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TIME-RESOLVED SPECTROSCOPY OF THE BRIGHT sdBV STAR BALLOON 090100001

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Abstract. We have obtained 2552 low-resolution spectra of the bright sdBV star Balloon 090100001, aiming to derive its pulsational characteristics. The data were obtained at the Nordic Optical Telescope during seven nights in 2004 August/September over a total time base of 38 nights. In this paper we present preliminary results obtained from frequency analyses and spectral modeling of phase-folded spectra. Additionally, we briefly discuss the prospect of mode-identification for the main modes in this star, using preliminary amplitude ratios derived from our spectra.

Key words: stars: subdwarfs – line: profiles – stars: early-type, oscillations – stars: variables: general – stars: individual: Balloon 090100001

1. INTRODUCTION

Oreiro et al. (2004) found high-amplitude photometric variability and labelled Balloon 090100001 as the brightest known pulsating subdwarf-B star ($B = 11.8$). Furthermore, Oreiro et al. (2004), Baran et al. (2005) and Baran et al. (2006) presented a rich p- and g-mode frequency spectrum, including a triplet close to the dominant frequency of 2.8075 mHz. The fact that both p- and g-modes have been discovered in this star shows that Balloon 090100001 is in essence part of both the slow and fast pulsating groups of subdwarf-B stars. Altogether, the brightness, the pulsational amplitude and the rich but seemingly non-randomly distributed frequency spectrum, make this star an excellent target for asteroseismological studies.

So far, several pulsating sdB stars have been studied using low-resolution spectrographs on intermediate-size telescopes, e.g., PB 8783 and KPD 1209+4401 (Jeffery & Pollacco 2000), PG 1605+072 (O'Toole et al. 2003), PG 1325+101 (Telting & Østensen 2004), as well as a few other studies in these proceedings. All these studies have shown that low-resolution spectroscopy gives additional information (with respect to photometric studies) regarding the fundamental parameters of the stars, and gives essential velocity information that characterises the pulsa-

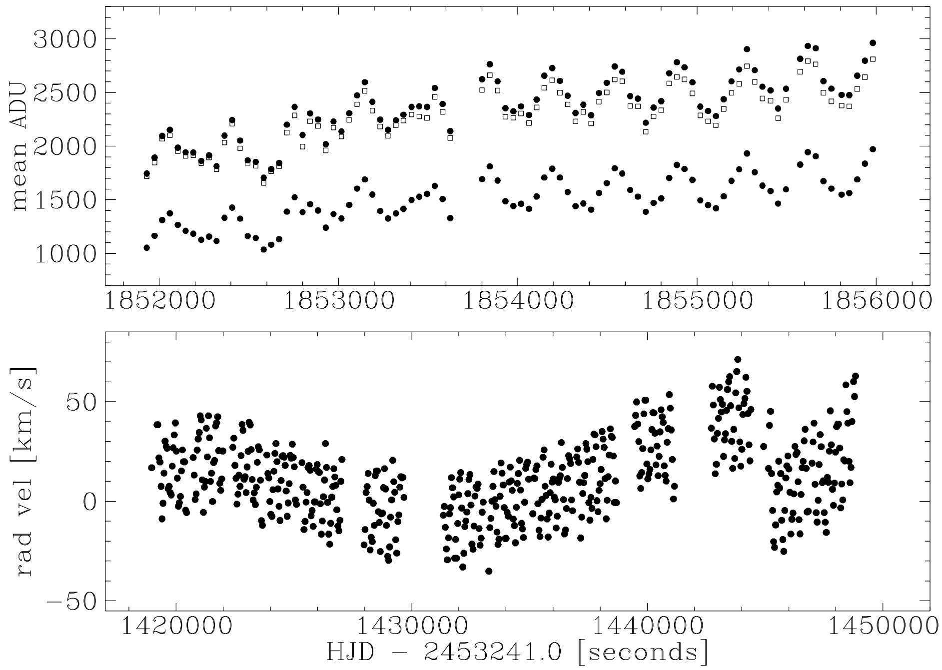

Fig. 1. Top: quasi-Strömgren u (lowest), v and b (open squares) light curve for about 1 hour of data. Bottom: radial velocities derived from cross-correlation for one night of data. The short-period variations reflect the main pulsation mode; the long term drifts and sudden shifts are (largely) instrumental effects.

tional behavior of these stars.

In this paper we present preliminary results derived from our data set that was obtained with the aim to put constraints on the pulsational characteristics of the star Balloon 090100001.

2. OBSERVATIONS

We observed the star during 7 nights in 2004 August/September over a total time-base of 38 nights. Our data set overlaps the photometric data set presented by Baran et al. (2006). We used the Andalucia Faint Object Spectrograph and Camera, ALFOSC, at the Nordic Optical Telescope on La Palma.

Our instrumental setup was: grism #16, CCD #8, and a long slit of 0.″8 width. This setup samples the wavelength region of approximately 3500–5060 Å, and gives a FWHM spectral resolution of about 3 Å corresponding to 54 km/s/pixel. We used an exposure time of 30 s, which hardly affects the amplitude of the main pulsation (P = 356 s) in terms of phase smearing. With appropriate binning and windowing in the spatial direction we achieved a cycle time of 43 seconds. Thorium-argon and helium arc-line spectra were made sandwiching 40 or less consecutive spectra.

The spectra were flatfielded and extracted using standard tasks within IRAF. The average signal to noise ratio of the individual extracted spectra is $S/N = 50$. A total of 2552 useful spectra were obtained.

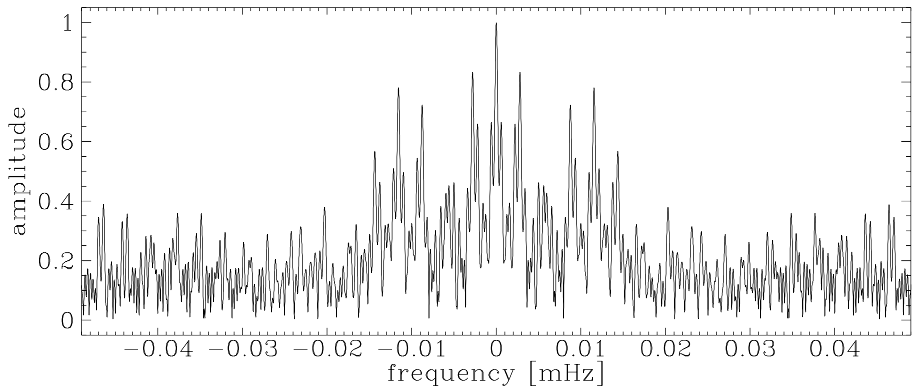

Fig. 2. The amplitude of the window function in Fourier space, showing strong 4-day and 1-day aliases.

3. RADIAL VELOCITIES AND SPECTROPHOTOMETRY

We used the cross-correlation routine FXCOR in IRAF using the mean spectrum as a template. The cross-correlation function (CCF) is dominated by the strong Balmer lines in the spectrum. We used the center of the CCF as a measure for the radial velocity of the star, and the FWHM of the CCF as a measure of the width of the Balmer lines, which in itself reflects the apparent surface gravity.

We used the average equivalent width (EW) of the Hγ–H9 Balmer lines as a further observable. To beat the noise in the wings of the profiles, each point in the profile was weighted with its own depth with respect to the continuum, implying the following non-standard form EW=$\sqrt{\Sigma(1-P(\lambda))^2} \times \Delta\lambda$, where $P(\lambda)$ is the line profile.

We also used our unnormalised spectra to obtain quasi-Strömgren *uvb* photometry from the mean count level in the following bands: 3515–3715 Å, 4000–4200 Å and 4600–4800 Å. For each band the mean count levels were put on a magnitude scale and were subsequently detrended as a function of time.

Figure 1 shows the radial-velocity measurements of one night of data, and a typical *uvb* light curve for about 1 hour of data. From the plot of the radial-velocity measurements it is clear that drifts in velocity and shifts due to recentering of the star on the slit. We have corrected for such instrumental/observational drifts and shifts by detrending appropriate chunks of radial-velocity data using first and second order polynomial fits. Note that such detrending can affect the amplitudes of low-frequency pulsational signal in the data.

4. FOURIER ANALYSES

We have analysed the quantities described above using a standard discrete Fourier transform. The distribution in time of the spectra results in strong 1-day and 4-day aliases (see the window function in Figure 2). Although the frequency resolution as obtained from the central window peak is on the order of 1 μHz, the severe aliasing pattern makes it difficult to separate real peaks from aliases.

Figure 3 shows the Fourier transforms of three of our observables, indicating the dominance of the main pulsation mode at 2.80749 mHz in the Fourier spectra.

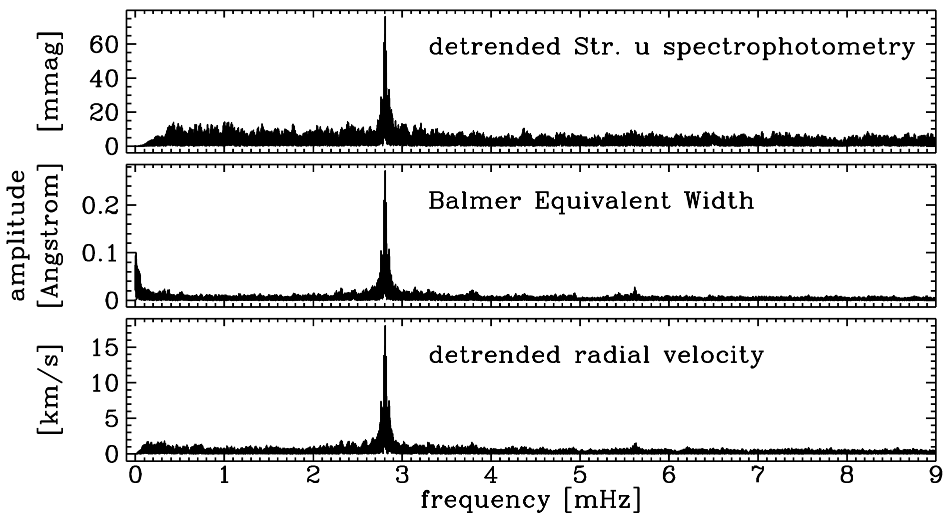

Fig. 3. Amplitude of Fourier transforms.

To estimate the errors on the amplitudes in Fourier space, we prewhitened the 25 strongest peaks and averaged the remaining amplitude spectrum between 0 and 15 mHz. The resulting error levels are 2.7 mmag for photometry amplitudes, and 0.24 km/s for the radial-velocity amplitude. The radial-velocity amplitude of the main pulsation mode is 18.0 km/s.

We have looked for the presence of other pulsation frequencies in the Fourier transforms of the observables. In Table 1 we list the pulsation frequencies from Baran et al. (2006), for which we find evidence in our data. Note that for some of these detections our data set alone would not suffice to label them as significant.

Table 1. Frequencies and B-mag amplitudes from Baran et al. (2006), for which we find evidence in our spectra. One asterisk denotes a corresponding peak, two asterisks denote a peak at an obvious alias.

mHz	mmag		mHz	mmag	
0.2724	2.89	**	2.8075	53.10	*
0.3658	2.71	*	2.8232	20.53	*/**
0.3257	1.09	**	2.8248	12.08	*
			3.7761	4.57	*

5. PHASE-FOLDED SPECTRA

In order to investigate the pulsational characteristics of the dominant mode (2.8075 mHz), we have phase-folded and averaged our spectra into 20 phase bins, each bin containing more than 100 spectra. The phase binning and subsequent averaging increases the S/N to better than 500 for the resulting spectra, and significantly reduces the variations that may be present at other frequencies. Besides

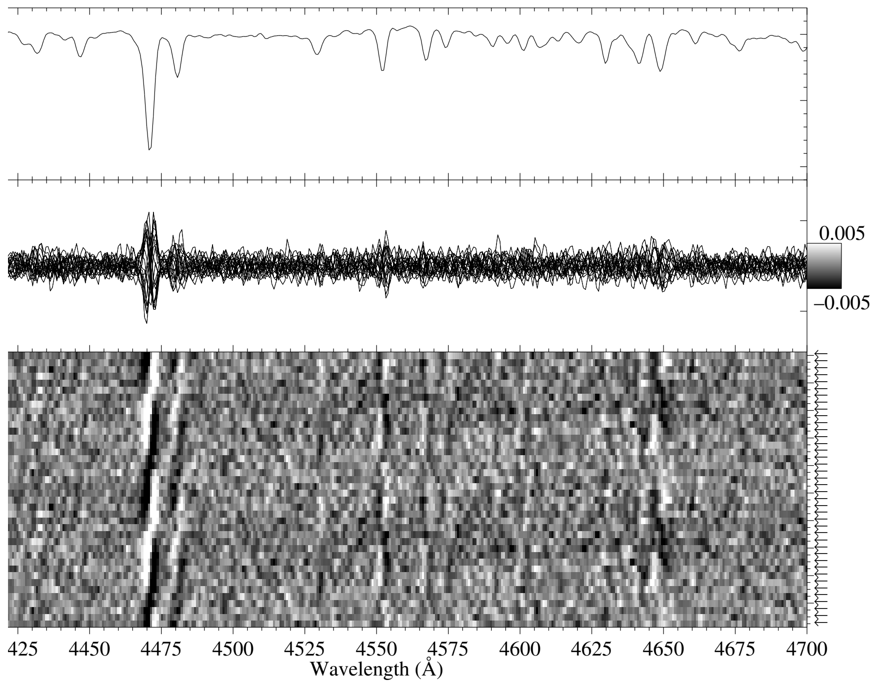

Fig. 4. Bottom panel: spectra folded to pulsational phase of the dominant mode (2.8075 mHz) and subsequently binned to 20 phase bins; the residual spectra are shown in grey-scale representation. Middle panel: overplot of the residual spectra. Top panel: average of all 2552 spectra. We show the wavelength region covering He I 4471 Å, Mg II 4481 Å, Si III 4552 Å, C III 4650 Å, to indicate the profile variations for these lines.

clear variations in the Balmer lines and He I lines, we detect pulsational variations in lines of heavier elements as well (see Figure 4).

We fitted the LTE spectral synthesis models of Heber et al. (2000) to each of the 20 phase-folded spectra to obtain values of the apparent effective temperature and apparent effective gravity. Both temperature and gravity show sinusoidal behaviour as a function of pulsation phase. The mean values are found to be $T_{\rm eff} =$ 28 700 K, $\log g = 5.39$ dex, with a helium abundance $\log(n(\mathrm{He})/n(\mathrm{H}))=-2.75$ dex that does not vary with pulsation phase. The pulsational amplitudes of apparent surface temperature and gravity are $\Delta T_{\rm eff} = 1250$ K, $\Delta \log g$=0.1 dex. The pulsational track of Balloon 090100001 is plotted in the gravity versus temperature diagram in Figure 5.

It is noteworthy that the main cause of the large variations in $\log g$ is the pulsational acceleration, which alters the surface gravity an order of magnitude more than the pulsational radius change does. Consequently, any type of modeling of p-mode line-profile and brightness variations for stars like Balloon 090100001 should account for the effect that the pulsational acceleration has on the surface gravity.

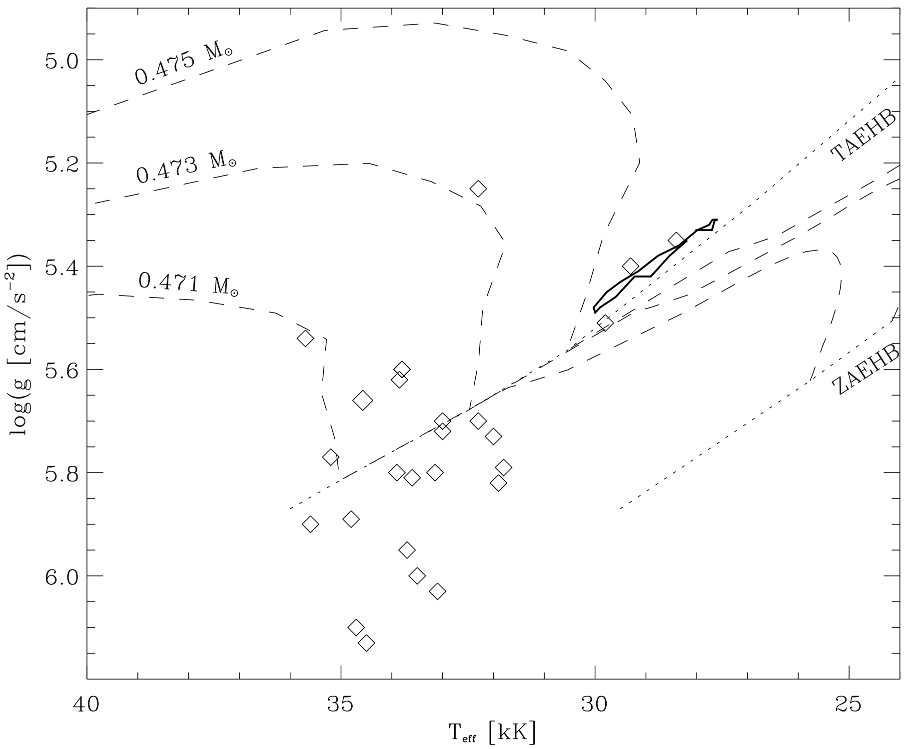

Fig. 5. Diagram of $\log g$ vs. $T_{\rm eff}$, with three evolutionary tracks from Dorman et al. (1993). In only six minutes the star sweeps through the diagram along the indicated pulsational track (the ragged closed contour close to the TAEHB). The diamonds depict all other known p-mode sdB pulsators.

6. TOWARDS MODE IDENTIFICATION

We computed *uvb* amplitude ratios for the main pulsation mode (2.8075 mHz) and for the strongest (2.8232 mHz) of the three frequencies that were identified by Baran et al. (2006) to form an equidistant triplet. Because of the triplet structure, this latter frequency is likely due to an $\ell = 1$ mode. Given its very high amplitude, the main pulsation mode is likely to be of low degree nature: $\ell < 3$.

The amplitude ratios A_v/A_u and A_b/A_u are plotted as a function of wavelength in Figure 6, similar to the diagrams presented by Ramachandran et al. (2004). Note that the stellar and pulsational parameters of the models presented by Ramachandran et al. (2004) are not consistent with those of Balloon 090100001.

We find that there is a clear separation between the amplitude ratios of the two modes, which indicates that it is unlikely that the two modes have the same pulsational degree ℓ, leaving as likely identifications of the main mode $\ell = 0$ and $\ell = 2$.

We prefer the $\ell = 0$ identification of the main mode, because of the high observed amplitude of that mode. Nevertheless, we are convinced that detailed modeling of the amplitudes as a function of wavelength, in a similar fashion as presented by Randall et al. (2006, these proceedings) and Green et al. (2006, these

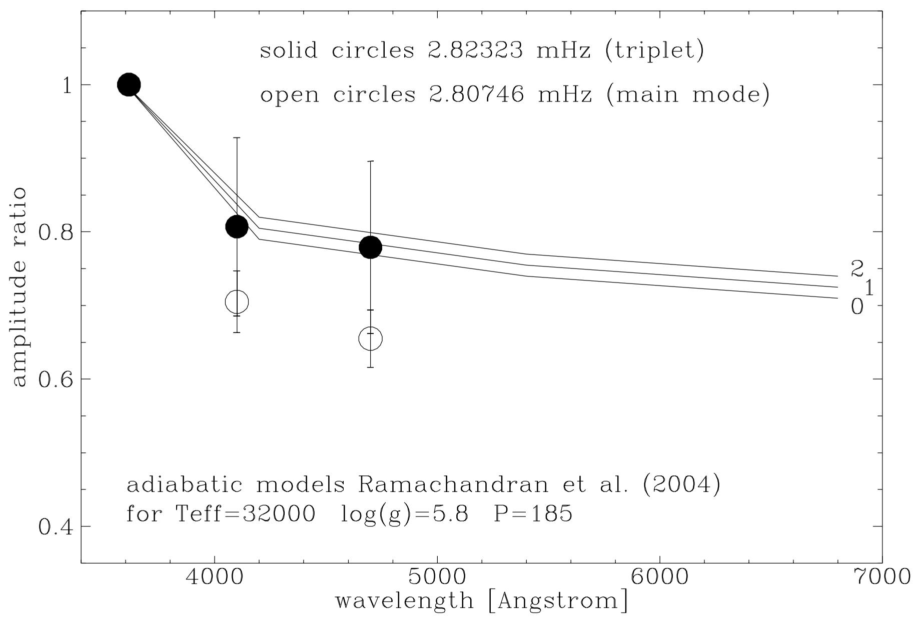

Fig. 6. Our *uvb* amplitude ratios compared with theoretical *UVBR* ratios for a sdB star hotter and more compact than Balloon 090100001 (see Ramachandran et al. 2004). Unlike the theoretical curves, our amplitude ratios show clear separation for the two modes.

proceedings), could provide further evidence to confirm our tentative identification of the main pulsation mode of Balloon 090100001.

7. SUMMARY AND PRELIMINARY CONCLUSIONS

We have obtained a large spectroscopic data set of Balloon 090100001, and find clear signatures of the main pulsation mode. In our Fourier periodograms we find further evidence for other previously known frequencies.

In the phase-folded spectra, as folded on the main pulsation period, we find clear pulsational variations in the Balmer and helium lines that are present in our spectra. Moreover, we find clear pulsational variations in lines of heavier elements as well.

The apparent pulsational variations of temperature and gravity, due to the main pulsation mode, are $\Delta T_{\rm eff} = 1250$ K and $\Delta \log(g) = 0.1$ dex (semi amplitudes). The radial velocity amplitude of this mode is 18 km/s.

We show that the *uvb* amplitude ratios, derived from our spectra, of the main mode and of the strongest of the triplet modes are not the same, indicating that these modes may have a different ℓ value. We tentatively identify the main mode to be a radial mode.

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