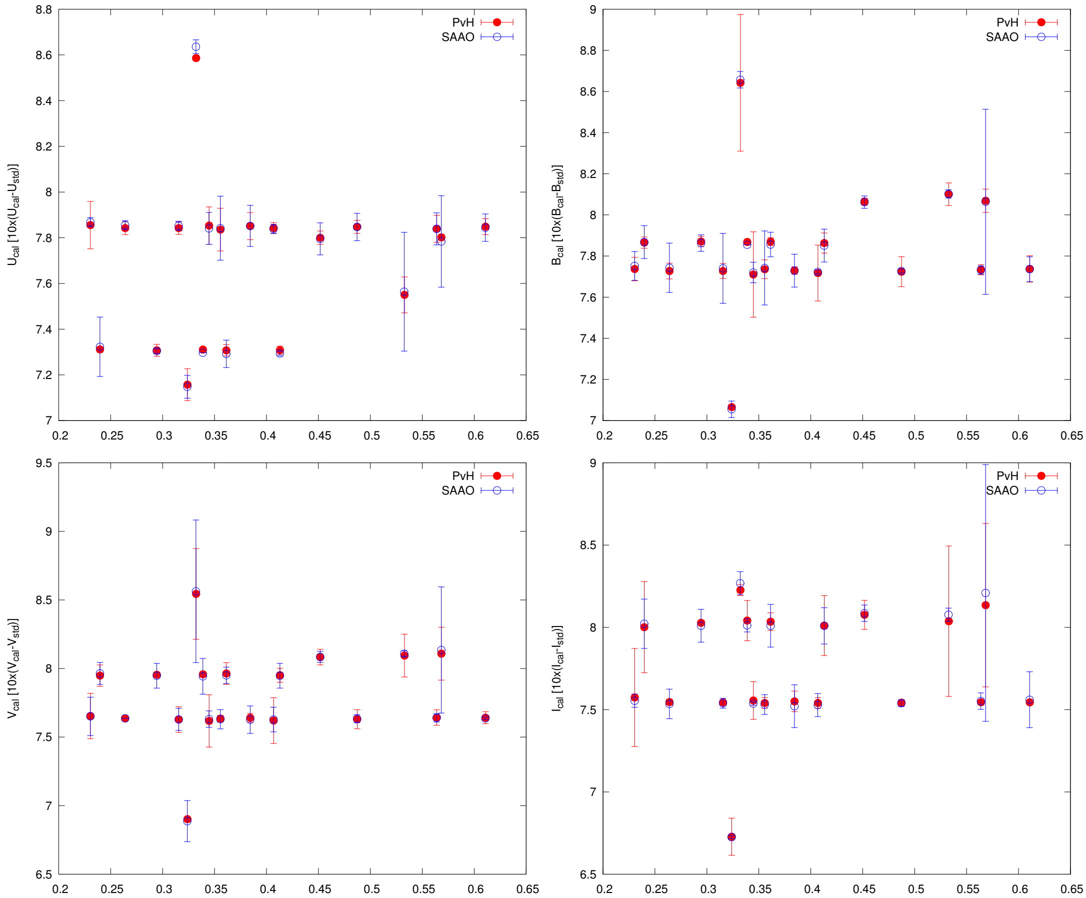

Figure 1. Comparison between the standardised magnitudes produced by the new software developed as part of this project ("PvH") with those produced by the current standard photometry reduction software in use at the SAAO ("SAAO"). All the standard star measurements on two nights (JD 2456408 and JD 245669, two nights of acceptable photometric quality) are combined in these plots. The x-axis shows the fractional HJD (with the integral JDs 2456408 and 2456699, respectively, removed) and the y-axis shows the calibrated magnitudes in the Johnson-Cousins filters used during this study. The error bars show the difference between the standardised magnitudes produced by the two software programmes and the true magnitudes of the standard stars - the difference is typically under 10mmag and so is multiplied by a factor of 10 in these plots for display purposes.

the two sets are virtually coincident indicates that the calibrated (or standardised) magnitudes produced using the new software agree well with those produced using the existing software. The error bars, which indicate an exaggeration of the magnitude difference between the calibrated magnitudes of the observed standard stars and their true magnitudes, further indicate that although there are a small number of cases in both system where this difference is large, neither system is clearly more accurate than the other. Figure 1 therefore indicates that the new reduction system is at least as accurate as the existing one.

5. Preliminary Results

The Johnson U filter photometry of HD 81589 was put through the data reduction system, in the process removing any erroneous data that could be attributed to poor photometric conditions.

Table 3. Frequencies identified in the HD 81589 U filter photometry. Frequency number 1 (marked with an asterisk) is probably a result of atmospheric variations. The specified phases are relative to the epoch JD 2450000.

No.	Frequency (cycles/day)	Amplitude (mag)	Phase (rad)
1*	0.387	0.0377 ± 0.001	2.573 ± 0.026
2	3.060	0.0208 ± 0.001	6.216 ± 0.055
3	8.34	0.0140 ± 0.001	5.461 ± 0.078
4	6.7	0.0147 ± 0.001	4.577 ± 0.076
5	5.15	0.0130 ± 0.001	4.623 ± 0.094
6	14.47	0.0083 ± 0.001	1.025 ± 0.127

In total, 1347 data collected over 19 nights were found to be viable, which were used in a frequency analysis process using the Lomb-Scargle algorithm.

Figure 2 shows the power spectrum produced from the photometry and table 3 lists the frequencies identified from it. Please note that this is simply a preliminary analysis. Note also that the lower frequency variations present in the power spectrum (most notably the peak at 0.387 cycles per day) are probably due to atmospheric transparency variations and do not represent pulsations within the star.

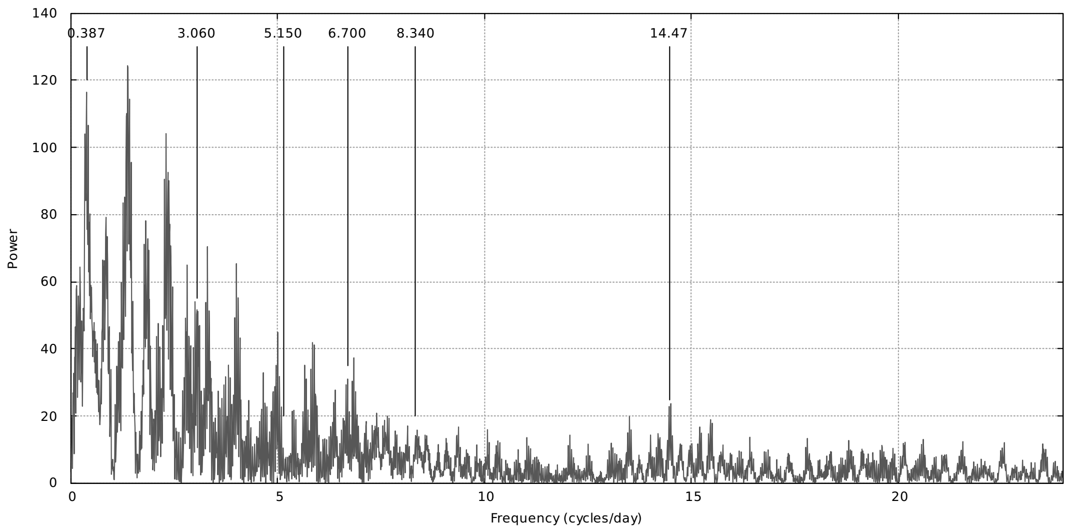

Figure 2. Power spectrum of the Johnson U filter photometry of HD 81589 with the identified frequencies indicated. Once the low-frequency signals are removed from the data, these peaks become prominent in the periodogram.

It is clear from figure 2 that sufficient data have been collected for this star - the focus of the observing campagin may now be shifted to the other candidates while a comprehensive frequency analysis can be done on the HD 81589 photometry in all available photometric filters. This is likely to be the case for HD 298682 and HD 133823 as well.

6. Future Work

The photometric component of the observing campaign for the candidates listed in table 2 is ongoing and is likely to continue until the $0.5-\mathrm{m}$ facility in Sutherland is closed down. At this time the observational burden will be shifted to one of the other manned ("small") telescopes in Sutherland (e.g. the $1.0-\mathrm{m}$) or to the Alan Cousins Telescope, which is expected to be ready for regular automated operation within the next few months. Spectroscopic observations of the candidates will (as mentioned in section 3) be continuing on the $1.9-\mathrm{m}$ telescope using the Cassegrain spectrograph and on SALT using RSS for the remainder of 2014.

The data reduction and analysis efforts are continuing and, as indicated in section 5, are likely to produce several positively identified pulsation frequencies for a number of stars in the near future.

Once the pulsation frequencies of a star are identified, the quantum numbers (n, l, m) corresponding to the pulsation frequencies are found by comparing the frequencies and relative amplitudes in a number of photometric filters to those predicted by stellar pulsation models for a model star similar in spectral type to the target star. This can be achieved by, for example, the FAMIAS software package (see [6]), provided that the effective temperature and metallicity parameters are fairly well-known. Pulsation modes with the same n and l, but different m are degenerate in the absence of rotation, but in the case of a rotating star can be distinguished from one another provided that there is sufficient resolution in the frequency domain. The frequency spacing between modes with the same n and l can then be used to calculate the rotation rate at the level within the star where the pulsations originate.

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