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PG 0014+067: WET OBSERVATIONS AND A NEW TWIST TO THE SDB STAR PUZZLE

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Abstract. In the Whole Earth Telescope (WET) observations of the sdBV PG 0014+067, made in 2004 October, we found a peculiar regularity of the pulsation frequencies reminiscent of asymptotic $p-$mode pulsation along with rotational splitting. This finding was amplified by adding additional modes found by observations with the WHT earlier in the year. To determine if this was a peculiarity of that star, we examined other sdBV stars that have extended-longitude coverage, and found a similar pattern in all of them. High-order $p-$mode pulsations (such as seen in the Sun and roAp stars) should not be present if our models of these stars and their pulsations are any guide to reality. The reasons behind this pattern are currently unknown.

Key words: stars: oscillations – stars: evolution – subdwarfs

1. INTRODUCTION

The pulsation frequencies seen in pulsating subdwarf (sdBV) stars show frequencies that are of the same order as the radial fundamental frequency. However, these stars generally show multiperiodic pulsation, with many modes seen within a relatively narrow frequency range. Correctly identifying the reason for this rich mode spectrum should reveal some fundamental features of the stars themselves. The leading candidate explanation is that we are seeing nonradial modes with degree ℓ ranging from 0 to 3 or 4; Brassard et al. (2001) demonstrate this for the star PG 0014+067 (hereafter PG 0014), while Kilkenny et al. (2002) follow a similar prescription for PG 1047+003. An alternate explanation is that we are seeing rotational splits of $\ell = 0$–2 modes in stars with rapidly rotating cores, which in turn are a consequence of differential rotation that develops on the red giant branch (Kawaler & Hostler 2005).

PG 0014, as one of the richest pulsators among the short period sdBV stars (i.e., the EC 14026 stars) is an excellent candidate to try to distinguish between these two possibilities. While Brassard et al. (2001) did demonstrate that this star is a rich pulsator, the data they used were single-site data and therefore could suffer from 1 c/d aliases. We observed PG 0014 in a massive multi-longitude run with the Whole Earth Telescope in 2004 October. The results of that run, combined with data from the William Herschel Telescope taken two months earlier (Jeffery et al. 2005) allow us to present a detailed frequency list with assurance that all are real periodicities and no daily aliases are present.

What we found is that, while the frequencies might be describable in terms of

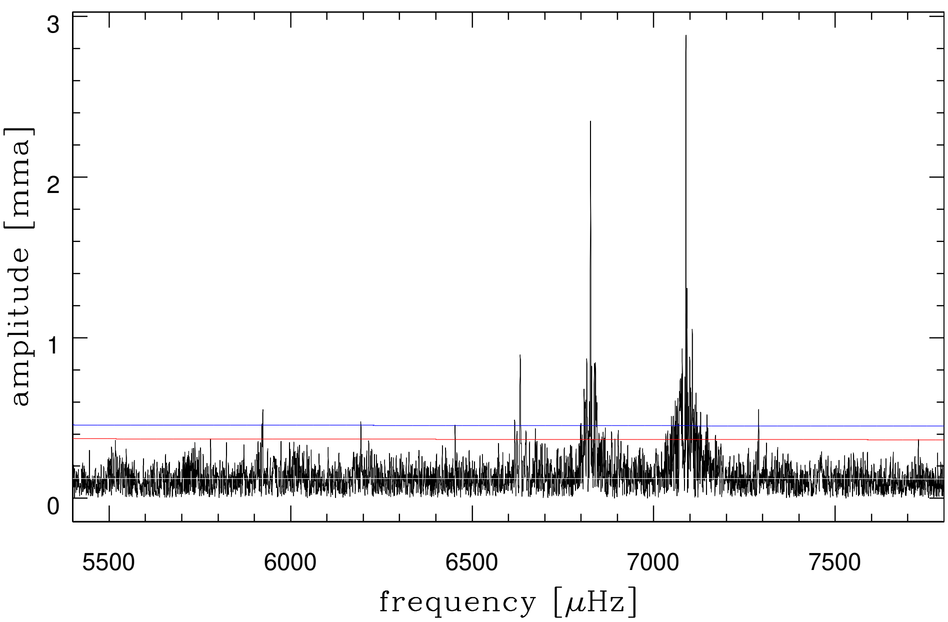

Fig. 1. Fourier transform of the WET data on PG 0014; the horizontal lines show noise levels of $3\,\sigma$ (lower) and $3.7\,\sigma$ (upper).

higher-than-usual values of ℓ or rapid internal rotation, they show a pattern that looks more like asymptotic $p-$mode pulsation. A similar pattern has been found in the other well-studied pulsating sdBV stars. Unfortunately, the models demand that these stars are displaying low-order $p-$mode pulsations, which show no such asymptotic patterns.

2. PG 0014 FREQUENCIES FROM WET AND ULTRACAM/WHT

The results of the WET run on PG 0014 will appear elsewhere (Vučković et al. 2005). We show the amplitude spectrum of the main region of interest in the WET data in Figure 1; the signal-to-noise level is sufficient to reveal peaks with amplitudes above about 0.45 mma. For possible lower-amplitude modes, we include in our analysis the frequencies found by Jefferey et al. (2005) in multicolor photometry of PG 0014 using Ultracam on the WHT; the merged frequency list is shown in Table 1. In creating this list, we used the WET data as the primary source, and added lower-frequency modes identified by Jeffery et al. (2005). Even though the Jeffery et al. (2005) data are mostly single-site, we are confident in their frequency identifications. This confidence comes from their identification of all modes that they have in common with the WET data, without a single instance of selection of a 1 c/d alias in their analysis. In Table 1, the Ultracam peaks are indicated in the Notes column, with the symbol (w) indicating that the mode was seen only in the combined Ultracam data (all colors).

The frequency list of PG 0014 displays some suggestive systematics; concentrating on the second column of Table 1 we see several modes with separations of approximately integral multiples of 90 μHz. Other separations of nearly 100 μHz

Table 1. Frequencies present in PG 0014 and a "model".

#	Freq. [μHz]	Amp. [mma]	Note	i	j	Model	Difference
2	5923.4	0.54	fine structure	0	0	5923.2	0.2
3	6193.5	0.44		3	0	5194.1	–0.6
4	6452.9	0.45		7	–1	6454.1	–1.2
5	6632.8	0.65	fine structure	9	–1	6634.6	–1.8
6	6646.5	0.60	UltraCam	8	0	6645.6	0.9
7	6659.9	0.34	UltraCam (w)	7	1	6656.5	–3.4
8	6726.8	0.37	UltraCam (w)	10	–1	6724.9	1.9
9	6826.1	2.38		10	0	6826.1	0.0
10	7088.7	2.98	fine structure	14	–1	7086.1	2.6
11	7187.5	0.66	UltraCam	14	0	7187.3	0.2
12	7289.0	0.65		14	1	7288.5	0.5

are apparent as well. Our initial inclination was to try to identify the 100 μHz splitting as a rotational splitting. While this large splitting could be caused by rotation, the implied rotation rate (if solid-body rotation) would be much larger than upper limits based on spectroscopic study of line profiles. On the other hand Kawaler & Hostler (2005) suggest that rapid internal rotation could produce large splits in a star with a slow surface rotation rate, but their predictions suggest that the splits of different modes should not show the same value.

3. A PHENOMENOLOGICAL MODEL

With two apparent splits present, we decided to explore an entirely phenomenological parametrization that could then be used to make an empirical fit to the observed frequencies. We chose a form reminiscent of asymptotic $p-$mode pulsation with a constant rotation frequency:

$$f(i,j) = f_o + i \times \delta + j \times \Delta, \tag{1}$$

where δ represents a small spacing (and i can range from 0 upwards) and Δ represents a large spacing (with j initially limited to being either –1, 0 or 1). In the equation above, f_o represents a zero-point for the fit with $i = j = 0$.

In the general case of fitting a set of frequencies, we perform a two-dimensional χ^2 minimization to find best-fit values for δ and Δ. Clearly, there is an aliasing problem when the combinations of i, j, δ and Δ produce commensurate spacings, so the χ^2 surface shows multiple minima. We break that degeneracy (when possible) by choosing the (δ, Δ) pair for which we have at least two modes with the same value of i but different j. In practice, we make the further requirement that the fit must include at least two different pairs of modes (i.e., modes with the same value of i) that show the same Δ; i.e., the fit must contain modes with (i_1, j_1), (i_1, j_2), (i_2, j_3) and (i_2, j_4). In a subsequent paper, we will show that enforcing these additional conditions on the fit criteria restrict the aliasing problem and greatly statistical significance of the fit.

For PG 0014 this procedure yields values of δ = 90.37, Δ = 101.22 and f_o = 5923.24 (all in μHz). Using these values in Equation 1, we find the model frequencies listed in Table 1. Note that the fit is extremely good – the 11 modes

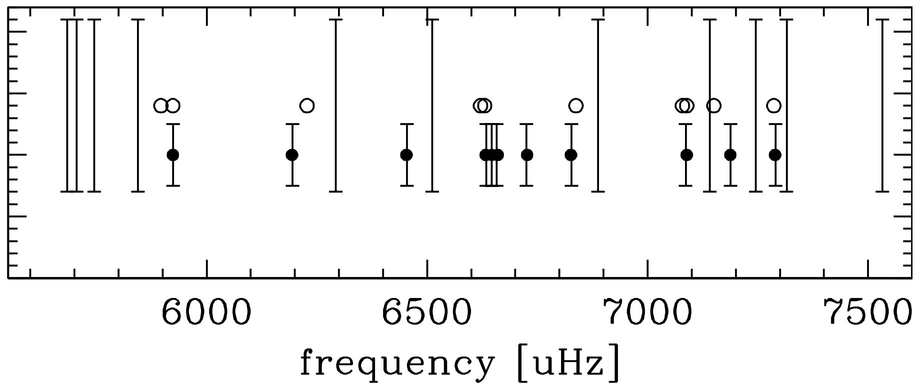

Fig. 2. Schematic diagram of the frequencies of PG 0014. The open circles are the frequencies in Brassard et al. (2001) and the long vertical lines are the frequencies of their best-fit stellar model. Closed circles represent the frequencies from the WET+UltraCam data (Table 1) and short lines give the fit to those frequencies using Equation (1) and the derived values for δ and Δ.

identified in the table are all fit to within 0.05 %, with an RMS difference of 0.013 δ. Figure 2 displays the closeness of the fit in comparison with the data, and with the fit frequencies from Brassard et al. (2001).

To estimate the statistical significance of this fit, we performed sets of 1000 trials with randomly chosen frequencies that span the same frequency interval. In each set of trials, the best fit (as judged by the RMS difference between the best model and the random frequency set) was tabulated. This procedure helped us determine the statistical significance of the star's fit by the model. In the case of PG 0014, the star departs from a random frequency distribution at the $4\,\sigma$ level.

Is this asymptotic pulsation? After all, high-order p-modes show a more-or-less constant frequency spacing; such sequences are seen in helioseismical data and in the rapidly oscillating Ap stars (see Kurtz et al. 2005).

The sequence of modes split by integral multiples of δ cannot be asymptotic $p-$mode behavior. Models of PG 0014, and sdBV pulsators in general, indicate that the radial fundamental frequency in the models is usually close (in frequency) to the observed mode frequencies. Asymptotic relations, such as Equation (1), are usually valid (at the few-percent level) only for values of $n \gg \ell$, or more generally for large values of n. Even so, the computed frequency separation for $p-$modes in sdBV models yields values of several hundred μHz – a factor of 10 or more larger than what PG 0014 shows.

4. IS PG 0014 A FREAK? NO...

To see if PG 0014 is just a strange star, we examined published frequency lists for other sdBV stars that are known to be rich pulsators and which have extended longitude coverage that ensures correct separation of true frequencies from diurnal aliases.

Table 3 shows that nearly all sdBV stars with extended-longitude coverage show similar splits across their temporal spectra. As an example, in Table 2 we show the frequency list for PG 1336-018 (from Kilkenny et al. 2003) along with the best-fit model using values of δ and Δ derived from the observed frequencies

Table 2. Frequencies present in PG 1336-018 and a "model".

#	Freq. [μHz]	Note	i	j	Model	Difference
1	4885.1		0	0	4886.7	1.5
2	5219.0		13	–1	5218.7	–0.3
7	5444.3		13	1	5447.6	3.3
3	5356.5		17	–1	5356.0,	–0.4
8	5470.9		17	0	5470.5	–0.4
11	5585.7		17	1	5585.0	–0.7
4	5369.4	no fit	–	–	–	–
12	5598.5	no fit	–	–	–	–
5	5392.2		18	–1	5390.4	–1.8
9	5505.6		18	0	5504.8	–0.8
13	5621.2		18	1	5619.3	–1.7
6	5435.4	doublet	16	0	5436.2	0.7
10	5516.7		15	1	5516.3	–0.5
14	5757.3	doublet	22	1	5756.7	–0.6
15	5891.5		26	1	5894.1	2.6
16	5916.3		30	0	5917.0	0.7

alone. We note that the value of Δ is precisely equal to the orbital frequency of this close binary, which is also (presumably) the rotation frequency of both stars if the system is tidally locked.

Another way to show the regularity to these patterns is through an echelle diagram (similar to those used in helioseismology and seismological observations of solar-type stars). Figure 3 shows such diagrams for PG 0014 and PG 1336-019.

5. AND SO, A MYSTERY

We stress that what we have done is to make a purely empirical fit to the observed frequencies – this is, essentially, simple numerology with NO known physics involved. While we have no explanation at all for why this works, there are several points that may be important.

Feige 48 has the lowest gravity of the bunch; the five frequencies from Reed et al. (2004) show a small splitting that is the smallest of the ensemble, but show no evidence of a second large spacing (Δ). Aside from PG 0014, there appears to be some correlation between $\log g$ and δ. Two stars show spectra that are completely

Table 3. Splittings found in pulsating sdBV stars.

Star	$\log g$	f_o [μHz]	δ [μHz]	Δ [μHz]	Significance
PG 0014	5.8	5923	90.4	101.2	4.0 σ
PG 1219	5.85	5812	60.5	–	3.7 σ
PG 8783	>5.6	7193	58.1	138.9	3.9 σ
PG 1047	5.9	6310	55.9	186.5	4.2 σ
PG 1336	5.7	4886	34.4	114.5	6.0 σ
Feige 48	5.5	2642	13.9	–	–

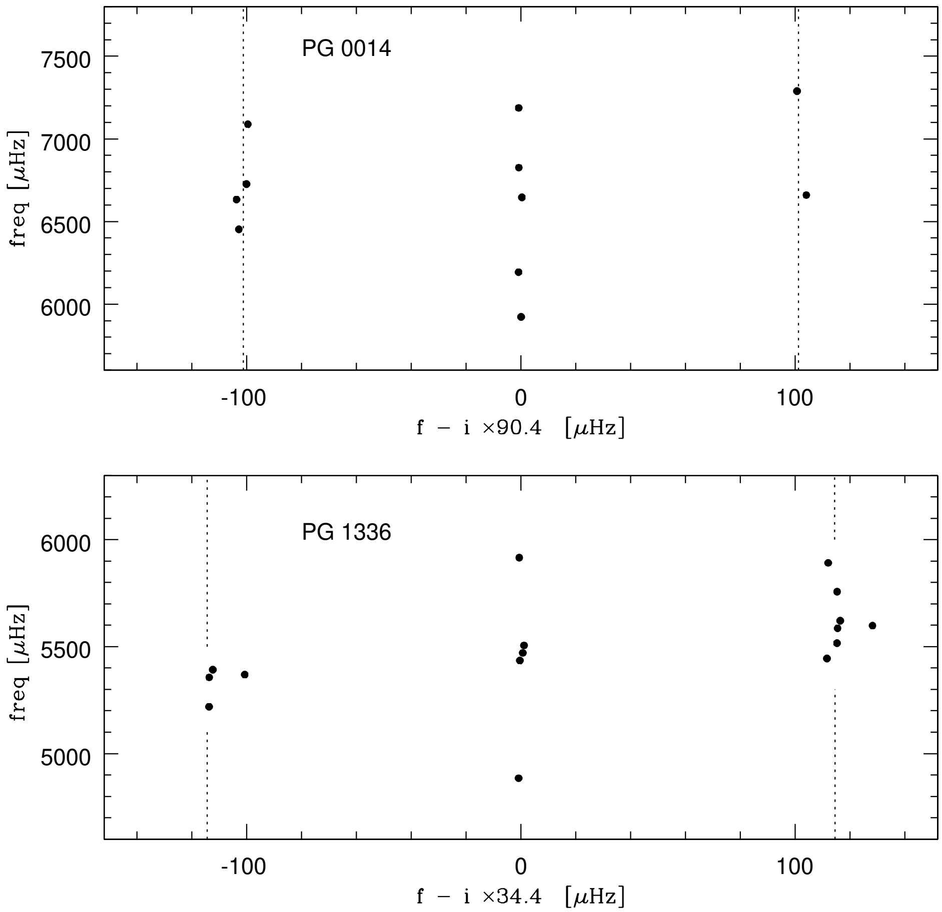

Fig. 3. "Echelle" diagrams of the frequencies in PG 0014 (top) and PG 1336 (bottom); the frequencies have been folded on the small spacing δ and stacked, showing the uniformity of the frequency spacings within the main band and the two side bands separated from the main band by the large spacing Δ.

described without the need of a large spacing. And, PG 1336 is a member of a close binary. The large spacing we identify is precisely equal to the orbital frequency. If we can assume that the stars in this system are tidally locked and therefore in synchronous rotation, then in this system at least the large spacing Δ can be identified with the stellar rotation rate. Reed (private communication) points out that the two modes, for which the spacing model fails, are those that display a pulsation geometry aligned not with the orbital plane, but pointing from the primary to the secondary.

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