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KPD 0629–0016, a slowly pulsating hot subdwarf star

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ABSTRACT

The results of nine CCD photometric observing runs on KPD 0629–0016 are presented. During six of the runs measurements were obtained alternately through *B* and *V* filters. Four periodicities, for which there is good agreement between the frequencies identified in the *B* and *V* data, were extracted: these lie in the range 46–81 min. A fifth lower frequency appears to be definitely present, but is very uncertain due to aliasing. The ratios of the mode amplitudes measured in *B* and *V*, and the phase differences between variations in the two colours, are compatible with pulsation theory.

Key words: stars: individual: KPD 0629–0016 – stars: oscillations – subdwarfs – stars: variables: other.

1 INTRODUCTION

The literature on observations of slowly pulsating sdB stars (PG1716 stars, after the prototype PG 1716+426) is still in its infancy. Studies of only a handful of stars have been published to date – PG 1716+426 (Green et al. 2003; Reed et al. 2004); PG 1627+017 (Randall et al. 2006a); PG0101+039 (Randall et al. 2006b); PG 1338+481 (Randall et al. 2006c); EC 21324–1346 (Kilkenny et al. 2007) and HE 0230–4323 (Koen 2007). Two hybrid rapid/slow sdB pulsators have also been discovered: Balloon 090100001 (Oreiro et al. 2005; Baran et al. 2005) and HS 0702+6043 (Schuh et al. 2006). We add to this small collection of papers by describing the discovery of pulsations in KPD 0629–0016.

Very little has been published on the object since it was discovered by Downes (1986) to be a $V = 14.9$ mag subdwarf B star. Wesemael et al. (1992) obtained Strömgren photometry of KPD 0629–0016, and this was used by Villeneuve, Wesemael & Fontaine (1995) to derive a *y*-band extinction of 0.7 mag, $T_{\rm eff} = 26\,766$K, and $5.2 \leqslant \log g \leqslant 5.5$. These attributes place it within the region in the $T_{\rm eff}$– $\log g$ plane occupied by the PG1716 stars (e.g. Fontaine et al. 2006).

The next two sections of the paper describe the acquisition and analysis of our photometric data, and a brief discussion is presented in Section 4.

2 THE OBSERVATIONS

Pulsations were discovered during the course of an observing run with the Steward Observatory 2.3-m Bok telescope on Kitt Peak, Arizona. The telescope was equipped with a CCD camera with a 2048 × 2048 chip; operated in 3 × 3 pre-binning mode (giving a useful scale of 0.45 arcsec pixel^{-1}), the readout time was 24 s. All measurements were made through a *B* filter.

Follow-up observations were made with the SAAO (South African Astronomical Observatory) CCD camera mounted on the SAAO 1.0-m telescope at Sutherland, South Africa. The SITe chip size is 1024 × 1024. No pre-binning was used, as this gave superior results – however, the readout time was an excruciating 60 s. Measurements were usually obtained alternately through *B* and *V* filters, although only the *B* filter was used for the first run, and only the *V* filter for the last. Given that the exposure times were of the order of 2 min, this means that successive measurements through a given filter were usually 6 min apart.

A log of the observations is given in Table 1.

Photometric reductions were completely standard; differential aperture magnitudes were obtained from the Kitt Peak observations, and differential profile-fitted magnitudes at SAAO. The results of the photometric runs are plotted in Figs 1–3. The pulsations are very obvious in the first run, but somewhat less so in the results obtained with the 1.0-m telescope. This is due to the lesser light-gathering power of the smaller telescope and the poorer time sampling.

We have also obtained eight low-resolution (∼9 Å) spectra of KPD 0629–0016 with the Boller & Chivens spectrograph on the 2.3-m Bok telescope (see Table 2). Meticulous cross-correlations of these spectra gave radial velocity errors of about 15–20 km s^{-1}. Since the overall s.d. of the determined velocities was 15.0 km s^{-1}, it is unlikely that the star is a radial velocity variable.

The spectra were combined, and line profiles compared to those of zero-metallicity atmospheric models by G. Fontaine (University of Montréal). The best fit was obtained with parameters $T_{\rm eff} = 27\,781 \pm 270$K, $\log g = 5.527 \pm 0.041$ and $\log {\rm He/H} = -2.746 \pm 0.118$. We are grateful to Prof. Fontaine for supplying this information.

The agreement between the photometric (see Section 1) and spectroscopic determinations of temperature and gravity is good.

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Table 1. The photometric observing log: T_{exp} is the exposure time and N the number of useful measurements obtained during a given run.

Starting time (HJD 245 0000+)	Filter	T_{exp} (s)	Run length (h)	N
2603.796	*B*	60	5.7	238
4092.457	*B*	120	3.1	60
4093.477	*V, B*	100–120, 100–120	2.7	28, 27
4094.366	*V, B*	100–120, 100–120	3.5	39, 40
4095.356	*V, B*	100, 100	5.5	64, 63
4096.349	*V, B*	100, 100	5.9	67, 65
4097.336	*V, B*	100, 100	6.1	71, 66
4098.318	*V, B*	90–110, 80–90	6.2	68, 64
4102.335	*V*	90	5.8	103

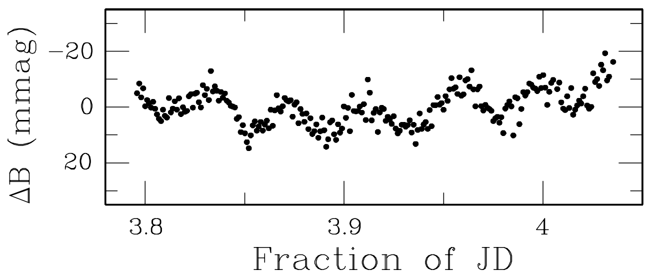

Figure 1. The discovery light curve of pulsations in KPD 0629–0016.

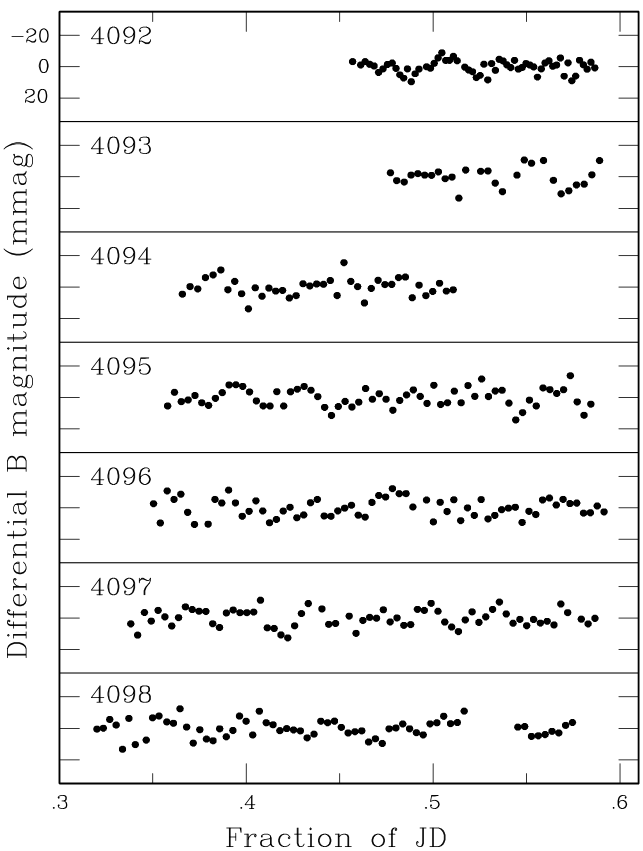

Figure 2. Follow-up observations in the *B* band. Each night's measurements have been detrended by subtracting a quadratic fit. The vertical width of each panel is 0.07 mag. Panels are labelled with the last four digits of the Julian Day of observation.

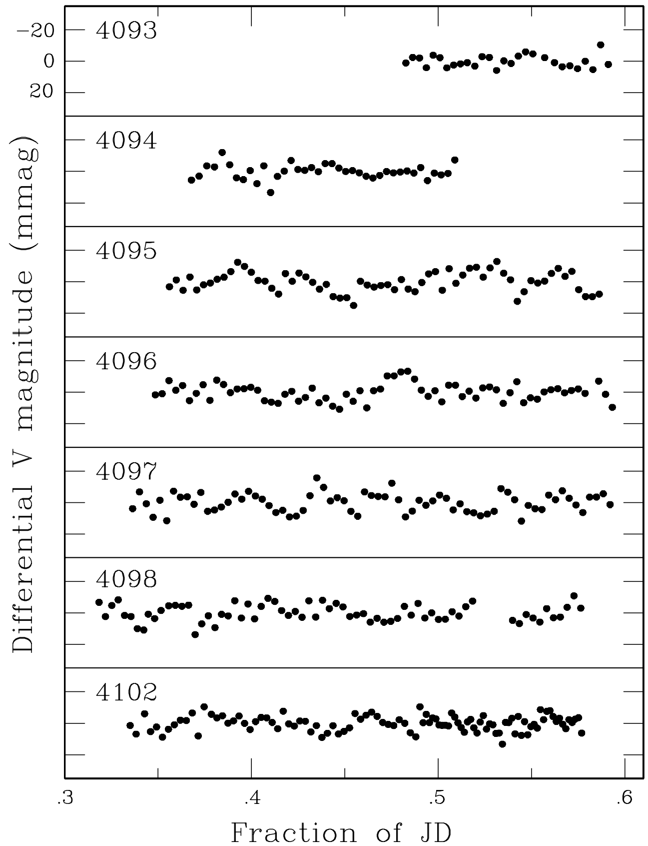

Figure 3. As for Fig. 2, but showing the *V*-band observations.

Table 2. The spectroscopic observing log.

Time (HJD 245 0000+)	Airmass (atm)	T_{exp} (s)	S/N
2555.9998	1.214	1200	107
2556.9842	1.241	1100	106
2620.8950	1.208	1100	98
2621.8579	1.183	1100	101
2622.8167	1.223	1100	92
2622.8330	1.197	1100	94
2669.7528	1.197	1100	102
2974.8710	1.194	1100	96

3 DATA ANALYSIS

Amplitude spectra of the individual photometric runs are plotted in Figs 4 and 5. Each nightly data set has been detrended by subtraction of a least-squares fitted second order polynomial. The discovery run shows evidence for the presence of four periodicities, with frequencies near 8.2, 15.0, 24.0 and 30.6 d^{-1}. The latter two features recur in the later photometry – see, for example, the panels for JD 245 4095 and JD 245 4097. On the other hand, there is no obvious feature near 15 d^{-1} in the SAAO photometry.

The level of variability appears to vary from night to night; for example, amplitudes are large on JD 245 2603 and JD 245 4095, and low on JD 245 4098 and JD 245 4102. The amplitudes in *B* and *V* are generally comparable, but, surprisingly, amplitudes in *V* are sometimes larger – see the features near 30 d^{-1} on JD 245 4097, and

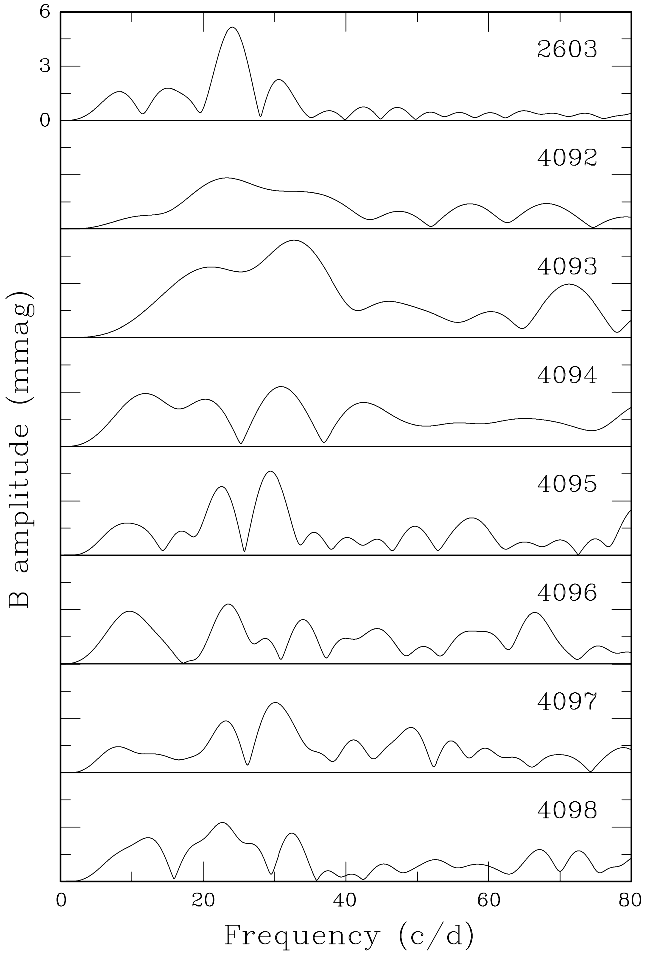

Figure 4. Amplitude spectra of the *B*-band data in Figs 1 and 2.

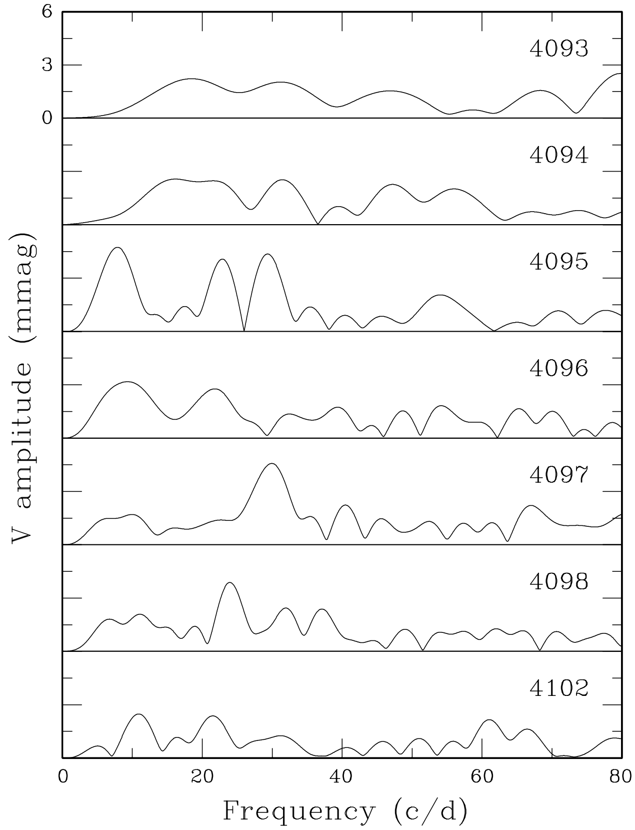

Figure 5. Amplitude spectra of the *V*-band data in Fig. 3.

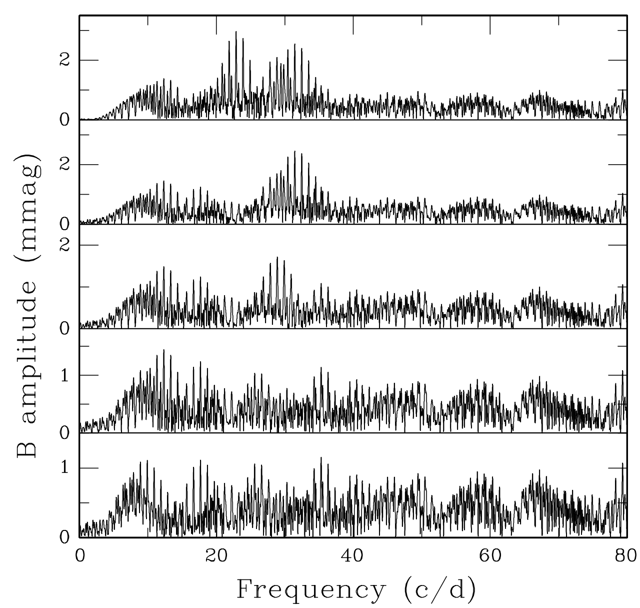

Figure 6. The amplitude spectrum of all the detrended SAAO *B*-band data is plotted in the top panel of the figure. The remaining panels show successive stages of pre-whitening of the data, that is, after subtraction of one, two and three best-fitting sinusoids.

the peaks near 23 d^{-1} on JD 245 4098. The variability in the peak amplitudes could, of course, be due to either (or both) interference between unresolved modes, or to intrinsic amplitude variability (due to redistribution of pulsation energy amongst different modes).

An amplitude spectrum of the combined SAAO *B*-filter data can be seen in the top panel of Fig. 6. The spectrum reaches a maximum at $f = 22.88 d^{-1}$. A sinusoid with this frequency was fitted to the data by linear least squares, and then subtracted from the data: the amplitude spectrum of the residuals is given in the second panel of Fig. 6. The results of three further stages of pre-whitening by best-fitting sinusoids are plotted in the figure. The amplitude spectrum of the final set of results left after removal of four sinusoidal components still shows several mounds of excess power, but it is not obvious that these are meaningful.

Results of the corresponding analysis of the *V*-band data are displayed in Fig. 7. There is good agreement between the two sets of results. Numerical values are given in the first four lines of Table 3 – for two of the four frequencies aliases have been identified. This is of course hardly surprising given that the observations are from a single site, and that the amplitudes are very low.

The spectra in the bottom panels of Figs 6 and 7 are compared in Fig. 8. Inspection of the diagram suggests that there may be matching features in the *V*-band data for peaks near 9, 18 and 35 d^{-1} in the *B*-band data. More detailed plots showed substantial frequency offsets between the *B* and *V* spectra in the frequency range 4–13 d^{-1}, but much better agreement near the two higher frequencies. Frequencies in which the spectra reach local maxima are listed in lines 5 and 6 of Table 3. There is excellent agreement for the lower of the two frequencies, but not for the frequencies near 35 d^{-1}. The formal s.e. for the difference between the *B* and *V* frequencies, expected on the

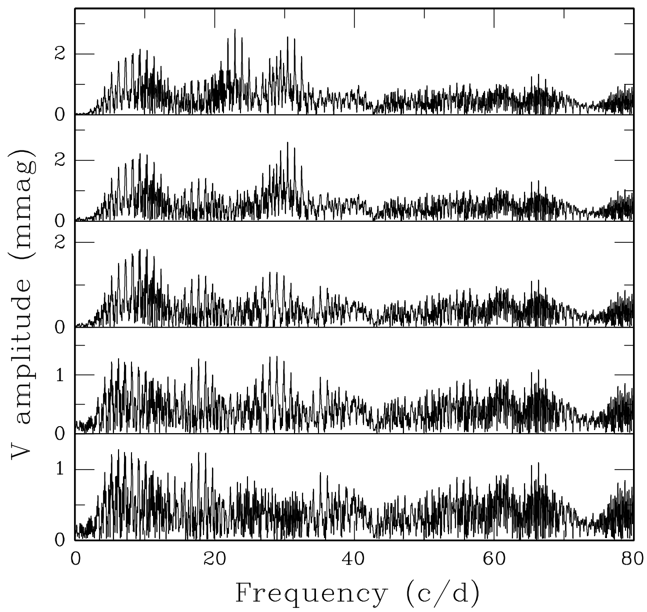

Figure 7. As for Fig. 6, but for the *V*-band data.

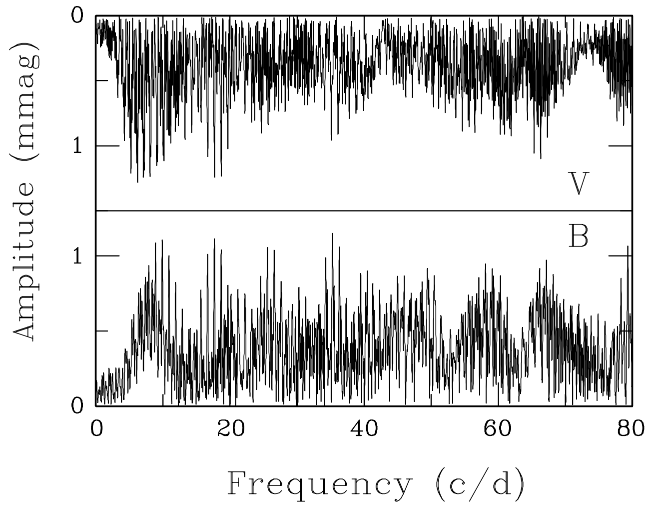

Figure 8. A comparison of the amplitude spectra in the bottom panels of Figs 6 and 7.

basis of the uncertainties given in Table 3, is 0.03 d^{-1}; the observed frequency difference of 35.30–35.23 = 0.17 d^{-1} is therefore more than 5 s.e. in size. The situation is complicated by the fact that the formal s.e. values are known to be underestimates for data such these – characterized by autocorrelation in the residuals – hence no definite conclusions can be drawn.

It may be seen from the above that there are five very likely periodicities in the light variations of KPD 0629–0016, with a possibility of a sixth. In order to improve on the parameter estimates in Table 3 sinusoids were fitted simultaneously to each of the two data sets. A non-linear least-squares method which optimizes the fit with respect to each frequency, amplitude and phase was used. In order for the the phases of sinusoids fitted to the *B*- and *V*-band data to be compared, the same aliases needed to be used for the two data sets: the frequencies extracted from the *B*-band data were used for this purpose. The results are given in Table 4 – these clearly differ very little from those in Table 3.

4 CLOSING REMARKS

(i) There is considerable low frequency (<15 d^{-1}) power left in the *V*-band residuals (see the bottom panel of Fig. 7). It is clear that at least two additional periodicities would be required to describe these variations. There is also non-negligible residual power at low frequencies in the *B*-band data (bottom panel of Fig. 6). It is conceivable that these slow brightness changes are due to variability intrinsic to KPD 0629–0016. A larger body of data, and more careful treatment of the data, will be required to establish this. Important relevant factors are differential atmospheric extinction effects; possible low level variability in comparison stars; and detrending of the data.

(ii) The uncertainty in the longer periods is further illustrated by the fact that the lowest frequencies identified from the *B*- and *V*-band data, respectively, are 3 d^{-1} aliases. (This assumes, of course, that the true frequencies are indeed the same – this does seem reasonable, given the close correspondence between their fractional parts.)

(iii) The frequencies and amplitudes found are unremarkable for a PG1716 star.

(iv) The ratios of the amplitudes measured in *B* to those measured in *V* conform, within the errors, to what is expected for modes with $\ell \leqslant 5$ (Randall et al. 2005). The same applies to the phase differences (see Table 4).

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Table 3. The results of the sequential fitting of sinusoids by least squares, followed by pre-whitening. Formal s.e. values are given in brackets. Determination of the first four lines of values is illustrated in Figs 6 and 7; the next two lines were obtained by targeting frequencies near 17 and 35 d^{-1}, as suggested by inspection of Fig. 8.

	B			*V*	
Frequency (d^{-1})	Period (min)	Amplitude (mmag)	Frequency (d^{-1})	Period (min)	Amplitude (mmag)
22.88 (0.011)	62.92 (0.030)	3.0 (0.4)	22.893 (0.008)	62.90 (0.023)	2.4 (0.3)
31.45 (0.011)	45.78 (0.017)	2.5 (0.3)	30.437 (0.009)	47.31 (0.013)	2.3 (0.3)
28.90 (0.017)	49.83 (0.029)	1.8 (0.3)	28.90 (0.014)	49.82 (0.024)	1.3 (0.3)
12.33 (0.020)	116.8 (0.19)	1.4 (0.3)	9.324 (0.0099)	154.4 (0.16)	1.9 (0.3)
17.68 (0.025)	81.4 (0.12)	1.1 (0.3)	17.70 (0.014)	81.34 (0.064)	1.2 (0.3)
35.30 (0.024)	40.79 (0.028)	1.2 (0.3)	35.13 (0.019)	40.99 (0.022)	0.9 (0.3)

Table 4. The results of the simultaneous fitting of sinusoids by non-linear least squares. Formal s.e. values of the frequencies and amplitudes are given in brackets.

B			*V*		
Frequency (d^{-1})	Amplitude (mmag)	Phase (rad)	Frequency (d^{-1})	Amplitude (mmag)	Phase (rad)
22.88 (0.009)	3.0 (0.3)	2.54 (0.22)	22.899 (0.007)	2.5 (0.3)	2.46 (0.26)
31.44 (0.010)	2.7 (0.3)	–0.27 (0.25)	31.425 (0.008)	2.0 (0.3)	0.075 (0.33)
28.89 (0.015)	1.8 (0.3)	–2.05 (0.37)	28.88 (0.013)	1.4 (0.3)	–1.72 (0.50)
12.33 (0.020)	1.3 (0.3)	–0.60 (0.47)	12.32 (0.013)	1.3 (0.3)	–0.048 (0.32)
17.68 (0.023)	1.1 (0.3)	2.49 (0.58)	17.70 (0.015)	1.2 (0.3)	2.11 (0.57)

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REFERENCES

Baran A., Pigulski A., Koziel D., Ogloza W., Silvotti R., Zola S., 2005, MNRAS, 360, 737
Downes R., 1986, ApJS, 61, 569
Fontaine G., Green E. M., Chayer P., Brassard P., Charpinet S., Randall S. K., 2006, Baltic Astron., 15, 211
Green E. M. et al., 2003, ApJ, 583, L31
Kilkenny D., Copley C., Zietsman E., Worters H., 2007, MNRAS, 375, 1325
Koen C., 2007, MNRAS, in press
Oreiro R., Ulla A., Pérez-Hernández F., Ulla A., Garrido R., Østensen R., McDonald J., 2005, A&A, 438, 257
Randall S., Fontaine G., Brassard P., Bergeron P., 2005, ApJS, 161, 456
Randall S. et al., 2006a, ApJ, 643, 1198
Randall S., Fontaine G., Green E. M., Brassard P., Terndrup D. M., 2006b, Baltic Astron., 15, 291
Randall S. et al., 2006c, ApJ, 645, 1464
Reed M. D. et al., 2004, ApJ, 607, 445
Schuh S., Huber J., Dreizler S., Heber U., O'Toole S. J., Green E. M., Fontaine G., 2006, A&A, 445, L31
Villeneuve B., Wesemael F., Fontaine G., 1995, ApJ, 450, 851
Wesemael F., Fontaine G., Bergeron P., Lamontagne R., Green R. F., 1992, AJ, 104, 203

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