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Multiyear and multisite photometric campaigns on the bright high-amplitude pulsating subdwarf B star EC 01541–1409

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ABSTRACT

We present follow-up observations of the pulsating subdwarf B (sdB) star EC 01541–1409 as part of our efforts to resolve pulsation spectra for use in asteroseismological analyses. This paper reports on data obtained from a single-site campaign, during 2008, and a multisite campaign, during 2009. From limited 2008 data, we were able to clearly resolve and pre-whiten 24 periods. A subsequent multisite campaign spanning nearly 2 months found over 30 individual periodicities most of which were unstable in amplitude and/or phase. Pulsation amplitudes were found to the detection limit, meaning that further observations would likely reveal more periodicities.

EC 01541–1409 reveals itself to be one of two sdB pulsators with many pulsation frequencies covering a large frequency range. Unlike the other star of this type (PG 0048+091), it has one high-amplitude periodicity which appears phase stable, making EC 01541–1409 an excellent candidate for exoplanet studies via pulsation phases. No multiplets were detected leaving EC 01541–1409 as yet another rich p-mode sdB pulsator without these features, limiting observational constraints on pulsation modes.

Key words: stars: individual: EC 01541–1409 – stars: oscillations – subdwarfs – stars: variables: general.

1 INTRODUCTION

Subdwarf B (sdB) stars are horizontal branch stars with masses $\approx 0.5\,M_\odot$, thin ($<10^{-2}\,M_\odot$) hydrogen shells, and temperatures from 22 000 to 40 000 K (for a review see Heber 2009). There are two known types of pulsating sdB stars (for a review, see Østensen 2010): short period (90–600 s) and long period (45 min to 2 h). This work concentrates on the short-period pulsators, which are designated as V361 Hya variables, but often referred to as sdBV stars, which we will do. They typically have pulsation amplitudes near 1 per cent, and detailed studies reveal a few to dozens of frequencies. The longer period pulsators are designated as V1093 Her variables and typically have amplitudes less than 0.1 per cent. They are also cooler than the V361 Hya type pulsators, though there is some overlap, and they are most likely g-mode pulsators.

Asteroseismology of pulsating sdB stars can potentially probe the interior structure and provide estimates of total mass, shell mass, luminosity, helium fusion cross-sections, and coefficients for radiative levitation and gravitational diffusion. To apply the tools of asteroseismology, however, it is necessary to resolve the pulsation frequencies and associate pulsation modes with periodicities. Recent

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observations from the *Kepler* spacecraft have allowed mode identification for the g-mode pulsators via period spacings and shown them to be low-degree ($\ell = 1$ and 2) pulsators (Reed et al. 2011a). However, only one p-mode pulsator is being observed by *Kepler* which means that ground-based observations will remain the main tool for their study in the foreseeable future. Typical observations use extensive photometric campaigns, preferably at several sites spaced in longitude to reduce day/night aliasing.

We have been engaged in a long-term programme to resolve poorly studied sdB pulsators, principally from single-site data, but using multisite campaigns as often as possible. This method has proved useful for several sdBV stars (Reed et al. 2004, 2006, 2007a,b, 2009, 2011a; Zhou et al. 2006). Here, we report the results of our observations of EC 01541–1409 (hereafter EC 01541), a bright, high-amplitude sdBV star. EC 01541 ($B = 12.1$) was discovered to be a member of the V361 Hya class by Kilkenny et al. (2009). Their observations covered five nights with the longest duration being 3.7 h. They also obtained a low-dispersion spectrum from which, using He I lines, they roughly estimated an effective temperature 'significantly hotter' than PG 1219+534, and Østensen et al. (2010a) obtained $T_{\rm eff} = 33\,500$ K and $\log g = 5.71$. There are no indications that EC 01541 is a binary from the spectroscopic observations.

2 OBSERVATIONS

Data were obtained from six different observatories, each with a somewhat different CCD setup. South African Astronomical Observatory's (SAAO's) 1.0-m telescope observed during both 2008 and 2009. These observations were made using the University of Cape Town CCD which is a Wright Instruments system utilizing a thinned, back-illuminated EEV P86321/T chip. It was used in frame-transfer mode so that there is essentially a continuous sequence of observations with no 'dead' time. Observations at the Baker Observatory (0.4 m) and Lulin Observatory (1.0 m) were obtained with Princeton Instruments RS1340 CCD cameras. Data from the Baker Observatory were binned 2 × 2 with an average dead time of 1 s, while observations from the Lulin Observatory used the full frame with an average dead time of 3 s. Mt. Suhora Astronomical Observatory (0.6 m) data were obtained with an SBIG ST-10XME CCD camera with a dead time of 3 s. At the Mercator 1.2-m telescope, we used the Merope CCD camera, which was recently upgraded with a new E2V frame-transfer CCD with 2048 × 3074 illuminated pixels (Østensen 2010). This instrument also had near-zero dead time. All observations used a red cut-off filter (BG38 or BG40), so the effective bandpass covers the B and V filters and is essentially that of a blue-sensitive photomultiplier tube. Such a setup allows us to maximize light throughput while maintaining compatibility with observations obtained with photomultipliers. We also obtained two-colour data using the Panchromatic Robotic Optical Monitoring and Polarimetry Telescopes (PROMPT; Reichart et al. 2005). Over five consecutive nights, we obtained Johnson U and V data from the PROMPT 0.4-m telescopes equipped with Apogee U47 CCDs. The dead time was about 5 s and there is a small gap each night while the telescopes switched sides of the German equatorial mount. In this paper, we only report on the V data. A follow-up paper will report on multicolour and time-resolved spectroscopic observations. Table 1 provides the details of our observations including date, start time, run length and integration time. The observations total over 210 h of data for the 2009 multisite campaign which spanned 37 d with a 10-d gap near the middle. Accurate time was kept using NTP (Baker and PROMPT observatories) or GPS receivers (Lulin, Mercator, SAAO and Suhora observatories) and corrected to barycentric time during data reductions.

Table 1. Observations of EC 01541.

Telescope	Date (UT)	Start (h:min:s)	Length (h)	Int. (s)
	2008 data			
SAAO 1.0 m	October 25	18:26:06	8.2	12
SAAO 1.0 m	October 26	18:16:40	7.3	10
SAAO 1.0 m	October 27	18:12:20	7.7	12
	2009 campaign, part 1			
SAAO 1.0 m	October 21	19:56:00	1.3	12
SAAO 1.0 m	October 22	19:10:20	6.9	12
Mercator 1.2 m	October 22	23:46:56	4.2	20
SAAO 1.0 m	October 23	19:05:55	3.9	12
Mercator 1.2 m	October 24	00:38:30	2.9	20
Baker 0.4 m	October 24	06:05:45	3.5	15
SAAO 1.0 m	October 24	20:09:40	5.4	12
Mercator 1.2 m	October 24	23:21:07	5.0	20
Suhora 0.6 m	November 25	19:20:25	6.1	15
Mercator 1.2 m	October 25	23:16:27	3.7	10
SAAO 1.0 m	October 26	18:43:15	7.1	12
Mercator 1.2 m	October 27	01:24:31	0.5	20
SAAO 1.0 m	October 27	20:29:20	2.7	12
Baker 0.4 m	October 29	03:33:40	1.1	15
Baker 0.4 m	October 31	04:21:45	5.3	15
Baker 0.4 m	November 1	02:39:23	7.0	15
Baker 0.4 m	November 2	02:47:30	8.6	15
Baker 0.4 m	November 3	02:55:00	1.0	15
Suhora 0.6 m	November 3	18:30:20	5.0	15
PROMPT5 0.4 m	November 4	00:46:13	6.8	20
Baker 0.4 m	November 4	02:51:30	6.0	15
PROMPT5 0.4 m	November 5	00:46:11	6.4	20
Baker 0.4 m	November 5	02:50:45	5.1	15
Suhora 0.6 m	November 5	20:55:06	4.9	15
PROMPT5 0.4 m	November 6	02:05:44	5.2	20
Baker 0.4 m	November 6	02:36:40	6.6	15
Baker 0.4 m	November 7	03:00:01	5.0	15
PROMPT5 0.4 m	November 7	04:17:27	5.2	20
PROMPT5 0.4 m	November 8	00:40:03	6.2	20
	2009 campaign, part 2			
Lulin 1.0 m	November 18	17:11:14	0.9	10
Lulin 1.0 m	November 19	10:46:14	7.2	10
SAAO 1.0 m	November 19	18:03:10	6.1	15
Baker 0.4 m	November 20	01:36:30	3.1	15
Lulin 1.0 m	November 20	10:04:34	7.8	15
SAAO 1.0 m	November 20	18:05:27	5.6	20
Lulin 1.0 m	November 21	15:56:14	1.9	20
SAAO 1.0 m	November 21	18:09:47	5.9	20
Lulin 1.0 m	November 22	15:56:10	1.9	15
SAAO 1.0 m	November 22	17:59:44	5.0	20
Lulin 1.0 m	November 23	11:48:25	5.9	15
Lulin 1.0 m	November 24	10:51:01	6.8	15
Lulin 1.0 m	November 25	11:37:00	6.0	15
Mercator 1.2 m	November 25	22:39:50	3.6	20
Baker 0.4 m	November 26	02:07:40	5.6	15
Lulin 1.0 m	November 26	12:23:21	5.2	15

Standard image reduction procedures, including bias subtraction, dark current and flat-field corrections, were followed using IRAF packages. Differential magnitudes were extracted from the calibrated images using MOMF (Kjeldsen & Frandsen 1992) or occasionally they were extracted using IRAF aperture photometry with

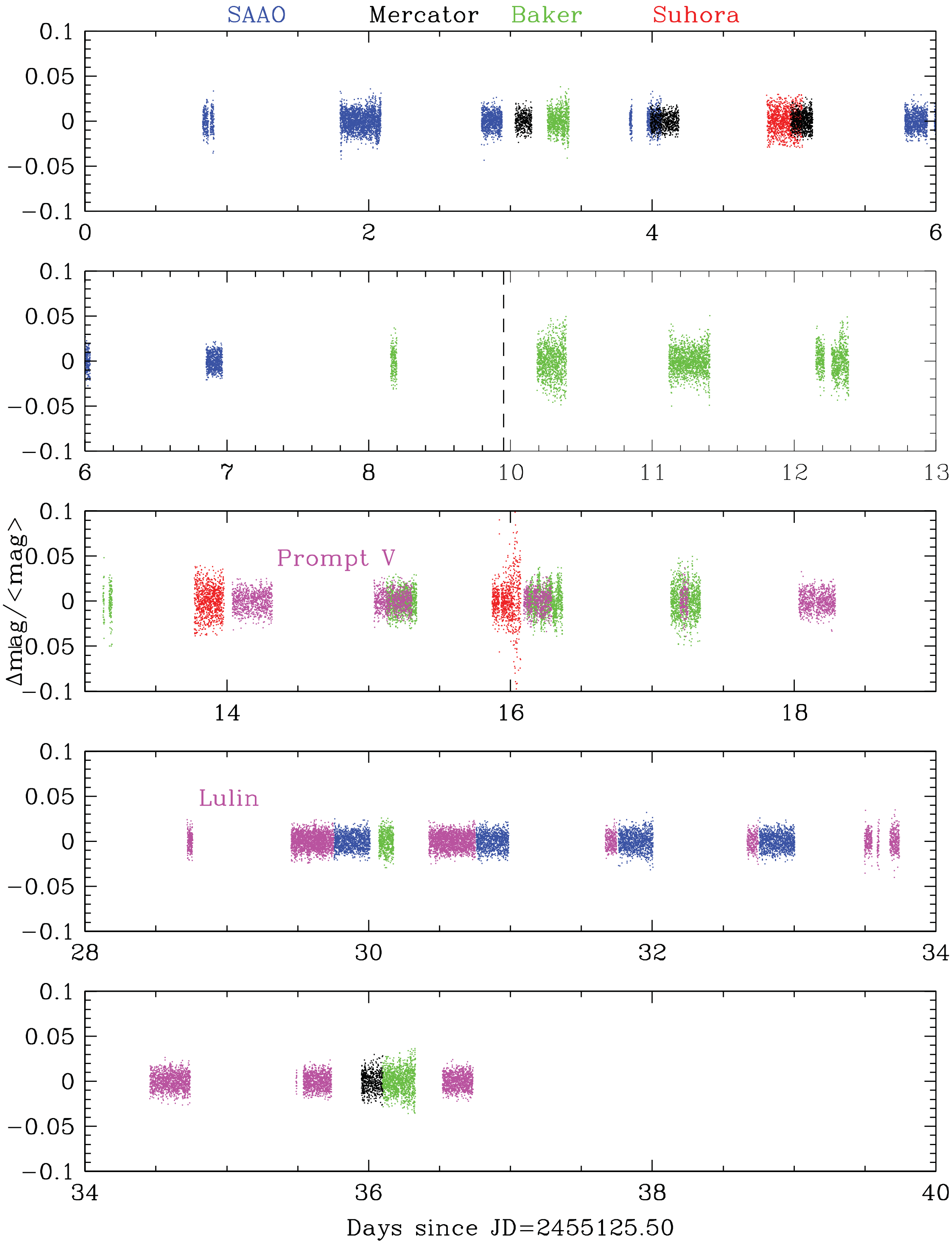

Figure 1. Light curves showing the 2009 data coverage. Each panel covers 6 d and the dashed vertical line indicates that day 9 was skipped as no data were collected. The top three panels are part 1 and the bottom two panels are part 2 of the campaign. Colour coded by observatory in the online version with the Prompt Observatory and Lulin Observatory sharing the same colour.

extinction and cloud corrections using the normalized intensities of several field stars, depending on conditions. As sdB stars are substantially hotter, and thus bluer, than typical field stars, differential light curves using an ensemble of comparison stars are not flat due to differential colour extinctions. A low-order polynomial was fitted to remove these trends from the data on a night-by-night basis. Light curves are shown in Fig. 1 (colour coded by observatory in the online version).

3 PULSATION ANALYSIS

2008 observations. During 2008, EC 01541 was observed during three consecutive nights collecting 23.2 h of data. These data have a 1/*T* resolution of 5.0 μHz and a 4σ detection limit of 0.37 mmag, where σ is the average value of the temporal spectrum outside regions containing pulsations. The temporal spectrum (or Fourier transform) is shown in Fig. 2 as well as the pre-whitening sequence. Frequencies, amplitudes and phases were determined by simultaneously fitting a non-linear least-squares solution to the data. We were easily able to pre-whiten 24 frequencies with residuals below the detection limit. The only peak remaining is the well-known SAAO telescope drive period near 8333 μHz. The frequencies, corresponding periods and amplitudes are provided in Table 2. Since pre-whitening effectively removed the pulsation peaks and corresponding aliases, we can deduce that over this 3-d span the amplitudes and phases were constant to within the detection limit. While the frequencies span more than 8 700 μHz, there are no combination frequencies.

2009 multisite campaign. During our 2009 multisite campaign, telescope time was assigned during two blocks separated by about 10 d. Thus, we examined the campaign as a whole and also by parts. The data have a 1/*T* resolution of 0.67, 1.44 and 0.32 μHz for part 1, part 2 and the combined data, and detection limits of 0.48, 0.32 and 0.33 mmag, respectively. The temporal spectra of the entire campaign and parts 1 and 2 are shown in Fig. 3.

For these data, pre-whitening was not as successful as during 2008. Even the high-amplitude peak, which pre-whitened nicely during 2008, left a residual just above 4σ in the combined 2009 data. This is most likely caused by amplitude variations across the duration of the campaign, which will be addressed in Section 4.2. Frequencies and amplitudes for the entire campaign and parts 1 and 2 are provided in Table 2. Note that in the table we have attempted to associate common pulsation frequencies from the different reductions. This includes those frequencies a daily alias away (e.g. f8 for which 2009 P2's frequency is nearly a daily alias smaller), and where crowded frequencies occur, matching by amplitude (e.g. f13 whereas 2009 P1's f12 is slightly closer in frequency). Data from part 2 with the worst temporal resolution but the lowest detection limit have the highest number of periodicities. We were able to fit and pre-whiten double the number of frequencies from part 2 compared to part 1, with the entire campaign having a number in between, as would be expected. 19 of the detections from part 2 have amplitudes lower than the part 1 detection limit, though four of these frequencies were detected in part 1 also. Since we detected the most frequencies with the lowest detection limit rather than the highest resolution, this suggests that unresolved frequencies are not a problem. Frequencies that are only detected once during 2009 are listed as *suggested* in Table 2 (s35–s45).

We also note that f31 is near to 2×f2 and f32 is near to 2×f3. This is most likely a chance occurrence as harmonic frequencies are normally caused by deviations from sinusoidal pulsations due to high amplitudes. Neither f2 nor f3 is sufficiently high and since f4 is an order of magnitude larger in amplitude and does not produce any combination of harmonic frequencies, f2 and f3 should not. Additionally, f31 and f32 are not at precisely

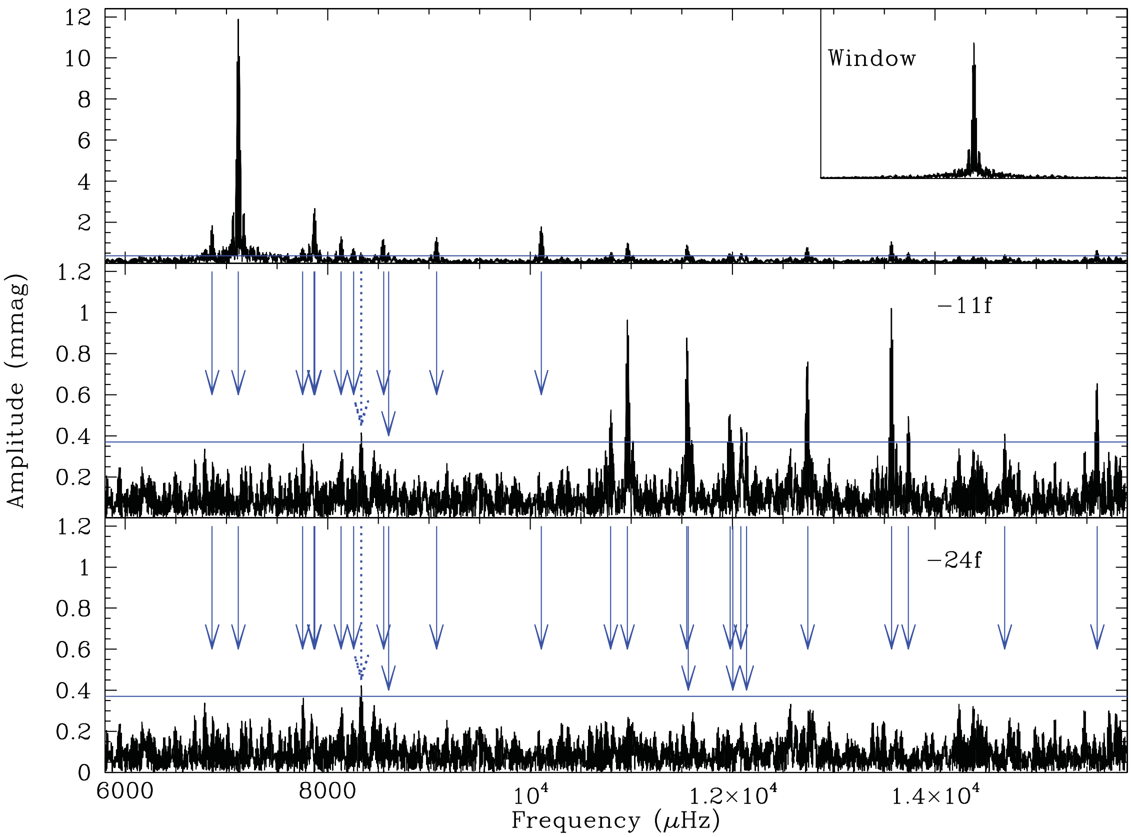

Figure 2. Temporal spectrum and pre-whitening sequence for the 2008 data set. The horizontal line indicates the 4σ detection limit of 0.37 mmag and the dotted arrow indicates the telescope drive period. The top panel shows a temporal spectrum for the original data (with a data window inset) and the next two panels show the spectrum pre-whitened by 11 and 24 frequencies, indicated by the arrows. The top panel has an amplitude scale 10 times that of the bottom two panels.

Table 2. Frequencies and amplitudes for EC 01541 from the 2008 single-site and 2009 multisite campaigns. (The entire campaign is noted as 2009 A, part 1 as P1 and part 2 as P2.) Formal least-squares errors are in parentheses.

ID	Frequency (μHz)				Amplitude (mmag)			
	2008	2009 A	2009 P1	2009 P2	2008	2009 A	2009 P1	2009 P2
f1	–	6098.892 (03)	6098.72 (08)	6098.83 (21)	–	0.34 (7)	0.43[a] (11)	0.37 (11)
f2	–	6785.089 (03)	6783.95 (06)	6787.06 (19)	–	0.39 (7)	0.57 (11)	0.41 (11)
f3	6859.47 (25)	6859.559 (11)	6859.27 (03)	6859.58 (06)	1.56 (18)	1.22 (9)	1.46 (12)	1.44 (11)
f4	7117.75 (03)	7117.487 (01)	7117.45 (01)	7117.51 (01)	11.90 (18)	8.91 (9)	8.62 (12)	9.45 (11)
f5	7753.07 (74)	7751.445 (24)	7750.59 (05)	7751.50 (12)	0.54 (18)	0.55 (9)	0.75 (12)	0.65 (11)
f6	7867.65 (39)	7865.937 (23)	–	7866.24 (20)	1.17 (18)	0.57 (9)	–	0.87 (11)
f7	7872.50 (17)	7872.860 (38)	–	7873.13 (21)	2.59 (18)	0.35 (9)	–	0.39 (11)
s35	–	–	8129.44 (05)	–	–	–	0.81 (13)	–
f8	8131.78 (32)	8130.198 (16)	8130.29 (05)	8121.62 (20)	1.25 (18)	0.83 (9)	0.91 (13)	0.41 (11)
s36	–	–	–	8241.85 (17)	–	–	–	0.48 (11)
f9	–	8249.048 (27)	–	8248.98 (20)	–	0.48 (9)	–	0.44 (11)
f10	8257.19 (49)	8255.486 (24)	8255.28 (05)	8255.93 (18)	0.81 (18)	0.56 (9)	0.74 (12)	0.48 (11)
f11	–	8313.775 (31)	–	8314.83 (09)	–	0.42 (9)	–	0.96 (11)
s37	–	–	–	8319.70 (17)	–	–	–	0.53 (12)
s38	–	–	–	8456.75 (13)	–	–	–	0.42 (07)
f12	–	8541.136 (22)	8549.88 (07)	–	–	0.60 (9)	0.59 (12)	-
f13	8552.55 (32)	8551.396 (15)	8552.50 (04)	8551.49 (07)	1.25 (18)	0.87 (9)	0.99 (12)	0.73 (07)
s39	–	–	8573.89 (06)	8583.03 (06)	–	–	0.71 (12)	0.94 (07)
f14	8602.16 (80)	–	–	–	0.51 (18)	–	–	–
f15	9075.81 (31)	–	–	–	1.25 (18)	–	–	–
f16	–	9249.812 (08)	9249.77 (02)	9249.73 (07)	–	1.34 (7)	1.90 (12)	0.72 (07)
s40	–	–	–	10 097.92 (14)	–	–	–	0.42 (08)
f17	10 111.69 (21)	10 109.903 (17)	10 110.23 (06)	10 109.33 (11)	1.82 (18)	0.64 (7)	0.69 (12)	0.54 (08)
f18	10 797.54 (33)	10 795.814 (30)	–	10 796.75 (15)	0.57 (08)	0.36 (7)	–	0.36 (07)
f19	–	10 951.287 (20)	10 951.16 (06)	10 951.39 (08)	–	0.55 (7)	0.55 (10)	0.69 (07)
f20	10 960.90 (19)	–	10 957.48 (06)	10 959.27 (12)	0.99 (08)	–	0.55 (10)	0.45 (07)
f21	–	11 016.662 (22)	11 015.69 (06)	11 016.31 (10)	–	0.49 (7)	0.63 (10)	0.56 (07)
f22	11 548.77 (27)	11 551.631 (18)	11 550.57 (06)	11 548.65 (09)	0.96 (12)	0.63 (7)	0.55 (10)	0.70 (08)
f23	–	11 558.130 (23)	–	11 552.03 (06)	–	0.47 (7)	–	1.06 (08)
f24	11 563.37 (42)	11 565.505 (25)	11 565.62 (05)	–	0.62 (12)	0.43 (7)	0.74 (10)	–
s41	–	–	–	11 580.28 (12)	–	–	–	0.49 (08)
s42	–	–	–	11 581.97 (13)	–	–	–	0.47 (08)
s43	–	–	–	11 962.29 (14)	–	–	–	0.39 (07)
f25	11 974.62 (35)	11 968.253 (26)	–	11 968.23 (12)	0.54 (08)	0.41 (7)	–	0.47 (07)
f26	12 002.55 (49)	–	–	–	0.40 (09)	–	–	–
f27	12 083.01 (49)	–	–	12 071.12 (14)	0.39 (09)	–	–	0.36 (07)
f28	12 139.38 (45)	–	–	12 141.08 (11)	0.43 (09)	–	–	0.46 (07)
s44	–	–	–	12 719.77 (18)	–	–	–	0.31 (07)
f29	12 730.79 (26)	12 734.196 (24)	–	12 734.10 (07)	0.73 (08)	0.46 (7)	–	0.72 (07)
f30	–	12 742.236 (29)	–	12 743.97 (09)	–	0.38 (7)	–	0.59 (07)
s45	–	12 749.315 (30)	–	–	–	0.37 (7)	–	–
f31[b]	13 568.75 (18)	13 568.065 (09)	13 568.10 (04)	13 568.15 (04)	1.02 (08)	1.14 (7)	0.99 (10)	1.22 (07)
f32[c]	13 737.52 (39)	13 736.871 (22)	–	13 736.95 (15)	0.49 (08)	0.48 (7)	–	0.34 (07)
f33	14689.44 (46)	–	–	–	0.42 (08)	–	–	–
f34	15 602.83 (29)	15 602.668 (25)	15 602.60 (05)	15 601.88 (13)	0.66 (08)	0.43 (7)	0.64 (10)	0.38 (07)
Limits	5.0	0.32	0.67	1.44	0.37	0.33	0.48	0.32

[a]This amplitude is below the formal 4σ detection limit, [b]is 2f2, and [c]is 2f3, though they are not likely overtones, based on amplitudes.

the harmonic frequencies, which they should be if that were the cause.

4 DISCUSSION

4.1 Comparison with the discovery data

The goal of our observational programme is to resolve the pulsation frequencies and characterize their amplitudes and phases for asteroseismic analysis. The discovery observations, of which only two runs were combined, have a temporal resolution of 10 μHz[1] and a detection limit of ∼2.0 mmag (Kilkenny et al. 2009). Our 2008 observations which seemed to resolve all the pulsations have twice the resolution with a detection limit over five times better. The 2009 observations obtained a temporal resolution 31 times better than the discovery observations with a detection limit slightly better than in 2008.

[1] Calculated as 1/*T* rather than the 1.5/*T* used in Kilkenny et al. (2009).

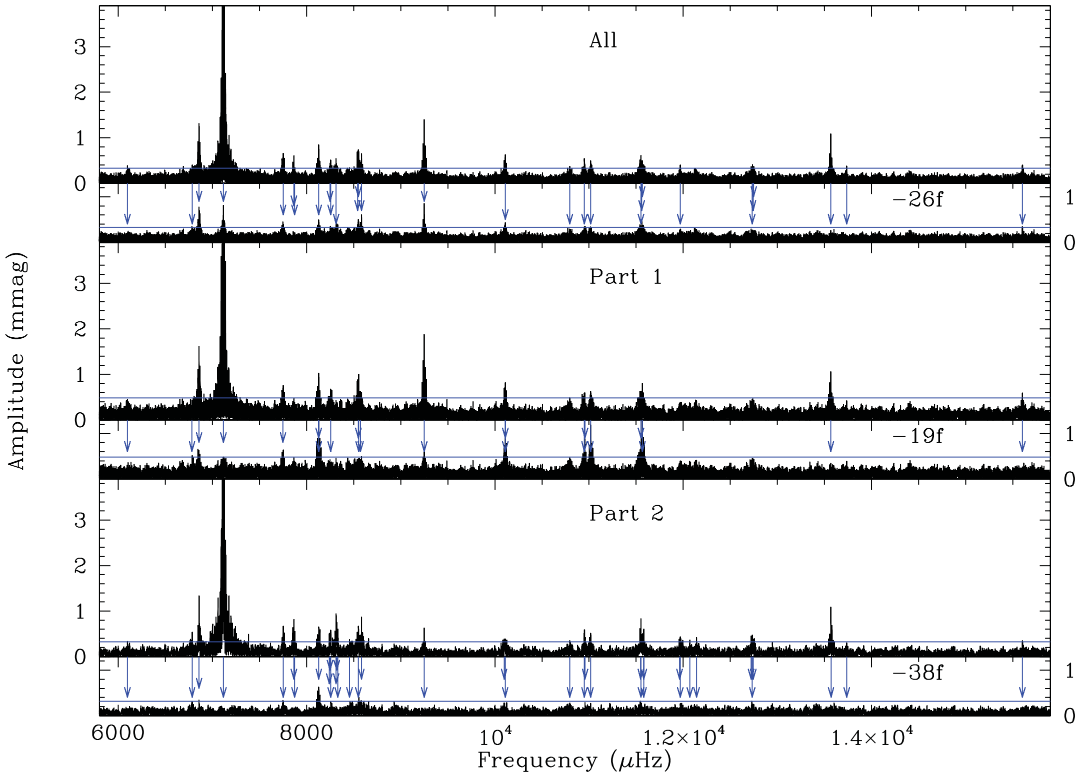

Figure 3. Temporal spectrum and residuals for the 2009 multisite campaign. The top two panels show the entire campaign, the next two part 1 and the bottom two part 2 of the campaign. The arrows indicate pre-whitened frequencies (26, 19 and 37 for the entire campaign, parts 1 and 2, respectively) and the horizontal lines indicate the 4σ detection limit. The vertical axis is truncated in the original spectra so the lower amplitude peaks may be seen.

The best measure of the success of follow-up observations is the number of additional frequencies detected. The discovery observations only revealed six frequencies, while the 2008 data contained 24 frequencies and the 2009 campaign detected 31 frequencies with 11 more listed as *suggested*.

4.2 Amplitude and phase variations

The majority of sdBV stars do *not* have stable amplitudes and/or phases (Reed et al. 2007b; Kilkenny 2010) and EC 01541 is no exception. The 2008 data pre-whiten below the detection limit, indicating that the amplitudes and phases were relatively stable during those three days, yet even in these data there are some signs of residuals, just below the detection limit. As the 2009 campaign covered significantly more time, it is no surprise that the temporal spectrum contains many residuals above the detection limit. Figs 4 and 5 show the amplitudes and phases of the four well-separated frequencies with average amplitudes greater than 1 mmag for the individual runs. The phases are fractional so that a change of 0.1 indicates a change of 10 per cent and normalized to zero phase.

In combining data from several different telescopes, most with different CCDs which may themselves have differing colour responses, it is possible to introduce systematic amplitude variations. There is no obvious evidence for this, as the amplitudes and/or phases do not appear to have any systematic trends which correlate with observatory. However, as the main periodicity (f4) is easily detected and can be measured with the highest accuracy, we used it to conduct an experiment. For this experiment, we assumed that the amplitude of f4 is constant across our multisite campaign and multiplied the individual light curves by a constant to bring them to an average value (9.0 mma). Amplitudes and phases were refitted (keeping the frequencies fixed) for the well-separated frequencies and pre-whitening was repeated for the modified light curve. The amplitudes (other than f4) remained variable and pre-whitening did not improve residuals. As such, we conclude that the amplitude variability is intrinsic to the star and not induced by detector efficiency.

For EC 01541, the main cause for the residuals appears to be amplitude variations. Only f3 shows sizeable phase variations, while f4 remains constant, except for one possible outlier. The amplitudes for f4 also change very little, though sufficient to cause the small residual in Fig. 3. The other three frequencies have significant amplitude variations, particularly during the first week of the campaign. At no time during 2009 were the pulsations stable over a 3 d period such as they were during 2008. While sufficient to subvert effective pre-whitening, the phases are too stable to indicate stochastically excited pulsations (Pereira & Lopes 2005; Reed et al. 2007b).

4.3 Constraints on the pulsation modes

In addition to detecting new frequencies, we wish to observationally correlate pulsation frequencies with modes. Pulsation modes are mathematically described by spherical harmonics with three quantum numbers, n (or k), ℓ and m. When present, rotation breaks the m degeneracy by separating each degree ℓ into a multiplet of $2\ell + 1$ components, so multiplet structure is a very useful tool to

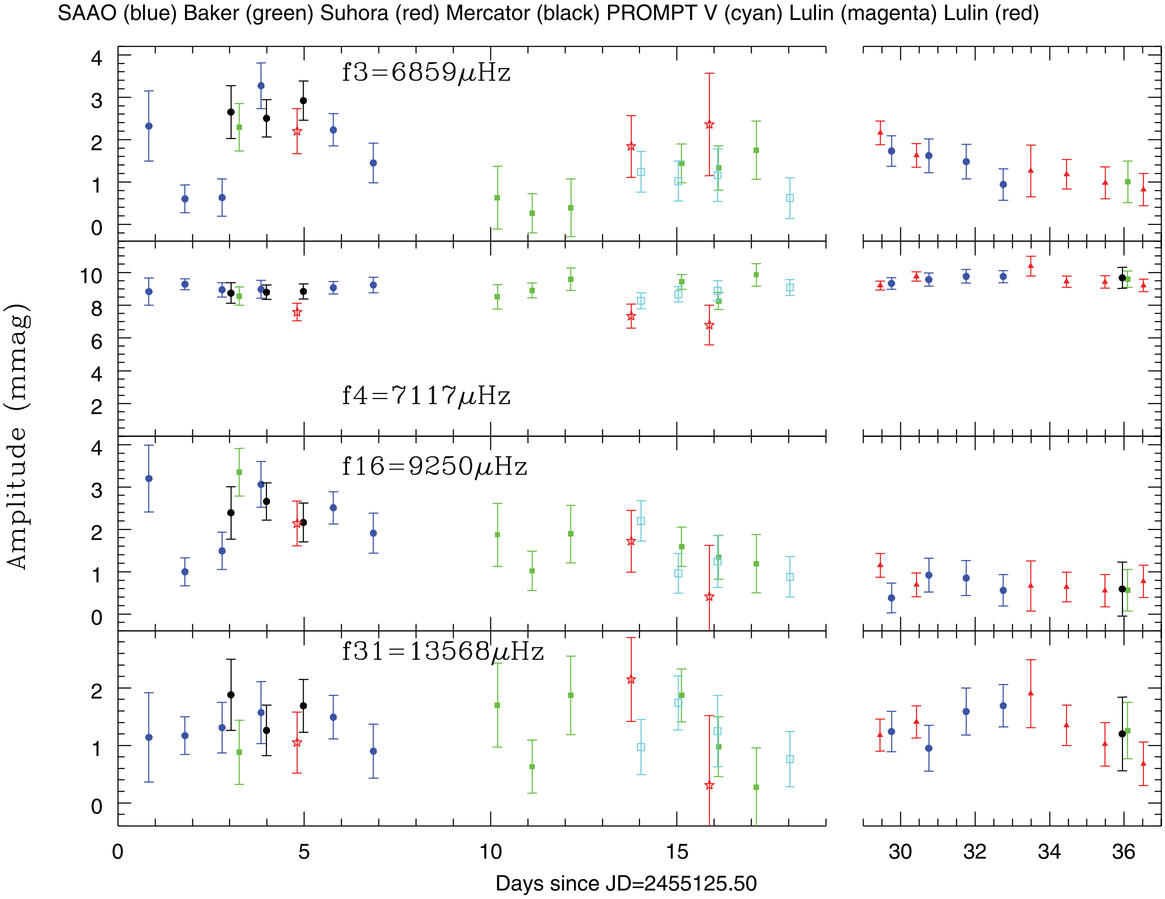

Figure 4. Amplitudes for well-separated frequencies with average amplitudes above 1.0 mmag.

correlate frequencies with modes (see Winget et al. 1991; Baran et al. 2009).

For slow rotators, as most sdB stars are thought to be (Heber, Reid & Werner 2000; Geier et al. 2010), rotationally split multiplets should be nearly equally spaced in frequency. Thus far only low-resolution spectra have been obtained for EC 01541 (Østensen et al. 2010a), which are not appropriate for measuring line broadening due to rotation. While these spectra are not optimal for discerning whether multiplets should be distorted by rapid rotation, the Balmer and helium lines are consistent with other sdB stars and can rule out rotation velocities >75 km s^{-1}, which means it is likely spinning slower than PG 1336−018 (with $v \sin i$ of 74.2 km s^{-1}, Vučković et al. 2009), which does appear to have evenly spaced multiplets (Kilkenny et al. 2003). So while EC 01541 appears to have 45 frequencies, there are no indications of multiplets evenly spaced in frequency, which is consistent with most pulsating sdB stars. Rather, the separations between frequencies are smoothly distributed.

Mode density can also be used to infer high-degree ($\ell \geq 3$) modes (see Reed et al. 2007b). A general rule is one n order per ℓ degree per 1000 μHz, producing three frequencies per 1000 μHz or nine frequencies if all possible m values are used. As we observe no indication of rotational multiplets, we infer that all $m \neq 0$ modes are degenerate, leaving some regions overdense for solely low-degree modes. For these regions, a few of the frequencies must either be $m \neq 0$ or $\ell \geq 3$ modes. If $m \neq 0$ modes are present, then even the densest frequency regions can be accommodated with $\ell \leq 2$ modes. As such, EC 01541 is not particularly dense.

5 CONCLUSIONS

From follow-up data acquired during 2008 and a multisite campaign in 2009, we have detected 34 frequencies, including the six from the discovery paper (Kilkenny et al. 2009). During three nights in 2008, EC 01541 appeared to have been amplitude and phase stable, but was not during 2009. We examined amplitude and phase stability, which has been used to infer stochastically excited oscillations in the sdBV star PG 0048 (Reed et al. 2007a) and possibly KPD 1930 (Reed et al. 2011b). While during 2009 the amplitudes varied, they were insufficient to be stochastically driven and the phases were reasonably stable. As EC 01541 is relatively bright with one high-amplitude phase-stable frequency, it is an excellent candidate for follow-up photometric studies to examine phase variations. Such variations have been used to detect planets (Silvotti et al. 2007).

Similar to other sdBV stars, EC 01541 is a rich pulsator yet has no indications of multiplets, which could be used to observationally constrain the modes. The mode density marginally indicates high-degree ($\ell \geq 3$) modes are present but while there are many pulsation frequencies, they are spread across ∼9000 μHz, which is rare for an sdBV star.

As in the discovery data, EC 01541 was dominated by a single high-amplitude periodicity with the remaining 33 having low

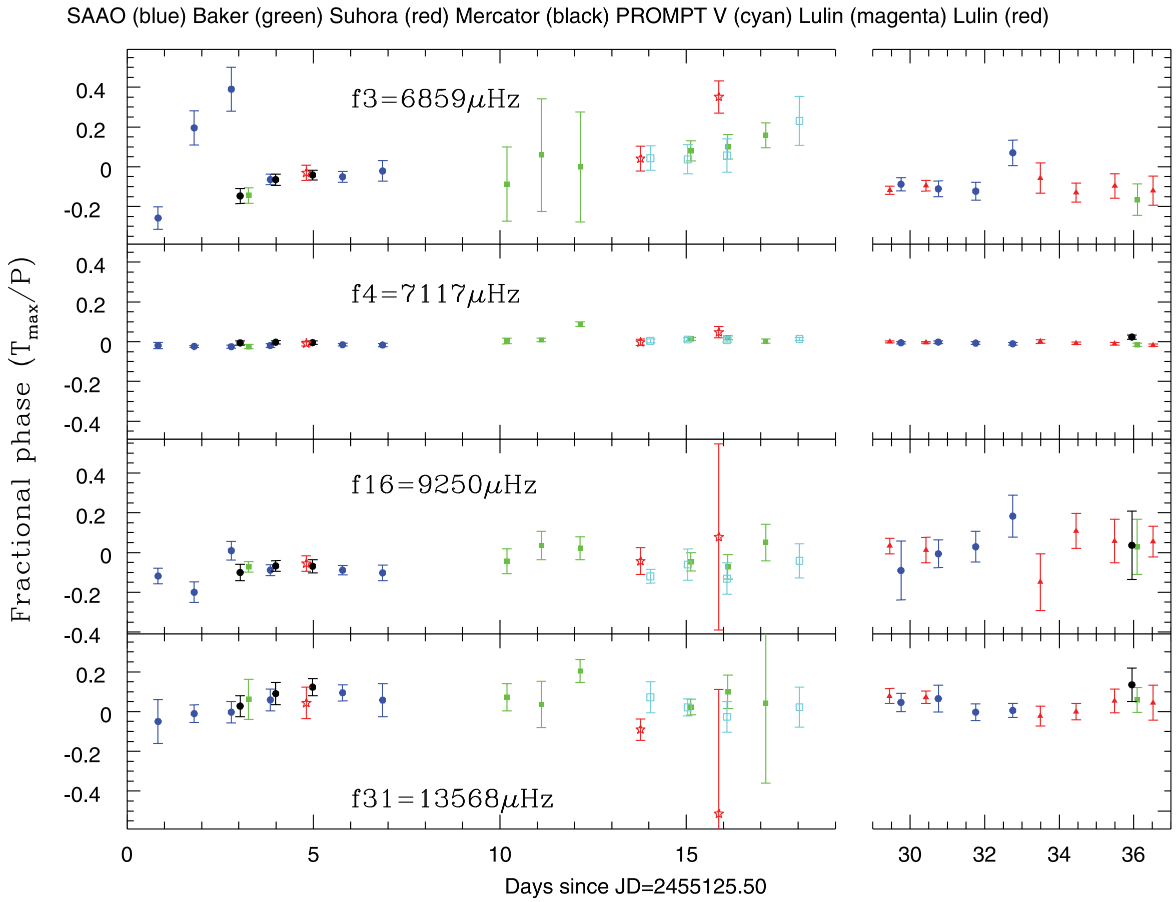

Figure 5. Phases for well-separated frequencies with average amplitudes above 1.0 mmag.

amplitudes right down to the detection limit. It is likely that data with an even lower limit would detect more frequencies, perhaps even including multiplets which would provide welcome constraints on modes. In addition to our photometric campaign, we also obtained some time-resolved spectroscopy which we will report on in a future paper, together with the PROMPT two-colour observations.

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