New β Cephei variable in the Southern open cluster NGC 6200: ALS 3728

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Abstract

We report the evidence of a new β Cephei type variable located in the Southern open cluster NGC 6200: ALS 3728. Spectroscopic and photometric observations of NGC 6200 stars were carried out at the South African Astronomical Observatory (SAAO) in 2011. It was found that ALS 3728 has a frequency of about 4.95 d\textsuperscript{-1} with highest amplitude. The star also shows a remarkable stillstand phase just before its light maxima which is a typical characteristic occurring among these type of stars. Furthermore, a mode identification is applied for the dominant frequency that is calculated from the Fourier analysis.

Keywords: (stars: variables:) stars: oscillations (including pulsations) – stars: individual (ALS 3728)

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1. Introduction

$\beta$Cephei variables are a well known group of Population I early B-type pulsators. Their pulsations were characterized by mono and multiperiodic variations with periods between 2 and 8 hours (Stankov & Handler, 2005). They are massive (8-18 $M_\odot$) near main sequence stars (Stankov & Handler, 2005) and pulsate both in $p$ (acoustic-pressure) and $g$ (gravity) modes caused by $\kappa$ mechanism through the elements of iron group (Cox et al., 1992; Dziembowski & Pamvatnykh, 1993; Dziembowski, Moskalik, & Pamvatnykh, 1993).

Recently, a number of short period variables were reported in the large scale surveys by Pojmanski (2002, 2003); Narwid et al. (2006); Pigulski (2005); Kolaczkowski et al. (2004). In particular, during the third stage of All Sky Automated Survey (ASAS-3), a catalog of over 38000 stars was published by Pigulski (2005) and new $\beta$ Cephei stars were defined as members of the Southern young open clusters. According to the survey, NGC 6200 is one of these clusters where new $\beta$ Cephei stars and candidate ones were discovered. The location of the cluster member $\beta$ Cephei pulsators on the Hertzsprung-Russell Diagram (HRD) can be used to obtain crucial information on their evolutionary stage and provides the determination of stellar mass, reddening and distance modulus by means of isochrone fitting method. The Southern open cluster NGC 6200 (age 8.5 Myr, (Kharchenko et al., 2005)) is a good candidate for such studies. Recently, $\beta$ Cephei type pulsations of ALS 3721, which is first observed by ASAS-3 survey (Pigulski, 2005), has been confirmed by Ulusoy et al. (2013).

For this study, we have selected ALS 3728 (GSC 08330-02266=NGC 6200
#3) which shows a very strong candidacy as a $\beta$ Cephei pulsator (Pigulski, private communication), to probe into oscillation properties in both photometric and spectroscopic view. The star observed by ASAS-3 survey, however, there is no other publication available in the literature to prove its $\beta$ Cephei type behaviour in detail. ALS 3728 is also one of the members of the Southern open cluster NGC 6200 and it is positioned at the Southern constellation Ara situated between Scorpius and Triangulum Australe. The first photoelectric and spectroscopic observations of the 15 stars in NGC 6200 were reported by Fitzgerald, Jackson, & Moffat (1977). They determined the colour excess and the distance modulus as: $E(B-V) = 0^m.63 \pm 0^m.07$, $11^m.9 \pm 0^m.2$ for the cluster respectively.

2. Spectroscopy

The spectroscopy of ALS 3728 was performed on 18 June 2011 with the Robert Stobbie Spectrograph (RSS) at the 11-m Southern African Large Telescope (SALT), Sutherland, South Africa. The RSS instrument reached $R \sim 3000$ spectral resolution for the spectra of ALS 3728. During the observing run, six spectra were acquired with exposure times set to 100 s and reached signal-to-noise ratio from 60 to 80, in the spectral range from 3925 to 5990 Å. Reduction and calibration of the data was made by the standard IRAF procedures including the \textsc{onedspec} and the \textsc{twodspec} packages, and \textsc{continuum} package for normalization.

In order to estimate atmospheric parameters of the star we compared the low-resolution averaged SALT spectrum with theoretical spectra calculated by Thierry Morel (Morel et al. 2006). The synthetic spectra were computed
with a hybrid non-LTE approach. Hydrostatic, plane-parallel, line-blanketed LTE atmosphere models were calculated with the ATLAS9 code (Kurucz, 1993), while a constant microturbulent velocity, $\xi_{\text{mod}} = 8 \text{ km s}^{-1}$ was adopted. The NLTE population numbers and synthetic spectra were computed using an updated version of DETAIL (Giddings, 1981; Butler, 1984) and SURFACE (Butler & Giddings, 1985) line-formation codes. DETAIL solves the radiative transfer and statistical equilibrium equations, while SURFACE calculates the emergent spectrum. The grid of synthetic spectra was calculated for effective temperatures between 15000 and 30000 K with a step equal to 1000 K and surface gravities ranging from 3.0 to 4.5 dex with a step equal to 0.1 dex. The analysis was based on the spectra computed with solar chemical composition and with microturbulence velocity equal to $8 \text{ km s}^{-1}$.

The determination of surface gravity log $g$ and effective temperature $T_{\text{eff}}$ was based on one Balmer line ($\text{H}\beta$), He I lines (4471, 4921 and 5876 Å), one He II line (4686 Å) and silicon lines Si III (4552, 4568, 4575 Å). Although the quality of the spectrum and signal-to-noise ratio were low the calculations were good enough to estimate the parameters. The best fit of the model fluxes to the observed lines was obtained as a result of minimizing residual standard deviation of the fit. The analysis resulted in $T_{\text{eff}} = 25000 \pm 2000 \text{ K}$ and log $g = 3.5 \pm 0.2$. Additionally, the projected rotational velocity $v \sin i$, was derived to be equal to $100 \pm 20 \text{ km s}^{-1}$. The results of the spectroscopic analysis are plotted in Fig. 1.
Figure 1: Observed (black) and synthetic (red-fitted) spectra of ALS 3728 for selected region. The observed lines fitted to model fluxes with $T_{\text{eff}} = 25000 \pm 2000$ K and $\log g = 3.5 \pm 0.2$.

3. Photometry

CCD photometry of ALS 3728 was obtained by using the 100-cm Elizabeth Cassegrain telescope at SAAO between the Julian dates 2455673.442-2455755.483. During the observations, a total of 311, 330, and 344 data points in the Johnson $B$, $V$ and $I$ filters were collected, respectively. CCD data reduction was performed following standard IRAF routines including the subtraktion of bias and dark frames and flat-field correction for each image. In order to derive instrumental magnitudes of ALS 3728 in the CCD field, aperture photometry technique was used by the DAOPHOT II package [Stetson, 1987]. As a comparison star,GSC 08330-02221 were used. The photometric light curves in the $BVI$ filters is shown in Fig. 2. The peak-to-peak amplitude of light variation of the star bf is equal to $0'''.16$ in the B.
In order to search for the variability period of the star, we used PERIOD04 (Lenz & Breger, 2005) software package. The package fits the observational data by using the least-square method and is based on classical Fourier analysis. The signal-to-noise ratio threshold was adopted to 4 (Breger, 2000). We proceed the analysis between 0 and 15 c/d limits following Balona et al. (2011). The analysis of ALS 3728 allowed us the determination of two dominant pulsation frequencies with strong signals (Table 1). Although several other frequencies were found for each filter individually, the large day gap in our observations was attributed as the cause of the presence of those frequencies. An additional frequency $f_3=9.97 \, \text{d}^{-1}$ can also be considered, however it can only be reached in the $V$ and $I$ filters. As can be seen from the Fig. 3, the highest peaks occur around $5 \, \text{d}^{-1}$. Table 1 lists the result of independent frequencies that were reached in all filters and their amplitudes, phases and signal-to-noise ratios. The agreement of the solution with observational data is shown in Fig. 2. Fig. 3 illustrates the spectral window and the amplitude spectra of $B$-filter data before prewhitening of any frequencies. We conclude that ALS 3728 shows $\beta$ Cephei type pulsational variability.

4. Mode Identification

The multicolour photometry was used to perform mode identification of ALS 3728. Despite the inadequate number of data points, we attempt to identify the spherical harmonic degree ($l$) for the dominant pulsation frequency of $f_1=4.96 \, \text{d}^{-1}$. For this purpose, we used the FAMIAS software package (Zima, 2008) adopting the $1.6 < M_\odot < 20$, ZAMS to TAMS and A04,
Table 1: Frequencies (d$^{-1}$), amplitudes, $A$ (mmag), and phases $\phi$ (radians) determined. Signal-to-noise ratio per frequency is given in the last column. The standard deviations in the last digits are given in parentheses.

| ID | Freq       | $A_B$        | $\phi_B$ | SNR |
|----|------------|--------------|----------|-----|
| $f_1$ | 4.96399(5) | 0.05947(47) | 0.86020(125) | 139 |
| $f_2$ | 13.43545(28) | 0.01139(47) | 0.11137(652) | 29  |

| ID | Freq       | $A_V$        | $\phi_V$ | SNR |
|----|------------|--------------|----------|-----|
| $f_1$ | 4.92624(4) | 0.05325(38) | 0.67982(114) | 214 |
| $f_2$ | 13.43887(24) | 0.01096(38) | 0.72779(563) | 14  |

| ID | Freq       | $A_I$        | $\phi_I$ | SNR |
|----|------------|--------------|----------|-----|
| $f_1$ | 4.95182(11) | 0.03758(55) | 0.87679(249) | 42  |
| $f_2$ | 13.41234(42) | 0.00826(55) | 0.35894(1005) | 6   |

Figure 2: The agreement between synthetic and observational light curves of ALS 3728. Solid lines are determined by frequency analysis.
Figure 3: The top panel shows the spectral window of the data. Frequency spectra of ALS 3728 is plotted in the bottom panel.
For the process of mode identification we follow the steps which are explained in detail by Ulusoy et al. (2013). The theoretical amplitude ratios of different degrees $l$ were computed in the range of $22500K < T_{\text{eff}} < 27500K$, $3.4 < \log g < 3.8$, and microturbulance $8 \text{ km s}^{-1}$ for the best solution. The results obtained with the stellar mass $15 M_\odot$ which is very close to the value of $15.18 \pm 0.17 M_\odot$ yielded by means of the formulae given by Torres, Andersen, & Giménez (2010) which gives mass and radius in terms of $T_{\text{eff}}, \log g$ and $Z$. The amplitude ratios normalized to B filter for the single mode are shown in Fig. 4.

5. Conclusion

The first evidence of the $\beta$ Cephei type variability of the star ALS 3728 is given in this study. To study seismic behavior of the star located in NGC 6200, we performed photometric and spectroscopic observations. Frequency analysis resulted with the two genuine frequencies, $f_1=4.96 \text{ d}^{-1}$ and $f_2=13.43\text{ d}^{-1}$. These frequencies refer that the star pulsates in the $\beta$ Cephei type range and are the first determined frequencies in the literature. In the light curves, a stillstand phase occurred just before the maximum brightness (Fig. 2). This phenomenon is one of the common characteristics observed among some $\beta$ Cephei stars (Jerzykiewicz & Sterken, 1984; Sterken et al., 1986; Pigulski & Kołaczkowski, 2002; Ulusoy, Engelbrecht, & Gülmez, 2012). The effect can be observed mostly during the pulsation period of the star before the maxima and it takes several minutes to half and hour. BW Vul is

\footnote{OPAL opacities computed with non-adiabatic Warsaw-New Jersey/Dziembowski code by J. Daszyńska-Daszkiewicz and P. Walczak (http://helas.astro.uni.wroc.pl).}
Figure 4: Results of the mode identification process. Amplitude ratios are given as a function of the central wavelength normalized to the Johnson B filter for $f_1$. The coloured lines in the panels represent different spherical harmonic degrees corresponding to different stellar models in the range of $22500 < T_{\text{eff}} < 27500$ K and $3.4 < \log g < 3.8$. The red (solid) lines indicate $l = 0$, the green (long-dashed) $l = 1$, the dark blue (dashed) $l = 2$ the purple (dotted) $l = 3$. The models computed a mass of $15 \, M_\odot$. The black crosses represent the observed values with their $1\sigma$ standard deviations for $f_1$. 

$A/A_B$
well known and well studied target among $\beta$ Cephei variables that also shows a remarkable stillstand phase (Jerzykiewicz & Sterken, 1984; Sterken et al., 1986) in the light curve. Several possible scenarios were suggested by many authors in the literature to explain this interesting feature. The one accepted for BW Vul is that the bump of the light curve caused by gas dynamics occurred between the two strong shock waves (Fokin et al., 2004; Smith & Jeffery, 2003; Mathias et al., 1998). The origin of first shock is connected to the inner parts of the star where the \( \kappa \) mechanism drives by the iron bump elements. It then brakes before reaching the stellar surface by the second shock that is originated from outer layers. In other words, the stillstand can be explained as the result of complicated atmosphere motions involved by the two shock waves.

Spectroscopic observations and analysis indicate that ALS 3728 has a high rotational velocity (\( v \sin i = 100 \pm 20 \text{ km s}^{-1} \)) with derived effective temperature \( T_{\text{eff}} = 25000 \pm 2000 \text{ K} \) and \( \log g = 3.5 \pm 0.2 \). Using the distance modulus of NGC 6200, \( m - M = 13^{m}.36 \), given by \textsc{webda} database the luminosity of the star is found to be \( \log L/L_{\odot} = 3.59 \). The apparent visual magnitude of the star was taken from \textsc{simbad} database and the solar absolute magnitude was adopted from Cox (2000).

Using the stellar parameters in the given range (\( 15M_{\odot} < 22500K < 27500K \), \( \log g > 3.4 \)) mode identification was carried out to determine the degree \( l \) for at least the primary oscillation mode of ALS 3728. Our results showed that the amplitude ratios for \( f_1 = 4.96 \text{ d}^{-1} \) are closely rep-
sented with the theoretical amplitude ratios between the values of $l = 0$ and $l = 1$. Due to the lack of observational data points, we can not reach a definite conclusion about the identification and further investigation is needed. However, the primary oscillation mode of ALS 3728 might be associated with the fundamental radial mode which could be mostly expected in these type of variables (Daszyńska-Daszkiewicz et al., 2002).

All in all, β Cephei members of open clusters play an important role in order to study their evolutionary state that can be found by using colour-magnitude diagrams. They indeed need necessary attention to understand the nature of their pulsations and possible correlations between pulsational parameters and metal abundance.

Acknowledgments

CU sincerely thanks the South African National Research Foundation (NRF) for the award of innovation post doctoral fellowship, grant No. 73446. EN acknowledges support from the NCN grant 2011/01/B/ST9/05448. Calculations have been carried out in Wroclaw Centre for Networking and Supercomputing (http://www.wcss.wroc.pl), grant No. 214. This paper uses observations made at the South African Astronomical Observatory (SAAO). Some of observations reported in this paper were obtained with the South African Large Telescope (SALT) carried out with the project ID number 2011-2-RSA_POL-ULUSOY as CU the P.I. The authors wish to thank SALT astronomer Dr. Petrie Vaisanen and Dr. Alexei Kniazev for helping the spectroscopic observations. The authors also thank Prof. Andrzej Pigulski for sharing information on the target selection. This study was made by using
the WEBDA database, operated at the Institute for Astronomy of the University of Vienna, the NASA Astrophysics Data System and the SIMBAD database, operated at CDS, Strasbourg, France.

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