Pulsating B stars in the LMC

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Abstract. The first discovery of Beta Cephei (BCep) pulsators in the LMC was announced nine years ago. This was a remarkable discovery, since theoretical analyses of pulsational stability had previously predicted that early B main-sequence stars with metallicities lower than Z = 0.01 should not pulsate at all. Following this announcement, and subsequent announcements of the discovery of 92 BCep candidates in the LMC, more detailed studies adopting a variety of opacity calculations and metal mixtures indicated that BCep pulsations could be explained in low-metallicity environments after all. In order to ascertain the nature of these pulsations, multi-colour photometry of sufficient precision is required. We have obtained 4 weeks of UBVI photometry on two fields in the LMC that surround stars which have been identified as strong Beta Cephei candidates from OGLE data. We report on pulsations detected in two stars taken from these fields.

1. Pulsating 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 by Pietrzynski et al. [1], 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.

Asteroseismology is currently the most powerful tool available to solve many outstanding questions in stellar structure and evolution [2], since the oscillation frequencies of a star depend very sensitively on the details of its structure and on its size. 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: i) Why have only a few O-type stars been identified as Beta Cephei-type pulsators? ii) What are the exact locations of the edges of the instability strip? The project being reported on is concerned with the latter of these two questions.

2. Metallicity and pulsation

Almost a full century after the original discovery of Beta Cephei-type variability, the driving mechanism for the pulsations was finally tracked down to the presence of a sharp, localised increase in opacity in the temperature zone where the iron-group elements are appropriately ionised. Naturally then, the extent of pulsation mode driving that can occur in an early B star will depend on its metal content. Until fairly recently, theoretical analyses of pulsational stability for early B stars had predicted that BCep pulsations would not occur in stars with metallicities lower than $Z = 0.01$ [3].

Pigulski and Kolaczkowski [4] announced the first discovery of Beta Cephei (BCep) pulsators in the LMC in 2002. A few years later, Kolaczkowski and Pigulski identified 92 BCep candidates in the LMC [5]. These discoveries were unexpected, since the average metallicity of stars in the LMC is well established at a value of $[Fe/H] = -0.03$ (with little dispersion around this value [6]), which corresponds to $Z = 0.008$ [7], lower than the metallicity threshold quoted above. Following the discovery of BCep stars in the LMC, more detailed studies adopting a variety of opacity calculations and metal mixtures indicated that BCep pulsations could be explained in low-metallicity stars after all [8].

3. The observing project

Precise studies of the pulsation properties of the newly-discovered BCep stars in the LMC are required to put the new modifications in the stellar models to the test. Multi-colour photometry across the optical spectrum is the most widely-used technique for identifying the non-radial degree ℓ of the pulsations (an important parameter that needs to be determined). Furthermore, the largest possible number of observations should be obtained, to raise the signal-to-noise ratio of the data high enough that a useful number of pulsation modes can be detected.

We have embarked on a multi-year project to meet these demands for a selection of the BCep candidates that have been announced. The first season of observations was conducted on the 1.0-m telescope at the Sutherland site of the South African Astronomical Observatory (SAAO). The first two target fields for the project contain two of the only three BCep stars that have been identified in the literature to date [4]. We conducted UBVRI photometry on these two fields for two fortnights, using the STE4 camera, and covering a total time base of 48.2 days. This allows for a frequency resolution of 0.03 cycles per day in the detection of periodic signals, using the criterion of Loumos and Deeming [9].

Typical examples of the two fields as they were captured through the B filter on the STE4 camera are displayed in Figure 1:

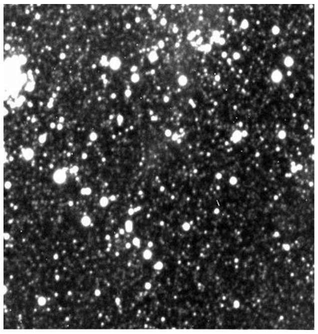

Figure 1(a). The field "LMC1".

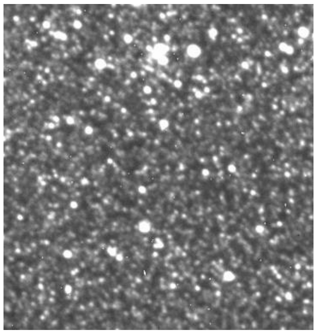

Figure 1 (b). The field "LMC2".

4. Results

Approximately 200 measurements in each of U.B,V,R and I were obtained on each of the two selected fields. The frames depicted in Figure 1 clearly show that there are dozens of stars in each field that can be explored for pulsation signatures. As a first step to ascertaining the quality of the output from this 4-week observing allocation, we compared our results to those obtained by Pigulski and Kolaczkowski [4] for the two stars that they identified in these fields: OGLE 051841.98−691051.9 (alias LMC1) and OGLE 052809.21−694432.1 (alias LMC2).

Table 1 displays frequencies and amplitudes found by Pigulski and Kolaczkowski (abbreviated as PK[4]) in the I filter and in our work in the B filter respectively:

Table 1. Comparison of frequency analysis for [4] and for this work.

Star		PK [4] (I) frequencies (c/d)	amplitudes (mmag)	Our work: (B) frequenccies (c/d)	amplitudes (mmag)
LMC1	f1	**5.179046**	5.1	**-**	
	f2	**3.495009**	3.9	**2.52 (alias?)**	14.9
	f3	**2.005502**	4.5	**2.01**	42.1
	f4	**1.684015**	3.1	**1.71**	20.0
	f5	**3.816132**	2.3	**3.76**	27.9
	f6	**-**		**5.41**	22.7
LMC2	f1	**3.497909**	12.4	**3.50**	17.3
	f2	**3.685343**	4.0	**-**	

For LMC1, we confirm all of the frequencies quoted in [4] (except for f1) if 2.52 c/d is regarded as a 1-day alias of 3.50 c/d (note that the resolution of our dataset is 0.03 c/d). Instead of f1 we find f6, differing from f1 by 0.2 c/d. It is interesting to note the amplitude ratios $A_{\mathrm{I}} : A_{\mathrm{B}}$ for the correlated modes, albeit from different observing programs, as displayed in Table 2:

Table 2. Amplitude ratios $A_{\mathrm{I}} : A_{\mathrm{B}}$ observed in LMC1, computed from our data (B) and the data reported in [4] (I).

Mode	$A_{\mathrm{I}} : A_{\mathrm{B}}$
f2	0.26
f3	0.11
f4	0.16
f5	0.08

As expected for an early B star, the amplitudes in I are considerably smaller than the amplitudes in B. However, the amplitudes in I are far *weaker* relative to the amplitudes in B than any current models predict. We are comparing amplitudes obtained from vastly different observing programs, which is far from ideal. A proper comparison of pulsation amplitudes across the optical spectrum can only be done once our data have been processed in all five colours.

From the perspective of stellar structure considerations, the relatively low values of the BCep frequencies detected make sense, since the BCep instability strip shrinks out to higher-mass stars as metallicity decreases (for example, see [8]) and we expect BCep pulsations to be excited only in high-mass (i.e earlier than B2-B3) stars in the LMC's low-metallicity environment. Pulsations in higher-mass stars will indeed have longer periods. This expectation is borne out for LMC1 by the colour-magnitude plot displayed in Figure 2 (taken from reference [4]). LMC1 is the star represented by the filled circle right at the top of the diagram. The calibrating scale (for luminosity class V stars) presented in the diagram suggests that LMC1 might even be a late O star.

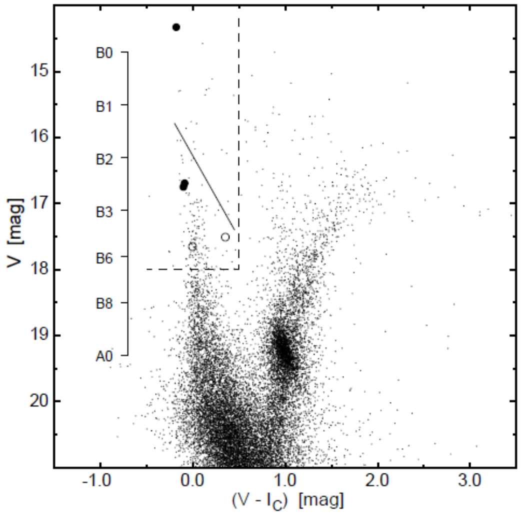

Figure 2. Colour-magnitude plot of stars in the LMC. From Pigulski & Kolaczkowski [4]

LMC2 appears to have a much more limited pulsation spectrum than LMC1. This suggests that LMC2 is perhaps right on the edge of the low-metallicity instability strip. It is represented by the lower of the two overlapping filled circles shown in Figure 2, corresponding to a B2.5 dwarf on the calibrating scale. Therefore, if it is tracing an edge of the instability strip, it has to be the *lower* edge. Interestingly, the $A_{\mathrm{I}} : A_{\mathrm{B}}$ ratio for the single mode we detected in LMC2 is 0.72, in line with theoretical predictions for a low-ℓ mode. The discrepancy between the amplitude ratios seen in LMC1 and LMC2 respectively warrants further investigation on our part.

5. Conclusions

We have shown that a 4-week multi-colour observing programme on a 1.0-m class telescope allows us to accurately glean multiple periods out of a BCep star in the LMC. We observed two fields in this first stage of the project; the signal-to-noise ratio could be improved by a factor of more than 50% by limiting a 4-week programme to one field only.

We have identified a number of multi-periodic variable stars in these two fields, besides the test cases of LMC1 and LMC2. It is envisaged that a programme covering 5 fields in total will deliver precise data on twenty-odd BCep stars – a sufficiently large sample to make significant impacts on the modelling of B stars of low metallicity.

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