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Discovery and asteroseismological analysis of a new pulsating DB white dwarf star, PG 2246+121

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ABSTRACT

We report 36.6 h of time-resolved CCD photometry of the DB white dwarf star PG 2246+121 and the discovery that it is a new pulsating variable. Analysis of our compact single-site data set allowed the detection of three mode multiplets, two triplets at 256 and 329 s, respectively, and one doublet at 286 s. The frequency splitting within those structures is exactly the same within the length and accuracy of our data set.

We argue that these multiplets are the result of non-radial g-mode pulsations, most probably of spherical degree $\ell = 1$, which then yields a formal stellar rotation period of 2.00 ± 0.12 d. We suggest that the excited modes are three consecutive radial overtones of order 3–7, most likely $k = 4, 5, 6$. This discovery's impact on the understanding of pulsating DB white dwarfs is discussed.

Key words: stars: individual: PG 2246+121 – stars: individual: ZZ Ceti – stars: oscillations – stars: variables: other.

1 INTRODUCTION

At first glance, the only technique that allows us to explore the deep interior structure of stars – asteroseismology – seems quite successful for the pulsating helium-atmosphere DB white dwarf (DBV) stars. The prototype DBV GD 358 is among the objects for which the most pulsation frequencies were detected (Winget et al. 1994; Vuille et al. 2000), which prompted detailed theoretical studies (Bradley & Winget 1994; Kawaler, Sekii & Gough 1999).

Understanding the DBV stars as a group is difficult. For a long time, all DBVs were believed to show large-amplitude ($A \approx 0.2$ mag) light variations on time-scales around 10 min, with the presence of many pulsation periods (the exception is PG 1351+489: Winget, Nather & Hill 1987).

This viewpoint has changed somewhat with the latest discovery, only the eighth DBV, EC 20058−5234 (Koen et al. 1995), which shows short periods (≈5 min) and low amplitudes (<0.05 mag). This is interesting as the coolest class of pulsating white dwarf, the hydrogen-atmosphere DAV stars, show a period–temperature relation (e.g. Bergeron et al. 1995) as expected from the changes of the star's interior structure as it cools through the instability trip. The same should be valid for the DBV stars; EC 20058−5234 may therefore not be an unusual example of its class.

In any case, an important step towards the understanding of the DBV stars as a class has been made by Beauchamp et al. (1999) who presented homogenous model-atmosphere analyses of a set of hot DB white dwarf stars, including all DBVs. Besides many other interesting results, they showed that EC 20058−5234 is most probably the hottest DBV and that in some temperature range all DB white dwarfs seem pulsationally unstable. The only exception would be the star PG 2246+121, which had however apparently never been tested for variability before. We took this as a motivation to perform this test and we indeed obtained a positive result.

In this paper we report the discovery of pulsations of PG 2246+121, dedicated follow-up observations and their analysis and interpretation.

2 OBSERVATIONS AND REDUCTIONS

We first observed PG 2246+121 with the University of Cape Town CCD camera (O'Donoghue 1995) on the 0.75-m telescope at the South African Astronomical Observatory's Sutherland station for approximately 1 h during two nights in 2000 April/May. The measurements were taken at the very end of the nights at high air mass and partly during morning twilight and are therefore not of outstanding quality. However, the amplitude spectra of both runs showed good evidence for short-term variability (Fig. 1).

Consequently, we re-observed the star during one week in 2000 October, with the same instrument, but on the 1.0-m telescope. We obtained data on six nights. During these observations, the CCD was operated in frame-transfer mode, which allows continuous integrations on the field of choice; integration times of 10 s were used (the discovery observations were taken as 20-s integrations in full-frame mode with a readout time of 3 s).

In 2000 October, PG 2246+121 was observed together with four comparison stars in the same CCD field; in April/May we could use six comparison stars because of the larger field of view.

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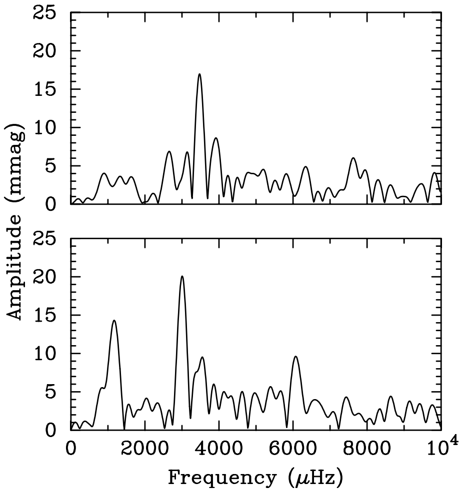

Figure 1. Amplitude spectra of the discovery observations of PG 2246+121; pulsational signals around 3000–4000 μHz are strongly suspected.

Table 1. Time-series photometry of PG 2246+121.

Telescope	Date (UT)	Start (UT)	Run length (h)
0.75-m	2000 Apr 30	03:00:38	1.22
0.75-m	2000 May 1	03:05:44	1.16
1.0-m	2000 Oct 3	18:03:19	6.45
1.0-m	2000 Oct 4	17:39:39	6.78
1.0-m	2000 Oct 5	17:28:26	7.00
1.0-m	2000 Oct 6	20:34:42	2.93
1.0-m	2000 Oct 8	17:33:38	6.61
1.0-m	2000 Oct 9	18:16:14	4.46
Total			36.61

No filter was employed. In every clear night, sky flat-fields were taken during twilight. Because of the efficient operation of the instrument, this resulted in more than 100 flat-fields per clear night. A detailed overview of our observations is presented in Table 1.

Data reduction was started with correction for bias and flat-field; a mean flat-field was used for each night separately. If no flats could be obtained in a given night, the correction was performed with the combined flat closest in time. Photometric measurements on these reduced frames were made with the program MOMF (Kjeldsen & Frandsen 1992). MOMF firstly performs iterative point-spread function fitting (PSF) photometry (determination of initial empirical PSF, initial sky determination, then improving the PSF and sky background measurement). A good determination of sky background is important for stars as faint as PG 2246+121 ($y = 16.73$, Wegner 1983) in particular, as we had a considerable contribution from moonlight on the last two nights; we used a fully local sky determination. The PSF photometry is followed by an aperture correction on the star-subtracted frames. The aperture sizes scale with the full width at half-maximum (FWHM) of the stellar images and the aperture yielding the lowest point-to-point scatter for the variable star measurements was chosen. The relative photometry is calculated with respect to a user-defined ensemble of comparison stars, the contributions of which are weighted with the inverse rms scatter of their measurements. In this way, very precise differential photometry can be obtained. All comparison stars proved to be constant within the accuracy of our data set.

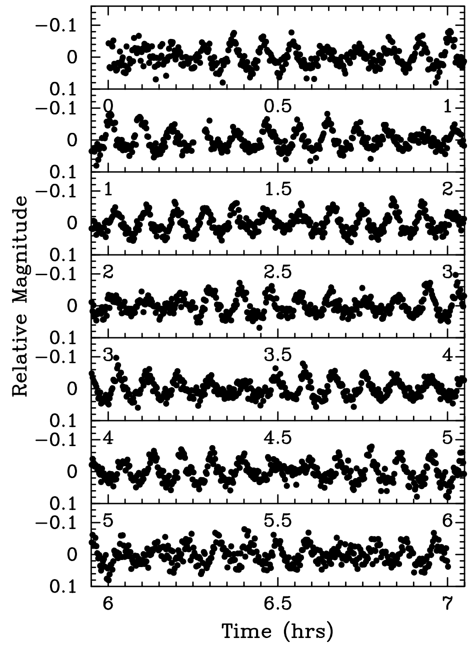

Figure 2. The reduced light curve of PG 2246+121 from the measurements obtained on 2000 October 5. Several features can be discerned: a typical light curve shape of a pulsating white dwarf (sharp peaks, flat bottom), some amplitude modulation resulting from beating and varying data quality caused by the effects of air mass and twilight.

We tested the resulting time series of PG 2246+121 for correlations with some observational parameters, such as air mass, seeing and (x, y) position of the star on the chip. We found a strong linear trend with air mass (differential extinction – the variable is much bluer than its comparison stars) and some correlation with x position (residual flat-field errors – the flat-fields showed some roughly vertical ‘ridges’), but no correlation with seeing or y position. The data were hence detrended with air mass and x position.

As the last two steps, residual low-frequency trends in the data were removed by means of low-order polynomials, and the times of measurement were transformed to a homogeneous time base. We chose Terrestrial Time (TT) as our reference for measurements on the Earth’s surface and applied a correction to account for the Earth’s motion around the barycentre of the Solar system. As this barycentric correction varied by about −1 s throughout the duration of a typical run, we applied it point by point. Our final time base therefore is Barycentric Julian Ephemeris Date (BJED). The final time series was subjected to frequency analysis; we show an example light curve in Fig. 2.

3 FREQUENCY ANALYSIS

Our frequency analysis was performed with the program PERIOD98 (Sperl 1998), which applies single-frequency Fourier analysis and simultaneous multifrequency sine-wave fitting. PERIOD98 can be used to calculate optimal solutions for multiperiodic signals including harmonic, combination, and equally spaced frequencies, which are often found in the analysis of the light curves of pulsating white dwarf stars; the program is therefore ideal for our analysis. We will focus on our data set from 2000 October in what

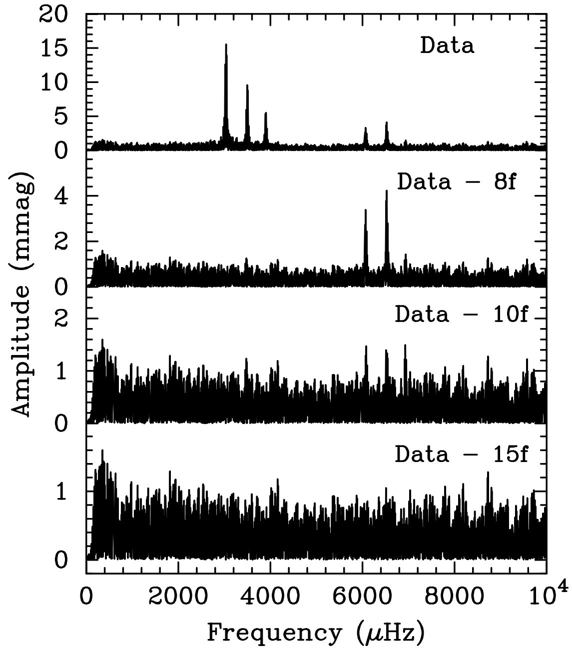

Figure 3. Results of consecutive prewhitening in our data for PG 2246+121. Uppermost panel: amplitude spectrum of the 2000 October data. Second panel: residuals after prewhitening of the features dealt with in Fig. 4. Third panel: residuals after prewhitening of these signals as well as their two strongest frequency combinations. Fourth panel: residuals after including all detected and suspected signals.

follows; the measurements from 2000 April are too few to be of much astrophysical interest. We merely comment here that they are consistent with the results reported below.

We started by calculating nightly amplitude spectra of our data. The amplitude spectra of the individual nights are different in appearance: the dominating peaks seem to occur at the same frequencies, but their amplitudes vary. The question naturally arises whether this is due to beating of multiple modes or caused by some other phenomenon; we will examine it in what follows.

We combined all our runs and calculated amplitude spectra for the resulting data set. The full amplitude spectrum is displayed in the upper panel of Fig. 3. One can discern three strong features between 3000 and 4000 μHz, and it appears that frequency combinations are present as well. We now concentrate on these three strongest structures.

In Fig. 4, we show consecutive prewhitening steps within these features by simultaneous optimization of the frequencies, amplitudes and phases of all the detected signals. In two cases we could remove three signals from the structures; in one case we found it to be composed of two frequencies and their alias patterns. We simply adopted the highest peak in each panel as the next frequency to be included; we marked these frequencies with arrows for clarity. In the second-to-lowest middle panel we marked another peak with an arrow and a question mark; we will return to it later.

In the lowest panel of Fig. 4, a schematic amplitude spectrum composed of the detected signals is shown. Two structures seem to be equally spaced triplets and the third one is a close doublet. The frequency spacings of the closely spaced consecutive peaks are the same within the errors.

We took this result as a motivation to test whether this spacing is indeed the same within the three mode groups. Consequently,

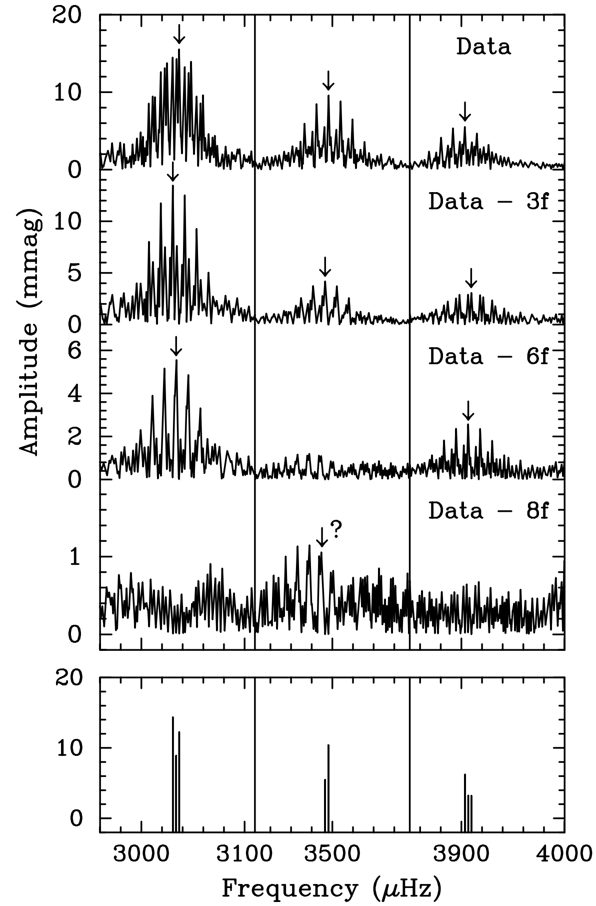

Figure 4. Amplitude spectra of our PG 2246+121 data in the vicinity of the dominating features (upper four panels). The lowest panel shows the detected frequencies with the corresponding amplitudes schematically.

we fixed it within PERIOD98, but allowed it to be optimized together with its parent frequencies, i.e. we fitted a function

$$f(t) = \sum_{k=-1}^{1} a_k \sin[2\pi(f_A + k\nu_{\rm sp})t + \phi_k] + \sum_{k=0}^{1} b_k \sin[2\pi(f_B + k\nu_{\rm sp})t + \psi_k] + \sum_{k=-1}^{1} c_k \sin[2\pi(f_C + k\nu_{\rm sp})t + \xi_k]$$

to the data, where the a_k, b_k, c_k are the amplitudes of the multiplet components, f_A, f_B, and f_C denote the frequencies of the central components, ϕ_k, ψ_k and ξ_k are the phases of the individual signals, t is time and $\nu_{\rm sp}$ is the splitting frequency.

Tests (checking for residual peaks in the amplitude spectrum after prewhitening the fixed solution, applying the Bayes Information Criterion) showed that our data are perfectly consistent with the hypothesis that this splitting frequency is the same for all its parent signals, which are themselves constant in frequency, amplitude and phase within the length and accuracy of our data set. We therefore adopt this fixed-frequency solution for the rest of this paper.

We then searched for further frequencies in the residual amplitude spectrum after removing the eight signals detected so

far from the data (second panel of Fig. 3). Two peaks clearly stand out, and they can be easily identified with sums of some of the eight original frequencies. Prewhitening these 10 signals from the light curve (by fixing the combination frequencies to the exact sum of those of their parents), some further peaks are discernible (third panel of Fig. 3). Many of them are consistent with 1 cycle d^1 aliases of combinations of the previously detected frequencies. One relatively high residual peak near 3500 μHz (the one labelled with a question mark in Fig. 4) would actually complete the doublet in this domain to a third equally spaced triplet. However, the application of Breger et al.'s (1993) amplitude signal-to-noise ratio criterion (requiring that the detection of an independent signal is secure if its amplitude exceeds four times the noise value in its frequency domain; signals the frequency of which can be predicted require $S/N > 3.5$) argues against a detection of this signal.

However, for some of the combination frequencies more than one identification is possible. These are frequency sums of different multiplets that are 'degenerate' because of the constant splitting within them; we adopted the one that has the simplest combination of parent modes. We therefore caution that some identifications in Table 2 may be incorrect.

In any case, we finally arrived at a 15-frequency solution. Prewhitening it from our data, only noise seems left behind (fourth panel of Fig. 3). The noise is however somewhat dependent on frequency. We compared our observational noise level with that expected from random noise with the same distribution as ours. We created several data sets consisting of our residual magnitudes shuffled in time and calculated the amplitude spectrum of those. We found that the level of random noise is only reached for frequencies larger than ≈5000 μHz; for frequencies lower than this the observational noise is enhanced.

Table 2. The multifrequency solution for our observations of PG 2246 + 121. Individual error estimates are quoted for the independent frequencies; those of the periods are then easy to infer. The amplitude uncertainty is ±0.3 mmag for all signals.

ID	Frequency (μHz)	Ampl. (mmag)	Period (s)	S/N
Directly detected signals				
$f_A - \nu_{sp}$	3030.57 ± 0.02	14.4	329.971	37.4
f_A	3033.65 ± 0.04	8.9	329.636	23.3
$f_A + \nu_{sp}$	3036.73 ± 0.03	12.3	329.302	32.5
f_B	3493.05 ± 0.06	5.1	286.283	13.8
$f_B + \nu_{sp}$	3496.13 ± 0.03	10.5	286.031	28.3
$f_C - \nu_{sp}$	3903.53 ± 0.05	6.1	256.179	20.3
f_C	3906.60 ± 0.10	3.1	255.977	10.3
$f_C + \nu_{sp}$	3909.68 ± 0.10	3.1	255.775	10.5
$2f_A$	6067.30	3.4		7.7
$f_A + f_B$	6526.70	4.2		10.2
Indirectly detected signals				
$f_A + f_C$	6940.25	1.5		4.7
$2f_A + f_B + \nu_{sp}$	9563.43	1.2		3.9
Suspected signals				
$f_B - \nu_{sp}$	3489.97 ± 0.27	1.1	286.535	3.0
$2f_A + \nu_{sp}$	6070.38	1.4		3.1
$f_A + f_B + 2\nu_{sp}$	6532.85	1.3		3.2
Splitting frequency				
ν_{sp}	3.078 ± 0.012			

Finally, we determined the error estimates for our multi-frequency solution. We adopted them by applying the formulae of Montgomery & O'Donoghue (1999). However, we caution that such formal error bars are almost always underestimates, but we believe that the values we quote are reliable within about 50 per cent. Our complete multifrequency solution is summarized in Table 2; the error estimate for the splitting frequency is the error of the mean of all the splittings within the three 'parent' modes, if their frequencies were left as free parameters.

4 ASTROPHYSICAL IMPLICATIONS

It is clear that the light variations of PG 2246+121 are due to stellar pulsation: their complexity leaves no room for alternative hypotheses, and the frequency distribution shows the typical behaviour of a non-radially pulsating star. The lengths of the periods also indicate non-radial gravity (g) mode pulsations, and we identify the eight frequencies between 3000 and 4000 μHz as resulting from independent pulsation modes.

These eight signals consist of two equally split frequency triplets and one doublet with the same splitting. We think that they are due to pulsation modes of spherical degree $\ell = 1$. Modes of $\ell > 2$ would suffer from a large amount of geometrical cancellation because of averaging over the visible disc of the star (Dziembowski 1977), and should therefore not be seen in photometric data of distant stars. The only remaining possibilities for the spherical degrees of the modes are therefore $\ell = 1$ or $\ell = 2$ or a mixture of these.

However, the exact equal spacing of the triplets and the doublet rules out that we see a mixture of $\ell = 1$ and $\ell = 2$: asymptotic theory predicts, and observations confirm (Winget et al. 1991), that frequency splittings resulting from rotation are different for such modes; they have a ratio $R_{1,2} = 0.6$. The resolution and precision of our data is sufficient to detect such discrepancies reliably, but there is not even a trace of them. The modes must therefore be either $\ell = 1$ or $\ell = 2$.

We think that the $\ell = 2$ interpretation is unlikely. Aside from the fact that $\ell = 2$ modes are rarely seen in pulsating white dwarfs (e.g. Winget et al. 1991; Robinson et al. 1995; Fontaine et al. 1996; Clemens, van Kerkwijk & Wu 2000; Kepler et al. 2000), it would require some mode selection mechanism or serendipity that $\ell = 2$ modes produced the observed consistent frequency pattern, whereas an explanation with $\ell = 1$ modes is quite natural.

Under this assumption one can infer a formal rotational time-scale of the star from the multiplet splitting. The result is 2.00 ± 0.12 d (the error estimate is caused by the unknown first-order rotational splitting coefficient $C_{k\ell}$, see Brassard et al. 1992b), which is quite typical for pulsating white dwarfs with an asteroseismologically determined rotation period. This result must however still be taken with some caution because of the unknown rotation curve in the stellar interior (Kawaler et al. 1999).

In principle, the pulsation periods of pulsating white dwarfs should allow an identification of the radial overtone number and an estimate of the stellar mass. This is, however, problematic for PG 2246+121, as it only has three radial overtones excited, because pulsation modes of DBV and DAV stars predominantly sample their outer regions, and because white dwarf models show severe mode trapping, which affects the mode eigenfrequencies (see Brassard et al. 1992a for extensive results and Bradley, Winget & Wood 1993 for some examples of DBV models). This means that we cannot put tight constraints on the radial overtone

and stellar mass. We only note that the period spacing of the three multiplets is consistent with that of $\ell = 1$ model frequencies of three consecutive radial overtones between $k = 3$ and 7 (Bradley et al. 1993), most likely $k = 4, 5, 6$.

Concerning the impact of this discovery on the understanding of DBV pulsations in general, we first note that PG 2246+121 fills a 'gap' in its instability strip (Beauchamp et al. 1999), in the sense that in a certain temperature range (the theoretical boundaries of which depend on the composition of the model atmospheres) it now seems that all DB stars are pulsationally unstable.

After EC 20058−5234, PG 2246+121 is the DBV pulsator with the shortest dominating pulsation periods and it has a rather low amplitude, which implies that EC 20058−5234 is probably not an exception among the DBV stars. We also note that the pulsation periods of the three excited multiplets are very close to those of prominent modes of EC 20058−5234 (257, 281 and 333 s, Koen et al. 1995). These authors also raised the question of whether there exists a period–amplitude relation such as for the DAV stars (Clemens 1994), and found no clear trend. Adding PG 2246+121 to the ensemble does not change this picture.

It is also conceivable that the DBV stars show very similar pulsational behaviour as a group, like the DAVs. The similarities of the periods of PG 2246+121 to some of those of EC 20058−5234 can be taken as a first clue. The origin of the DB white dwarfs, and thus DBVs, is however a matter of debate. One scenario assumes that different evolutionary 'channels' exist (e.g. see Nitta & Winget 1998) for single and binary star evolution. In that case one would expect a mixed set of DBVs coming from both 'channels'. On the contrary, spectroscopically determined mass distributions (Beauchamp et al. 1996) suggest that the DB white dwarf stars are quite homogenous. Asteroseismological investigations will be able to address this problem from a different viewpoint.

Regrettably, many DBVs are still poorly observed, which is an obstacle to the studies mentioned above. We have therefore started a systematic investigation securing time-resolved CCD photometry of these stars in the hope of answering at least some of these open questions.

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