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HE 0230−4323 revisited: a new rapidly pulsating sdB star

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ABSTRACT

HE 0230−4323 is a hot sdB star in a binary system. An earlier work demonstrated that the light curve of the system shows a strong (∼4 per cent) reflection effect and also appears to exhibit photometric variations of the type associated with the slowly pulsating class of sdB star (multiple periods in the range ∼1–2 h). In this paper, we show that HE 0230−4323 is, in fact, a *rapidly* pulsating sdB with at least five frequencies between 3227 and 3532 μHz (periods between 310 and 283 s). The long periods previously claimed were the result of undersampling the light curve at a time interval very close to that of the short periods. The interpretation of the very slow variation (∼0.45 d) as a reflection effect in a close binary is unaffected by these new results.

Key words: stars: individual: HE 0230−4323 – stars: oscillations – stars: variables: other.

1 INTRODUCTION

The star HE 0230−4323 was discovered to be very blue by the Hamburg/European Southern Observatory survey (Wisotzki, Reimers & Wamsteker 1991) and classified sdB by Altmann, Edelmann & de Boer (2004). Koen (2007, hereafter Paper I) has summarized the available data for this star; relevant quantities are the atmospheric parameters determined by Lisker et al. (2005), namely $T_{\rm eff} = 31\,550$ K and $\log g = 5.60$, and the fact that whilst there is no evidence from broad-band colours or spectral appearance that the star has a companion, radial velocity variations show it to be a close binary with a period of ∼0.4515 d (Edelmann et al. 2005).

In Paper I, HE 0230−4323 was shown to exhibit complex photometric variations taking two forms.

(i) A large-amplitude (∼4 per cent) variability with a time-scale longer than any of the observational runs on individual nights (typically around 7 h). By folding the observations on the binary period (0.45 d), this was identified as a substantial reflection effect, amounting to about 4 per cent in *V* and 3 per cent in *B*.

(ii) Much more rapid variations, with amplitudes less than 1 per cent, measured at 32–39 cycles d^{-1} (periods of about 2700–2200 s) changing after several nights to 8–16 d^{-1} (about 11 000–5400 s). Given that the visible component of the binary is an sdB star, it seemed highly likely that the star was a slow pulsator of the type discovered by Green et al. (2003).

The reflection effect seems well established by Paper I and we do not here discuss it further. The slow pulsations, however, had a number of puzzling features.

(i) The temperature of the star, 31 500 K, places it in the region of the *rapidly* pulsating sdB stars (first reported by Kilkenny et al. 1997), and there is a clear distinction in temperature/gravity space between the rapidly and slowly pulsating stars (Green et al. 2003) with the boundary between them populated by a few 'hybrid' stars (near $T_{\rm eff} = 29\,000$ K) which exhibit pulsations of both types (see fig. 2 of Charpinet et al. 2007, for example). No slow pulsators are known nearly as hot as 31 500 K.

(ii) Very unusually, the variations in *B* and *V* appeared to be almost exactly 180° out of phase for pulsations on all time-scales observed.

(iii) Although sdBV stars commonly exhibit amplitude variations, the changes observed in HE 0230−4323 are unusual in that the 32–39 d^{-1} variations switch rapidly to 8–16 d^{-1}, essentially from one night to the next.

These features were sufficiently odd that we had planned a multisite campaign to investigate the system further. Fortunately, before the campaign started, it was realised that the sdB star is not a slow pulsator but a rapid one. Given the data presented in Paper I (Figs 1–3), this seems improbable, but is in fact a simple undersampling error, illustrated schematically in Fig. 1. We show later in this paper that HE 0230−4323 has several pulsations in the range 283–310 s. A representative value of 285 s is assumed for Fig. 1. In Paper I, the first four nights were sampled (*B* and *V* filters) with a cycle time of about 255 s. The frequency difference between 285 and 255 s is 0.00 392–0.00 351 = 0.00 041 Hz, equivalent to about 2440 s or about 35 d^{-1} – as observed. In the last two nights, the cycle time was increased to about 275 s, giving a frequency difference of about 0.00 012 Hz or about 10 d^{-1} – again, as observed. The situation is more complicated because the star is multiperiodic, but the sudden shift in observed frequencies is explained by the change in

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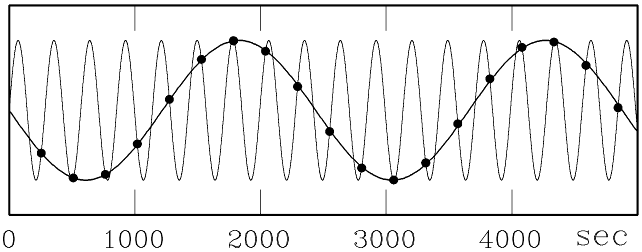

Figure 1. Undersampling HE 0230−4323. A representative sinusoidal variation with a period of 285 s (light line) is sampled at a similar rate of once every 255 s (dots). The observer sees variation at the frequency difference, in this case 35 cycles d^{-1} (0.00 041 Hz) or a period of about 2440 s (heavy line).

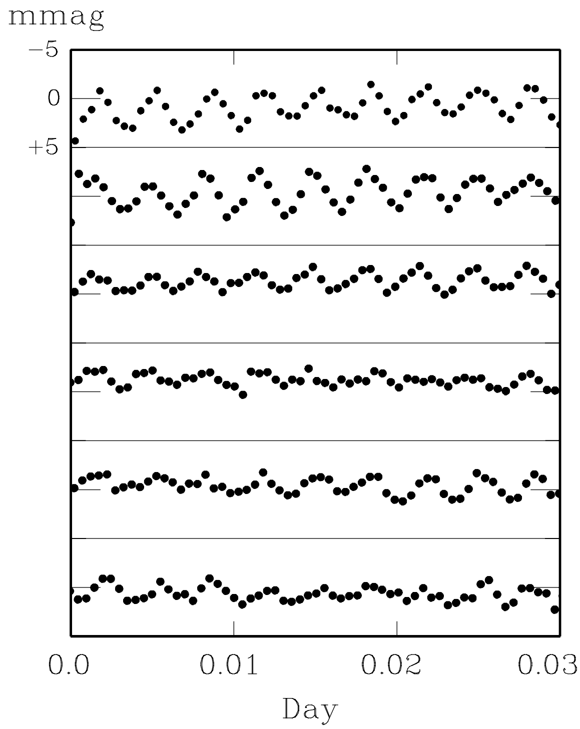

Figure 2. HE 0230−4323: partial *B* light curve from 2008 November 25/26. Observations run left-to-right and top-to-bottom. The ∼5 min oscillations are evident – especially in the top two panels – as is the complex beating.

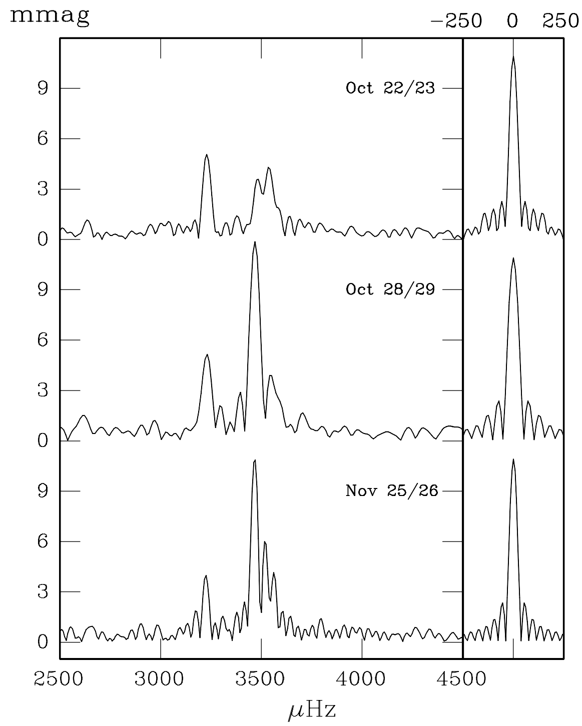

Figure 3. Periodograms for the three 2008 runs on HE 0230−4323. The data sets are in the range 6–8 h long and the corresponding window functions are shown in the right-hand panels.

Table 1. Log of the new high time resolution observations of HE 0230−4323. All runs used the SAAO 1-m telescope.

Date	Photometer	Filter	Exposures (s)	Run (h)
2008 October 22/23	UCTCCD	*V*	15	6.7
28/29	UCTCCD	*V*	15	6.0
November 25/26	SAAO STE3	*B*	25	8.0
2009 September 19/20	UCTCCD	*B*	20	1.9
20/21	UCTCCD	*B*	20	2.5
22/23	UCTCCD	*B*	20	2.4

the (under) sampling rate; the high temperature is explained because the star is a *rapid* pulsator, not a slow one; and the 180° apparent phase shift between *B* and *V* is a result of the fact that the filter integrations are separated by almost exactly half of the sampling time – and therefore close to half of the (short) periods.

In the remainder of this paper, we present the evidence for rapid variations in HE 0230−4323.

2 ‘HIGH-FREQUENCY’ OBSERVATIONS

The photometric data described in this section were mostly obtained with the University of Cape Town CCD photometer (O’Donoghue 1995) on the 1.0 m telescope at the Sutherland site of the South African Astronomical Observatory (SAAO). This photometer uses a small Wright Instruments Peltier-cooled camera with a 576 × 420 thinned, back-illuminated EEV CCD. It is operated in frame-transfer mode which reduces the usable part of the CCD to 380 × 260 pixels but has the massive advantage that there is effectively no time lost between integrations so that rather short integration times are possible (down to ∼8 s, unbinned) without huge inefficiency. Observations on one night were made on the same telescope with the more conventional SAAO STE3 camera, which uses a SITe 512 × 512 detector. This instrument has a read-out time of nearly 20 s, so that a 25 s integration time (Table 1) only allows a sampling time of about 44 s. Different integration times and filters were used, as indicated in Table 1 which gives a log of the high time resolution observations presented here.

Photometric reductions were performed using an automated version of DOPHOT (Schechter, Mateo & Saha 1993). Both profile-fitted and aperture magnitudes were calculated but because HE 0230−4323 is relatively bright, we have found the aperture magnitudes to be better (in the sense of having less scatter) on almost all nights. A sample (*B*) light curve from 2008 November 25/26 is plotted in Fig. 2.

In ‘high-speed’ photometry, our general procedure has been to correct target stars differentially on a night-by-night basis to remove any rapid transparency variations using other stars on the chip. In the case of HE 0230−4323, there is only one suitable bright star in the (rather small) field of the UCTCCD and this is a close double which has presented reduction problems in variable seeing. We have therefore only used data from photometric nights and have not differentially corrected the target star. Although photometric variation caused by the reflection effect must be present in all our data, the dominant term in the longer data sets is clearly the atmospheric extinction (the shorter sets are fairly flat), so we have corrected for extinction effects by removing a quadratic term from each night's observations. As can be seen from Fig. 2, this simple procedure 'flattens' the observations adequately.

3 ANALYSIS

The frequency analyses described in this paper were carried out using the EAGLE software written by Darragh O'Donoghue which produces Fourier amplitude spectra following the Fourier transform method of Deeming (1975) as modified by Kurtz (1985).

Of the runs listed in Table 1, the three made in 2008 are of quite useful length; the others are rather short. In Fig. 3, we show the periodograms for the 2008 nights. It is immediately clear that there is a persistent frequency near 3200 μHz, a much stronger feature near 3450 μHz (which, however, is much reduced in the top panel – October 22/23), and some power around 3500–3550 μHz.

We have extracted peaks, one at a time from all the nights listed in Table 2, adopting an approach of not worrying about ad hoc criteria such as 'four times the noise' (see Koen 2010 for a critique of this particular criterion) but rather looking for frequencies, which appear in two or more periodograms. The results are listed in Table 2 where it can be seen that there are at least three strong candidates near 3230, 3470 and ∼3500 μHz. These are the frequencies clearly visible in Fig. 3 and, as noted above, even from this relatively small amount of data, it is clear that amplitude variation (or unresolved frequency beating) is occurring; an apparently common property of the pulsating sdB stars (Kilkenny 2010).

We have also examined the merged observations from two close nights in 2008 October and three in 2009 September, although the data are not extensive and the gaps between them are large compared to the data set lengths. The results for the combined data are shown in Fig. 4 and the extracted frequencies are listed in Table 3, and essentially confirm the findings summarized in Table 2. There is a strong frequency near 3470 μHz (∼288 s); this might be two frequencies (resolved by the longer baselines) – or reflect the fact that this frequency has a very variable amplitude (see Table 2). There is also good evidence for at least two more frequencies, near 3230 μHz (∼309 s) and 3550 μHz (∼282 s). The relatively poor agreement between 2008 October and 2009 September almost certainly results from aliasing caused by the rather small numbers of observations in the latter data set – and is reflected in the very broad window function shown in the bottom panel of Fig. 4.

Table 2. Frequencies extracted from each single night of observations logged in Table 1. Numbers in square brackets are the amplitudes in mmag.

Date	Extracted frequencies (μHz)			
	(∼310 s)	(∼288 s)	(∼285 s)	(∼282 s)
2008 October 22/23	3227 [5]	3466 [2]	3498 [3]	3535 [4]
28/29	3226 [5]	3466 [12]		3553 [3]
November 25/26	3226 [4]	3465 [11]	3510 [4]	3548 [3]
2009 September 19/20		3461 [6]		
20/21	3198 [3]	3440 [4]		3532 [8]
22/23	3234 [4]	3492 [14]		

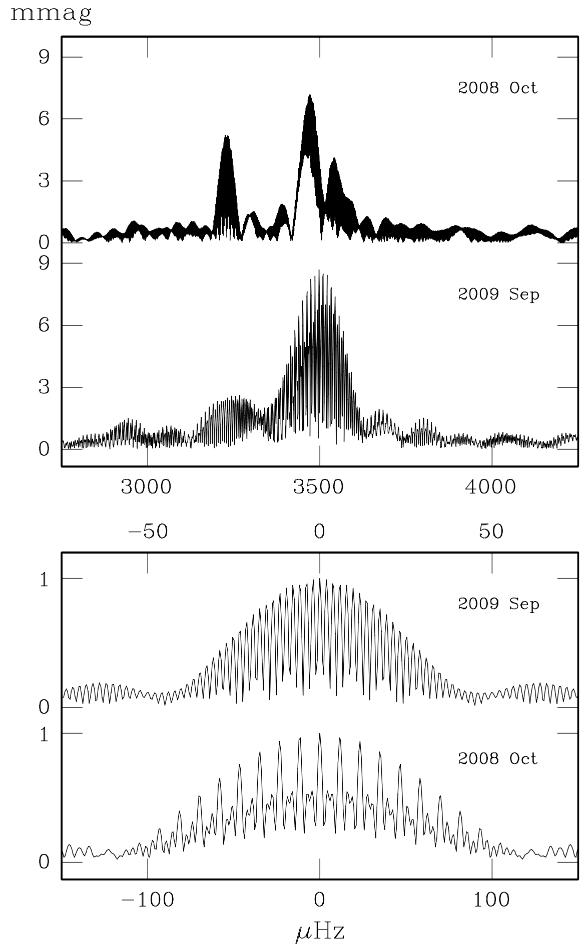

Figure 4. Upper panel: periodograms for the 2008 October (two nights) and 2009 September (three nights) observations of HE 0230−4323. Lower panel: the corresponding window functions on a much-expanded scale (note that the two abscissa scales in the lower panel are not the same).

Table 3. Frequencies extracted from multiple nights in 2008 October (two nights) and 2009 September (three nights).

2008 October			2009 September		
f (μHz)	Amp (mmag)	P (s)	f (μHz)	Amp (mmag)	P (s)
3471	7	288.1	3497	9	285.9
3464	5	288.6	3438	3	290.8
3233	5	309.3	3273	3	305.5
3550	3	281.7	3534	4	282.9
3510	2	284.9			

4 'LOW-FREQUENCY' OBSERVATIONS

As noted in Section 1, a multisite campaign had been arranged under the misapprehension that HE 0230−4323 was a slow pulsator. As a prelude to this campaign, eight nights of low time resolution photometry were obtained in 2008 October, again using the STE3 CCD camera on the 1.0-m SAAO telescope (see Section 2). The bulk of the observations (all nights except the last) was made by cycling through the Johnson *B*, Johnson *V* and Strömgren *b* filters, with exposure times of 80, 60 and 130 s, respectively. No pre-binning was used, so the readout time was about 20 s, and the total cycle time of the order of 330 s. On the last night, only the *B* filter was

Table 4. Log of the new low time resolution observations of HE 0230−4323. Measurements were made in Johnson *B* and *V*, and Strömgren *b*, except for the last night, when only *B* was used. The last three columns give the number of usable measurements in *B*, *V* and *b*.

Starting time (HJD 245 0000+)	Run length (h)	*N* *B*	*V*	*b*
4751.3340	7.0	71	67	70
4752.3567	6.6	64	65	64
4753.3022	5.2	51	51	50
4754.3056	2.4	25	25	24
4756.2937	4.9	41	44	37
4757.2966	7.8	111	108	49
4758.2931	8.0	84	84	84
4759.3006	7.2	405		

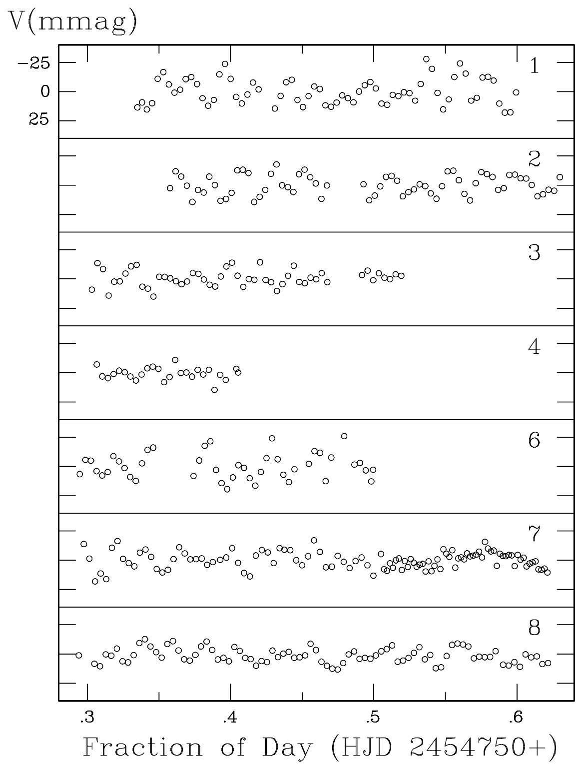

Figure 5. The low time resolution *V*-band measurements of HE 0230−4323. Observations on each night have been pre-whitened by a third-order polynomial. The vertical size of each panel in the plot is 0.08 mag. Panels are labelled with the last digit of the Julian day of observation.

used, with exposure times of 40–50 s. Furthermore, the CCD was pre-binned, which resulted in a readout time of about 5 s. A log of the observations is given in Table 4.

Photometric reductions were as for the higher time resolution observations. The field of view included three bright stars which could potentially be used as local standards; one of these was generally excluded as its photometry was at times poor (see also Section 2). The *V*-band results are plotted in Fig. 5, as an illustration of the nature of the data. The observations for each night have been pre-whitened by a third-order polynomial in order to remove the effects of differential extinction (HE 0230−4323 is, of course, very blue), and also the slow variations due to the reflection effect. All the low time resolution data discussed below have been similarly detrended.

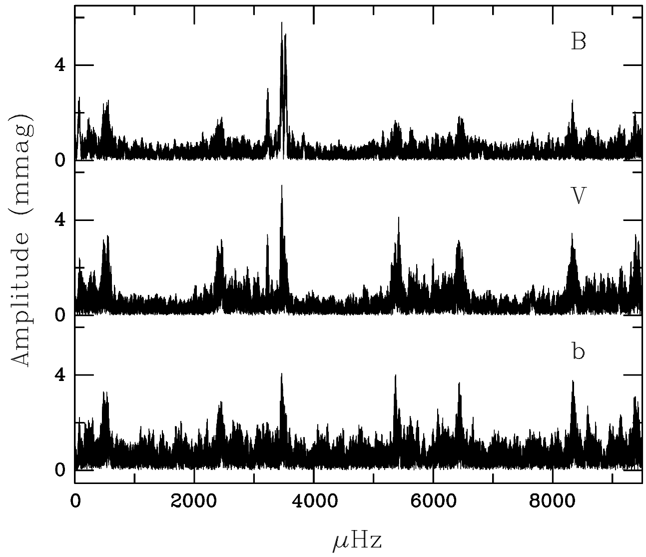

Figure 6. Amplitude spectra of the complete data for each of the three filters. Nightly data sets were pre-whitened by subtraction of a least squares fitted third-order polynomial.

5 ANALYSIS

Given the error made in Paper I, it might seem unduly optimistic, even foolhardy, to attempt to analyse data obtained at about half the Nyquist frequency (a rate close to the periods sought). However, the observations listed in Table 4 are of significant number (almost 900 in *B*); they cover a decent baseline (a week) and have a fair 'filling factor' (nearly 30 per cent); importantly, they are obtained in three colours, so the results can be intercompared; finally – and critically

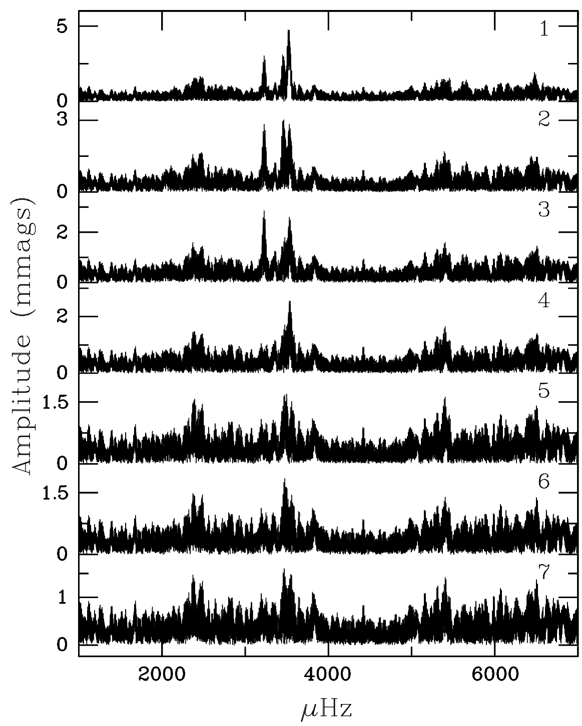

Figure 7. Successive stages of pre-whitening of the *B*-band data. Each panel is labelled with the number of sinusoids which have been removed from the full data set. Note the different scales on the ordinate axes of the different panels.

Table 5. Results of the sequential fitting of sinusoids by least squares, followed by pre-whitening. The formal uncertainties in the last quoted digits are given in brackets. Asterisks mark cases where the *V*- or *b*-band frequency is a probable 1 cycle d^{-1} (11.57 μHz) alias of the corresponding *B*-band frequency.

B		*V*		*b*	
Frequency (μHz)	Amplitude (mmag)	Frequency (μHz)	Amplitude (mmag)	Frequency (μHz)	Amplitude (mmag)
3465.92(6)	5.9(4)	3465.78(8)	5.4(5)	13463.8 (1)	4.1(6)
3516.40(6)	4.8(4)	3516.4 (1)	3.5(4)		
3227.2 (1)	2.8(4)	3227.0 (1)	3.1(4)		
3462.87(9)	3.1(4)	*3451.51(9)	4.4(4)	*3453.4 (2)	2.9(5)
3530.7 (1)	2.6(4)	*3543.9 (1)	2.5(4)		
3498.3 (2)	1.7(4)				
3477.5 (1)	1.8(3)				
				3491.4 (1)	3.4
		5996.6 (1)	2.5(3)		
		5722.4 (1)	2.0(3)		

– we know from the results derived in Section 3 where to search in the periodogram for the correct frequencies.

Amplitude spectra of all the low time resolution observations for each of the three filters are given in Fig. 6. Each night's data have again been detrended by subtracting a third-order polynomial. The alias pattern is very interesting, with groups of peaks separated by about 3000 μHz. In paper I, it was erroneously assumed that the correct frequencies were below 1000 μHz; the high time resolution observations show that the correct aliases are those in the interval 2000–4000 μHz. The fact that the peaks in this interval are particularly prominent in the *B*-band spectrum can be ascribed to the better time resolution of the JD 245 4759 measurements (see Table 4).

The small amplitudes in *b* are noteworthy. The lesser width of the filter required long exposure times – 130 s – and this meant that integrations were almost half a pulsation cycle long. There was therefore considerable loss of information in the *b*-band data.

A process of successive frequency pre-whitening is illustrated in Fig. 7, for the *B* data – each panel is labelled with the number of frequencies which have been pre-whitened. There is clearly still an excess of power near 3500 μHz in the bottom panel, but identification of the correct frequency is unlikely. In fact, the more cautious analyst may prefer to stop after five frequencies have been identified. That particular choice would be vindicated by the excellent agreement between the first five frequencies extracted from the *B*-band data, and those seen in the *V*-band observations (see Table 5). In the case of the *b* filter, there are only three amplitude spectrum peaks which are convincingly above the noise level, and the agreement with frequencies in the *B* and/or *V* data is unimpressive. This can be explained by the relatively high-noise level, and the long exposure time of the *b*-band measurements.

6 CONCLUSIONS

We have shown that, contrary to the findings of Paper I, HE 0230−4323 is not slowly pulsating but is a rapidly pulsating sdB star. From several series of observations, it appears that we can identify, with some confidence, at least five frequencies near 3227 μHz (period = 309.9 s), 3466 (288.5 s), 3463 (288.8 s), 3516 (284.4 s) and 3532 μHz (283.1 s). The two frequencies near 3465 μHz might be resolved or could reflect the fact that a single frequency has a variable amplitude. The nature of our observations – particularly the low-frequency data – makes amplitude determination less certain.

The previously noted variability at the binary orbital frequency (0.45 d) which was attributed to reflection effect in the system is a conclusion unaffected by this new result.

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REFERENCES

Altmann M., Edelmann H., de Boer K. S., 2004, A&A, 414, 181
Charpinet S., Fontaine G., Brassard P., Chayer P., Green E. M., Randall S. K., 2007, in Handler G., Houdek G., eds, The Future of Asteroseismology, Communications in Asteroseismology Vol 150. Austrian Academy of Sciences Press, Vienna, p. 241
Deeming T. J., 1975, Ap&SS, 36, 137
Edelmann H., Heber U., Altmann M., Karl C., Lisker T., 2005, A&A, 442, 1023
Green E. M. et al., 2003, ApJ, 583, L31
Kilkenny D., 2010, The Fourth Meeting on Hot Subdwarf Stars and Related Objects. Ap&SS, in press
Kilkenny D., Koen C., O'Donoghue D., Stobie R. S., 1997, MNRAS, 285, 640
Koen C., 2007, MNRAS, 377, 1275 (Paper I)
Koen C., 2010, The Fourth Meeting on Hot Subdwarf Stars and Related Objects. Ap&SS, in press
Kurtz D. W., 1985, MNRAS, 213, 773
Lisker T., Heber U., Napiwotzki R., Christlieb N., Han Z., Homeier D., Reimers D., 2005, A&A, 430, 223
O'Donoghue D., 1995, Baltic Astron., 4, 519
Schechter P. L., Mateo M., Saha A., 1993, PASP, 105, 1342
Wisotzki L., Reimers D., Wamsteker W., 1991, A&A, 247, L17

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