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

CA Engelbrecht[1] , C Ulusoy[1] , T Gülmez[1] & FAM Frescura[2]

[1]Department of Physics, University of Johannesburg, PO Box 524, Auckland Park 2006, Johannesburg. [2]School of Physics, University of the Witwatersrand, Private Bag 3, WITS 2050, Johannesburg.

E-mail: chrise@uj.ac.za

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: i) What are the precise boundaries of the *instability strip* (in the HR diagram) associated with Beta Cephei-type pulsations; ii) How low can the *iron-group metal content* in a main-sequence early B star go before pulsations become quenched? Since it is the iron-group elements that enable the kappa-mechanism to drive pulsations in early B stars, the width and length of the B-star instability strip is heavily dependent on *metallicity*. However, the detailed nature of this dependence is not clear. Following the announcement of potential pulsations in B stars discovered in OGLE data on the LMC [1], and in ASAS-3 data on Galactic stars [2], the reliability of current theoretical models of B stars in correctly quantifying the connection between metallicity and pulsational behavior in early B stars has come under question. This has prompted us to embark on a long-term observational project to bring quantitative evidence of the connection between metallicity and pulsation to the fore.

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 between July 2010 and May 2011. These data were obtained with the UCTCCD operating on the 0.75-m telescope of the South African Astronomical Observatory (SAAO) at Sutherland, as well as with the STE4 CCD operating on the 1.0-m telescope at the same site. We have also obtained 4 weeks of UBVI photometry on three distinct 5 arcmin x 5 arcmin fields in the LMC, over a period spanning from December 2010 to March 2012. All of these data were obtained with the STE4 CCD camera operating on the 1.0-m telescope at Sutherland. 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 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. One full pulsation period covers the range between the two maxima in the curve. 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 stillstand is a phenomenological feature that is seen in light curves as well radial velocity curves of a few Beta Cephei stars. In figure 1, it appears between the values 0.55 and 0.60 of the fractional day. The theoretical explanation for the stillstand in BW Vul is based on the motions of opacity-driven shocks through the stellar envelope. A key finding is that the model only works for exceptionally high values of metallicity [9]. It will be interesting to determine whether the same holds for the star we have discovered in NGC6200.

The Lomb-Scargle periodogram for the same star's V data is depicted in figure 2. The aliasing envelopes corresponding to a number of Beta-Cephei-type pulsations 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. Each of the coloured, "ribbon-like" features corresponds to a specific spherical harmonic degree of the pulsation mode (ℓ = 0, 1, 2 and 4 resepctively). Each evolutionary stage considered produces a single 'line' of each colour; the spread of evolutionary age considered results in the 'broadening' of the various lines into coloured 'bands'. The observed amplitudes (indicated by black dots with vertical error bars) correspond very well to predictions for the radial mode (the red band).

A similar treatment of the second strongest pulsation in this star implies that it is a quadrupole (ℓ = 2) 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. Preliminary results obtained from the analysis of only 2.5 weeks of data are very encouraging. Lomb-Scargle 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 in this star. The four-sigma (in the classical statistical sense) detection thresholds are shown. This is a common detection threshold applied in confirming the presence of pulsation in a star (although it is sometimes incorrectly applied in the literature). 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.

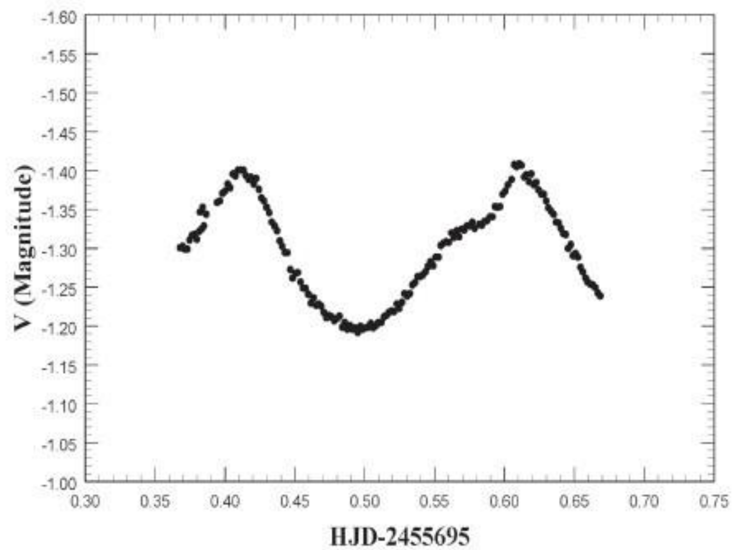

Figure 1. Light curve of the pulsating B star in NGC 6200 in the Johnson V filter. The abscissa records time in fractions of a day, while the ordinate records the V magnitude relative to an arbitrary zero-point.

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 that multiple pulsation periods can successfully be gleaned from 4-week observing campaigns on pulsating B stars in the LMC. We anticipate that longer observing campaigns on stars in the LMC will also allow photometric pulsation mode identification. Spectroscopy obtained with the Southern African Large telescope (SALT) will be used to explore the correlation (if any) of metal content in the detected pulsating B stars with their pulsation characteristics.

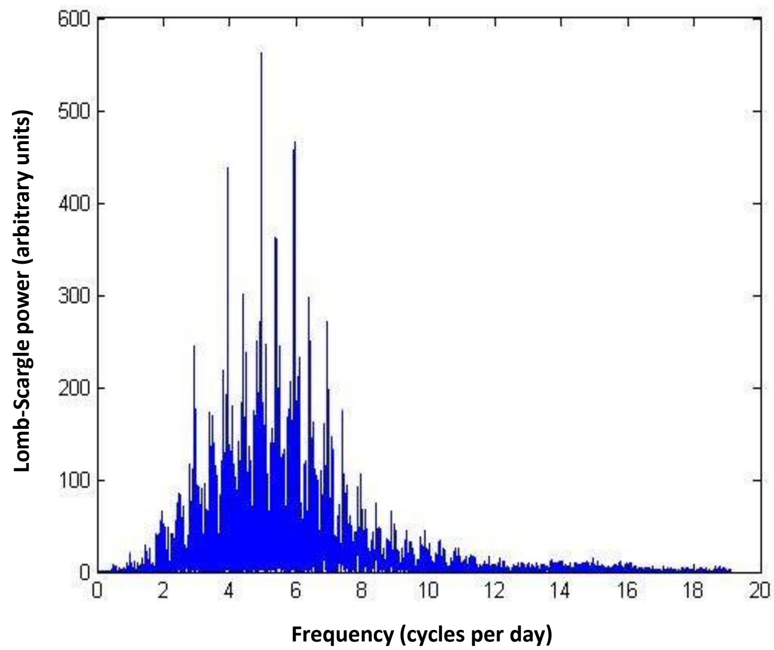

Figure 2. Periodogram of V data obtained for the pulsating B star in NGC 6200 reported here.

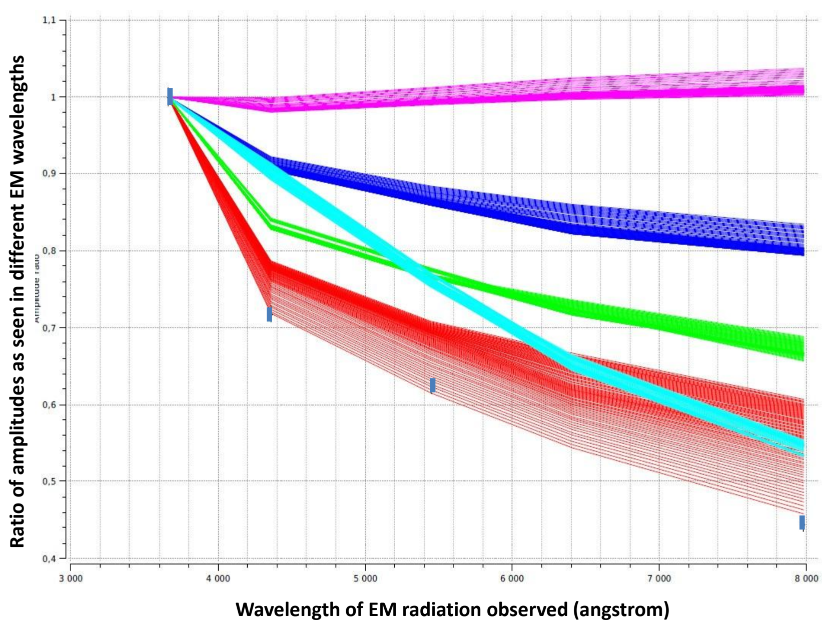

Figure 3. Observed pulsation amplitude ratios (small vertical bars) for the same pulsating B star in NGC6200, superimposed on ratios for various theoretical models computed for a 15 solar-mass star.

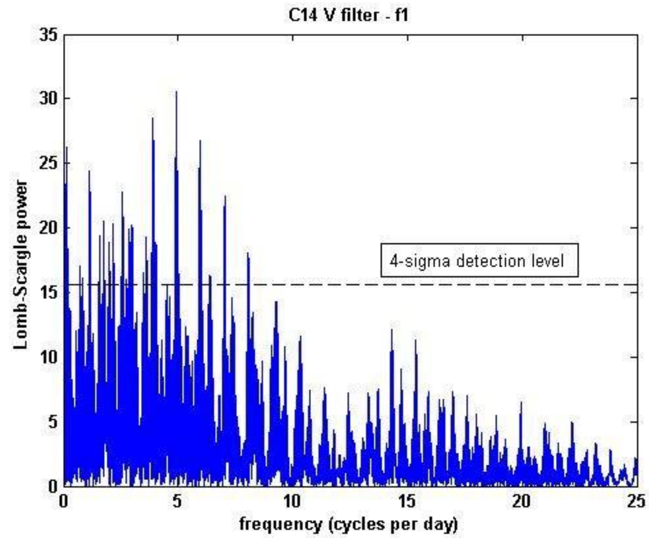

Figure 4. Lomb-Scargle periodogram for target C14 in the LMC, after subtraction of a least-squares fit of a 3-day period (related to the sampling of the observations) - from 2.5 weeks of data. The primary pulsation mode in this star is represented by the tallest peak in the periodogram.

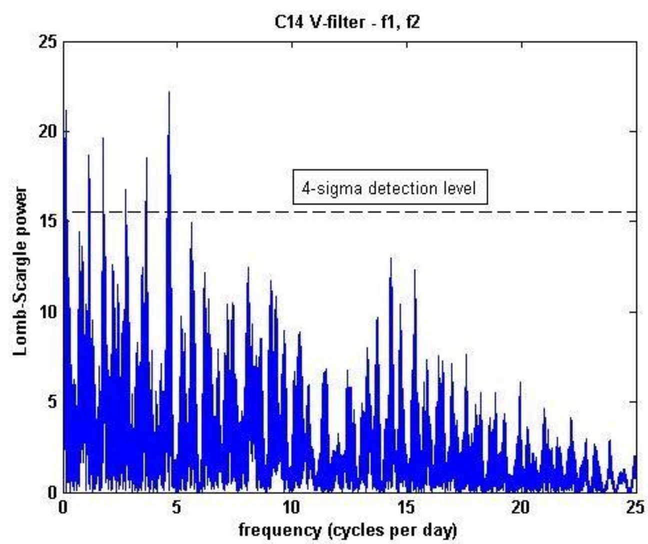

Figure 5. Lomb-Scargle periodogram for target C14 in the LMC, after subtraction of a combined least-squares fit of the 3-day period and the primary pulsation period from 2.5 weeks of data. T he secondary pulsation mode in this star is represented by the tallest peak in the periodogram.

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