Pulsation mode identification for B stars recently discovered in the Galaxy and the LMC

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Abstract. Following the announcement of potential B star pulsators discovered in OGLE data on the LMC [1], and in ASAS-3 data on Galactic stars [2], various long-term photometric campaigns on a variety of B stars have been conducted by the authors since late 2009. This paper summarises the recent results of these campaigns.

1. The motive for pulsation mode identification

A sustained increase in the breadth and depth of observational data on stellar behaviour has made it clear that current models of stellar structure and evolution need significant refinements (see, for example, recent reviews by Christensen-Dalsgaard and Christensen-Dalsgaard & Houdek [3]). The field of asteroseismology provides valuable tools for achieving this. This is in large part due to the rapid increase in both the quantity and the quality of observational data on pulsating stars, as a result of extensive ground-based surveys such as OGLE and ASAS [4] and dedicated space telescopes (MOST, CoRoT, *Kepler* and BRITE – [5]), as well as the increase in computing power that now allows fully 3-D simulations of stellar interiors to be performed [6]. Since the vibrational properties of any physical medium depend very sensitively on fine details of the interior structure and the physical dimensions of the medium, and measurements in the time domain can be made particularly precisely, a study of the vibrations of stars can provide remarkably detailed knowledge of their structure and interior dynamics. An essential prerequisite for this process to succeed is the determination of the modal identities of the periodic signals detected in stars.

2. The motive for studying B stars

Early B stars are very likely to become progenitors of supernovae that will produce a neutron star as the core remnant. A precise understanding of early B stars is essential for a precise understanding of the formation and character of the lower-mass population of core-collapse supernovae. The degree of uncertainty in our present descriptions of stellar structure and evolution is illustrated in a recent paper [7], where the mass value of a classical Cepheid variable, determined from traditional evolutionary models, was shown to be approximately 20% in error. Equally dramatic improvements in our understanding of the detailed structure and evolutionary timescales of B stars are possible. Such improvements will have a significant impact on our understanding of the formation of supernovae, and also on our understanding of the formation and character of pulsars. Supernovae play an important role in the study of a wide variety of astrophysical and cosmological problems, while pulsars are set to play a key role in the science programmes of MeerKAT and the SKA. Furthermore, main-sequence B stars form part of the continuum of stellar classes on the sequence, from red dwarfs through to super-massive stars, and are important to understand in their own right.

3. Our projects

Early B stars show dominant pulsations with periods in the range 3 – 8 hours. Many of the pulsation modes have relatively low amplitudes, requiring extensive observation to raise the signal-to-noise ratio to sufficient levels. Early B stars that display such pulsations are classified as Beta Cephei stars (after the prototype). Two of the most important questions about early B stars that invite an asteroseismological answer are concerned with the *instability strip* associated with Beta Cephei-type pulsations: One of the key parameters that determines the width and length of the B-star instability strip is the *metallicity* of the pulsating star. The search for a match between metallicity and pulsation has been the main constituent of the authors' observational research programme over the past few years.

We report here on the results of two projects aimed at exploring an observational correlation between metallicity and pulsation: Both projects involve detailed, long-term observational studies, necessary to determine frequencies, amplitudes and phases of multiple pulsation modes in each star with sufficient precision to make a clear identification of mode type.

One project focuses on open clusters in the Galaxy, the other on the Large Magellanic Cloud (LMC). We have obtained 6 weeks of UBVI photometry on pulsating stars in the open cluster NGC6200, spanning a total observing period of 11 months. We have also obtained 4 weeks of UBVI photometry on three distinct 5 arcmin x 5 arcmin fields in the LMC. Theoretical pulsation models of B stars predict that the respective amplitudes of any particular pulsation mode, as detected through various filters, depend quite strongly on the median wavelength of the filters. The amplitudes further depend quite sensitively on fundamental stellar parameters such as metallicity, mass and age, as well as on preconceived values of stellar opacity and stellar composition spectra. Consequently, a precise determination of pulsation amplitudes in each of the U, B V and I filters may be compared with theoretically predicted values for various combinations of the aforementioned parameters.

4. Results

A well-sampled light curve (obtained through the V filter) of one of the pulsating B stars in NGC 6200 appears in Figure 1. The "stillstand" phase on the ascending leg of the light curve is a rare feature and is reminiscent of the high-amplitude Beta Cephei pulsator, BW Vul.

The V-filter Lomb-Scargle periodogram for the same star is depicted in Figure 2. The aliasing envelopes corresponding toanumber of Beta-Cephei-type pulsaions can be clearly seen.

Finally, the relative amplitudes of the strongest pulsation found in this star, as detected through the U, B, V and I filters respectively, are shown superimposed on a grid of plots of predicted amplitude ratios for various evolutionary stages of a 15 solar-mass star in Figure 3. The coloured, "ribbon-like" features correspond to different degrees of pulsation mode. The observed amplitudes (indicated by black dots with vertical error bars) correspond very well to predictions for the radial mode.

A similar treatment of the second strongest pulsation in this star implies that it is a quadrupole mode.

A somewhat sterner observational challenge was posed by the B stars in the LMC, with average V magnitudes around 16.5, as opposed to magnitudes of 9.5 for the stars in NGC6200. Nonetheless, the results obtained from the analysis of only 2.5 weeks of data is very encouraging. Periodograms of 2.5 weeks of V data for one of the fainter targets in the LMC are shown in Figures 4 and 5. The highest peaks seen in these two periodograms correspond to the strongest two Beta Cephei-type pulsations. The four-sigma (in the classical statistical sense) detection thresholds are shown. Once analysis of the full dataset is completed, we expect at least a third (and perhaps a fourth) distinct pulsation to be detected above this threshold.

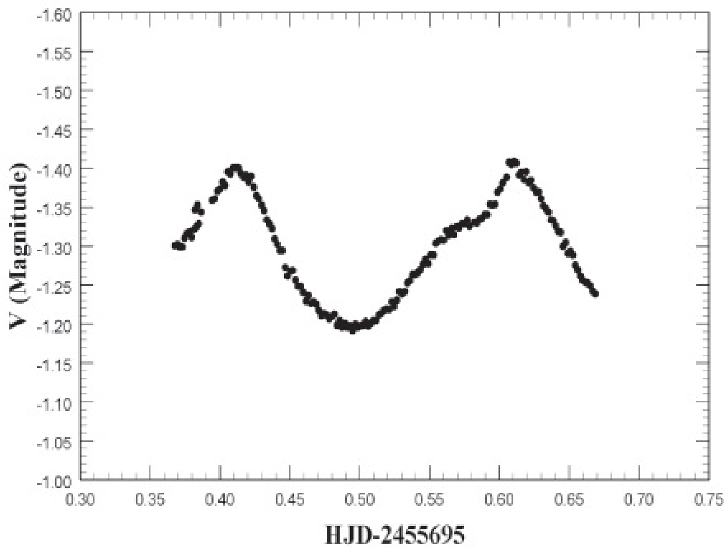

Figure 1. V light curve of pulsating B star in NGC 6200

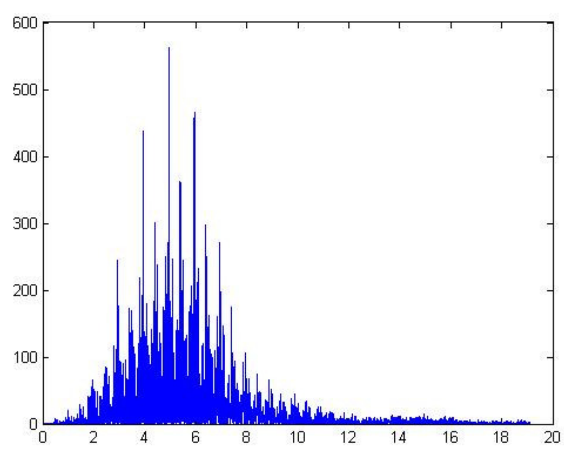

Figure 2. Periodogram of V data obtained for the same pulsating B star in NGC 6200.

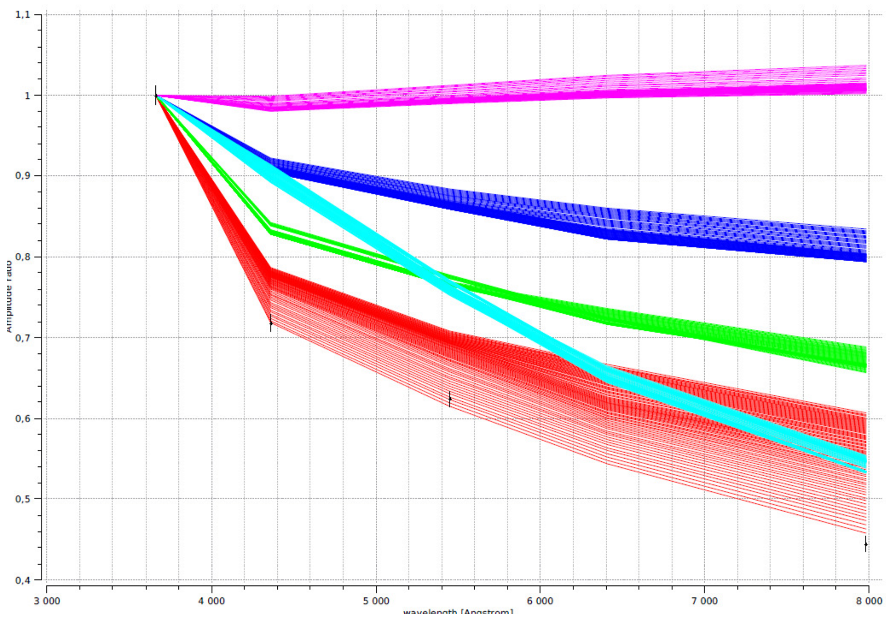

Figure 3. Observed pulsation amplitude ratios for the same pulsating B star in NGC6200, superimposed on theoretical models computed for a 15 solar-mass star. The observed amplitudes in UBVI are indicated by black dots with vertical error bars)

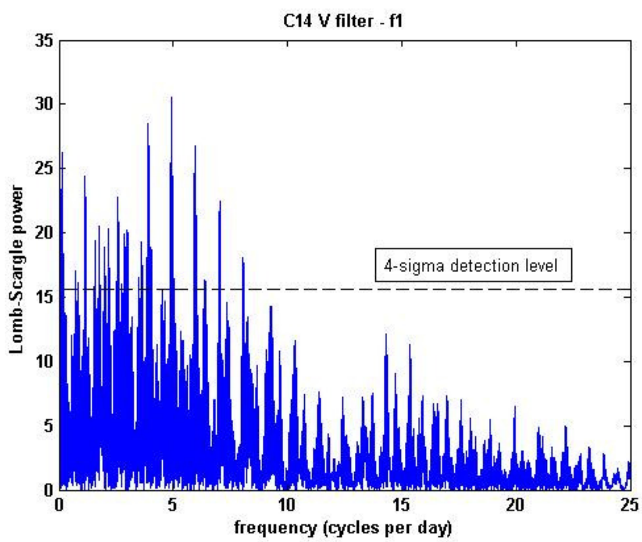

Figure 4. Lomb-Scargle periodogram for target C14 in the LMC, after subtraction of a least-squares fit of a 3-day period (related to the sampling of the observations) from 2.5 weeks of data. The primary pulsation mode in this star is represented by the tallest peak in the periodogram.

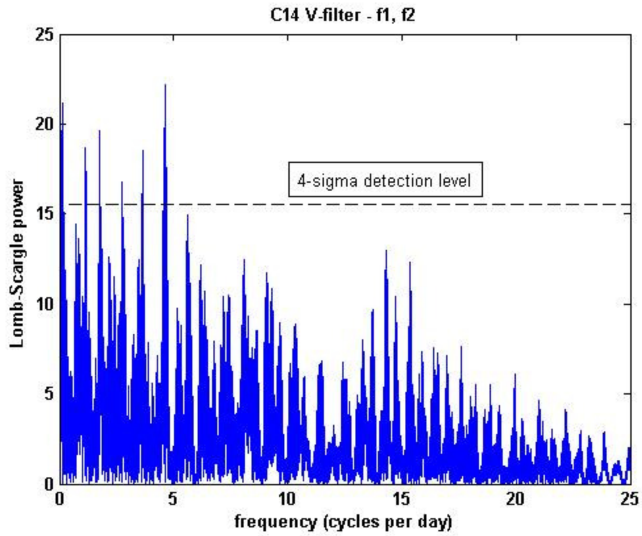

Figure 5. Lomb-Scargle periodogram for target C14 in the LMC, after subtraction of a combined least-squares fit of the 3-day period and the primary pulsation period from 2.5 weeks of data. The secondary pulsation mode in this star is represented by the tallest peak in the periodogram.

5. Conclusions

We have shown that a 6-week multi-colour observing programme on a 1.0-m class telescope allows us to glean relative (in UBVI) pulsation amplitudes from pulsating B stars in open clusters with sufficient precision to perform photometric mode identification. We have also confirmed earlier findings that multiple pulsation periods can successfully be gleaned from 4-week observing campaigns on pulsating B stars in the LMC.

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