Multisite campaign on the open cluster M67. III. δ Scuti pulsations
in the blue stragglers

H. Bruntt1, D. Stello1,2,3, J. C. Suárez4,5, T. Arentoft2,6, T. R. Bedding1, M. Y. Bouzid7, Z. Csubry8, T. H. Dall9,10, Z. E. Dind1, S. Frandsen2,6, R. L. Gilliland11, A. P. Jacob1, H. R. Jensen2, Y. B. Kang12, S.-L. Kim13, L. L. Kiss1, H. Kjeldsen2,6, J.-R. Koo12, J.-A. Lee13, C.-U. Lee13, J. Nuspl8, C. Sterken7, and R. Szabó8,14

1School of Physics, University of Sydney, NSW 2006, Australia
2Institut for Fysik og Astronomi (IFA), University of Aarhus, DK-8000 Aarhus, Denmark
3Department of Physics, US Air Force Academy, Colorado Springs, CO 80840, USA
4Instituto de Astrofísica de Andalucía, CSIC, CP3004, Granada, Spain
5Observatoire de Paris, LESIA, UMR 8109, Meudon, France
6Danish AsteroSeismology Centre, University of Aarhus, DK-8000 Aarhus, Denmark
7Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium
8Konkoly Observatory of the Hungarian Academy of Sciences, H-1525 Budapest, PO Box 67, Hungary
9Gemini Observatory, 670 N. A'ohoku Pl., Hilo, HI 96720, USA
10European Southern Observatory, Casilla 19001, Santiago 19, Chile
11Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, USA
12Department of Astronomy and Space Science, Chonnam National University, Daejeon 305-764, Korea
13Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea
14Physics Department, University of Florida, Gainesville, FL, 32611, USA

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ABSTRACT

We have made an asteroseismic analysis of the variable blue stragglers in the open cluster M67. The data set consists of photometric time series from eight sites using nine 0.6–2.1 meter telescopes with a time baseline of 43 days. In two stars, EW Cnc and EX Cnc, we detect the highest number of frequencies (41 and 26) detected in δ Scuti stars belonging to a stellar cluster, and EW Cnc has the second highest number of frequencies detected in any δ Scuti star. We have computed a grid of pulsation models that take the effects of rotation into account. The distribution of observed and theoretical frequencies show that in a wide frequency range a significant fraction of the radial and non-radial low-degree modes are excited to detectable amplitudes. Despite the large number of observed frequencies we cannot constrain the fundamental parameters of the stars. To make progress we need to identify the degrees of some of the modes either from multi-colour photometry or spectroscopy.

Key words: stars: individual: EX Cnc, EW Cnc, stars: blue stragglers, stars: variables: δ Scuti, open clusters: individual: M67 (NGC 2682)

1 INTRODUCTION

We present the asteroseismic analysis of a new data set comprising photometry of the old open cluster M67 (NGC 2682) from nine telescopes during a 43-day campaign with a total of 100 telescope nights (Stello et al. 2006; hereafter Paper I). The main goal of the campaign was to detect oscillations in the stars on the giant branch (Stello et al. 2007; hereafter Paper II). Here we analyse the variability of the blue straggler (BS) population.

BS stars are defined as being bluer and more luminous than the turn-off stars in their parent cluster, and they are found in all open and globular clusters where dedicated searches have been made. BSs are important objects since they are directly linked to the interaction between stellar evolution of binaries and the cluster dynamics. In the cores of globular clusters the stellar density is high and direct stellar collisions may explain the existence of some of the BS stars (Davies & Benz 1995). However, in open clusters the density of stars is much lower and stellar collisions are rare (Mardling & Aarseth 2001). BSs in open clusters are therefore generally thought to be formed as the gradual coalescence of binary stars (Tian et al. 2006). Hurley et al. (2005) made a simulation of M67 that took into account stellar and binary star evolution, in ad-
condition to the dynamical evolution of the cluster. Their simulation showed that around half of the BSs were formed from primordial binary systems and the other half from binary stars that had been perturbed by close encounters with other stars.

While several of the known BSs in clusters are located near the main sequence inside the classical instability strip, only around 30% show δ Scuti pulsations (Gilliland et al. 1998). These objects are particularly interesting because their masses can in principle be inferred from comparison with pulsation models. Bruntt et al. (2001) studied the variable BSs in the globular cluster 47 Tuc, and could determine the mass of one of them to within 3.5% from a comparison with models in the Petersen diagram.

We have made a search for oscillations in eight BS stars in the instability strip in M67 (Fig. 1). In particular, we have studied the two known variable BS stars EW Cnc and EX Cnc. The δ Scuti pulsations in these stars were discovered by Gilliland et al. (1991) and pulsation modelling was done in detail by Gilliland & Brown (1992). The current data set has a significantly higher signal-to-noise (S/N) than the previous studies (Gilliland & Brown 1992; Zhang et al. 2005) and a superior spectral window. We have for the first time unambiguously detected a very large number of frequencies, comparable in number to the recent ambitious campaigns on field δ Scuti stars like FG Virginis (Breger et al. 2005). We characterize EW Cnc and EX Cnc using a grid of seismic models, but unlike Gilliland & Brown (1992) we also include the effects of rotation (in both equilibrium models and seismic oscillations).

Rotation will affect the internal structure of the stars, induce mixing processes (Zahn 1992; Heger, Langer & Woosley 2000; Reese, Lignières & Rieutord 2006), and cause significant asymmetric splitting of multiplets even in these moderately rapid rotating stars (Saio 1981; Dziembowski & Goode 1992; Soufi, Goupil & Dziembowski 1998; Suárez, Goupil & Morel 2006).

Figure 1. The colour-magnitude diagram of M67 based on standard $B - V$ and $V$ magnitudes. The solid line is an isochrone for an age of 4 Gyr. The locations of EW Cnc and EX Cnc have been marked with boxes and six other blue stragglers in the instability strip (dashed lines) are marked with filled circles.

2 BLUE STRAGGLER TARGETS

The locations of EW Cnc and EX Cnc in the colour-magnitude diagram of M67 are given in Fig. 1. We also analysed six other BS stars inside the instability strip and they are marked by filled circles. The $B - V$ colours and $V$ magnitudes are taken from Montgomery, Marschall & Janes (1993). Only stars observed during the present campaign are plotted. We have plotted an isochrone taken from the BaSTI database (Pietrinferni et al. 2004) for an age of 4.0 Gyr with composition $Z = 0.0198$, $Y = 0.2734$, adopting a distance modulus of $(m - M)_V = 9.7$. The instability strip is marked by dashed lines and is taken from Rodríguez & Breger (2001). It has been transformed from the Strömgren to the Johnson system using the calibration in Cox (2000). A finding chart showing the locations the BS targets is given in Fig. 2.

Figure 2. Finding chart for the blue stragglers we have analysed with ID numbers from Sanders (1977). The image is from the STScI Digitized Sky Survey.

3 OBSERVATIONS

The data were collected in 2004 from January 6 to February 17 during a multisite observing campaign with nine 0.6-m to 2.1-m class telescopes. The photometric reduction was done using the MOMF photometric package (Kjeldsen & Frandsen 1992, Sects. 5–6). The details of the observations and photometric data reduction were given in Paper I.

The choice of filters was made to optimize the signal-to-noise for the observations of the giant stars in M67 (see Paper II). All sites used the Johnson $V$ filters except Kitt Peak, where a Johnson $B$ filter was used. The bright BS star EX Cnc was saturated in about half of the $B$ images. We have a total of 450 hours of observation and about 15,000 data points for each star. The typical point-to-point scatter for EW Cnc and EX Cnc varies greatly from site to site, and lies in the range 1–8 mmag. By comparison, Gilliland & Brown (1992) used 37 hours of observation to obtain 2458 CCD frames with 2 mmag point-to-point noise, which is similar to our best sites.

The complete light curve of EW Cnc is shown in the top panel in Fig. 3. The middle and bottom panels show the details of the light curves of EW Cnc and EX Cnc during 24 hours. We have used...
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Figure 3. The complete light curve of EW Cnc is shown in the top panel. The details of 24 hours with nearly full coverage are shown in the two bottom panels for EW Cnc and EX Cnc where different symbols are used for each observing site. The continuous curves are the fits to the light curves.
Table 1. For case A and B we give the noise level in the amplitude spectrum at high frequencies ($700 \pm 60 \mu$Hz) and the height of the first alias peak in the spectral window. The results for our preferred cases are printed in italics.

| ID | $f$ [\mu Hz] | $\alpha$ [mmag] | $\phi$ | S/N |
|----|-------------|----------------|------|-----|
| f1 | 217.993(4)  | 2.66(2)        | 0.05(1) | 48.0 |
| f2 | 233.789(6)  | 1.79(3)        | 0.95(2) | 31.8 |
| f3 | 363.811(4)  | 1.29(3)        | 0.00(1) | 26.9 |
| f4 | 322.244(5)  | 1.17(3)        | 0.76(1) | 23.8 |
| f5 | 435.39(1)   | 0.94(4)        | 0.19(3) | 20.8 |
| f6 | 254.66(1)   | 0.93(3)        | 0.94(3) | 16.2 |
| f7 | 308.81(1)   | 0.75(2)        | 0.66(3) | 14.7 |
| f8 | 435.82(3)   | 0.55(4)        | 0.62(7) | 12.2 |
| f9 | 367.83(1)   | 0.58(3)        | 0.93(3) | 12.2 |
| f10| 508.98(2)   | 0.53(2)        | 0.15(4) | 11.6 |
| f11| 443.07(3)   | 0.46(3)        | 0.78(7) | 10.1 |
| f12| 299.25(1)   | 0.51(2)        | 0.96(4) | 9.7  |
| f13| 470.16(2)   | 0.41(3)        | 0.93(5) | 9.1  |
| f14| 474.36(2)   | 0.40(3)        | 0.34(5) | 8.8  |
| f15| 513.75(2)   | 0.40(2)        | 0.50(5) | 8.6  |
| f16| 184.69(5)   | 0.46(3)        | 0.47(7) | 8.6  |
| f17| 485.12(2)   | 0.38(3)        | 0.76(6) | 8.5  |
| f18| 442.59(3)   | 0.37(4)        | 0.64(7) | 8.2  |
| f19| 530.87(3)   | 0.36(2)        | 0.62(7) | 7.5  |
| f20| 375.96(3)   | 0.33(3)        | 0.09(7) | 7.0  |
| f21| 354.22(3)   | 0.33(3)        | 0.92(9) | 6.9  |
| f22| 351.48(7)   | 0.33(4)        | 0.00(6) | 6.8  |
| f23| 202.14(3)   | 0.37(3)        | 0.06(7) | 6.7  |
| f24| 441.59(2)   | 0.30(3)        | 0.98(6) | 6.7  |
| f25| 557.87(3)   | 0.32(3)        | 0.15(8) | 6.7  |
| f26| 445.43(3)   | 0.29(2)        | 0.23(9) | 6.5  |
| f27| 593.32(3)   | 0.30(2)        | 0.82(7) | 6.2  |
| f28| 506.27(4)   | 0.28(2)        | 0.72(9) | 6.0  |
| f29| 311.87(5)   | 0.29(2)        | 0.13(8) | 5.7  |
| f30| 590.05(4)   | 0.27(2)        | 0.5(1)  | 5.7  |
| f31| 586.55(5)   | 0.26(3)        | 0.5(1)  | 5.5  |
| f32| 337.43(4)   | 0.25(3)        | 0.8(1)  | 5.2  |
| f33| 329.42(2)   | 0.25(3)        | 0.95(7) | 5.1  |
| f34| 586.15(5)   | 0.24(3)        | 0.1(1)  | 5.1  |
| f35| 400.09(5)   | 0.24(3)        | 0.4(1)  | 5.1  |
| f36| 235.14(3)   | 0.28(3)        | 0.3(1)  | 4.9  |
| f37| 475.67(5)   | 0.20(2)        | 0.5(1)  | 4.5  |
| f38| 413.53(6)   | 0.20(3)        | 0.7(1)  | 4.4  |
| f39| 625.85(4)   | 0.21(2)        | 0.8(1)  | 4.3  |
| f40| 315.65(4)   | 0.20(2)        | 0.3(1)  | 4.1  |
| f41| 421.70(4)   | 0.19(2)        | 0.8(1)  | 4.1  |

different symbols for the five sites contributing to the light curve, as indicated in Fig. 3. The abbreviations for the five observatories are the same as in Paper I. The solid curves are the final fits to the complete data set (see Sect. 4.4).

4 TIME-SERIES ANALYSIS

4.1 Data point weights

As can be seen qualitatively in Fig. 3 and as described in detail in Paper I the quality of the photometry varied a lot from site to site, in many cases from night to night, and sometimes also during the night at a given site. To optimally extract the pulsation frequencies from the time series we have assigned weights to each data point.

We calculated two kinds of weights, “scatter weights” ($W_{scat}$) that are based on the scatter in the time series and “outlier weights” ($W_{out}$), which suppress extreme data points. The weights were calculated for each telescope and each star. The scatter weights were determined from the average point-to-point scatter in a large ensemble of reference stars, as described in detail in Appendix A1.

To calculate the outlier weights, we used the deviation from zero of both the target star and the reference stars, as described in Appendix A2.

4.2 Combining observations in $B$ and $V$

At Kitt Peak we used a Johnson $B$ filter while all other sites used the Johnson $V$ filter. The Kitt Peak data were collected simultaneously with several other sites (see Fig. 2 in Stello et al. 2006) but since the precision is far superior we decided to include it. The $B$ filter data comprise 1459 data points (9%) for EW Cnc and 598 points (4%) for EX Cnc.

When combining the data we must correct for the dependence of the pulsation amplitude on the filter by scaling the $B$ filter data. The scaling was found by measuring the amplitude ratios of the seven dominant frequencies in EW Cnc when using the $B$ and $V$ filters alone. The mean amplitude ratio was $0.74 \pm 0.02$, which is the scaling we applied. We also scaled the scatter weights found in Appendix A1 to ensure that the signal-to-noise is preserved. The mean phase shift is $5.7 \pm 4.3\%$, which is not significantly different from zero.

To make sure that our results are not affected by the inclusion of the scaled $B$ data, we repeated the analysis described below when using only the $V$ data. For both stars we found exactly the same frequencies except for two frequencies in EW Cnc and three frequencies in EX Cnc. The most significant of these frequencies has S/N = 5.2 while the others have S/N below 4.4. The slight differences we find in the frequencies and amplitudes are within the uncertainties found in Appendix B. We are therefore confident about combining the $V$ data with the scaled $B$ data.

4.3 The optimal amplitude spectrum

We calculated the amplitude spectrum both with the optimal spectral window and with the lowest noise level (see Kjeldsen et al. 2005). To do this we made the time-series analysis for two different approaches:

Case A: We computed the average light curve by binning all data collected within 8-minute intervals. In the binning process we took into account the different quality of the data points by using weights
Figure 4. Amplitude spectra of EW Cnc (left panels) and EX Cnc (right panels) for the binned light curves (case A, top panels) and the noise optimized light curves (case B, bottom panels). The residual spectrum is shown below each plot and the insets show the spectral windows. In the residual spectra the dashed grey lines mark the average noise level.

$W_{\text{scat}} \cdot W_{\text{out}}$ for $n = 2$ in Eq. [A3]. We did not use weights when computing the amplitude spectrum a second time.

Case B: No binning, but each data point was given the weight $W_{\text{scat}} \cdot W_{\text{out}}$ when calculating the amplitude spectrum.

It was case A that provided the optimal spectral window. The amplitude spectra of EW Cnc and EX Cnc for case A are shown in the top panels in Fig. 4. The residual spectrum after extracting the oscillation frequencies (see Sect. 4.4) is shown in each panel and the insets show the spectral windows, which have sidelobes at ±1 c d$^{-1}$ and ±2 c d$^{-1}$ of ≃ 23%.

The lowest noise level was found in case B. We tried both $n = 1$ and 2 in Eq. [A3], but found that for $n = 1$ the noise level was 5–10% lower, and in addition the ±1 c d$^{-1}$ sidelobes were slightly lower. The fact that we found the lowest noise level for $n = 1$ indicates that $1/(W_{\text{scat}} \cdot W_{\text{out}})$ is the best approximation to the true variance in the time series. We note that this was also concluded by Handler (2003). The amplitude spectra for case B are shown in the bottom panels in Fig. 4.

While the noise level is significantly lower for case B, the spectral window has much lower sidelobes in case A. In Table 1 we compare the noise levels and aliases. The noise was calculated in a frequency band of $760 \pm 60$ µHz in the residual spectra.

In Appendix B we have made simulations of the time series to check whether case A or B gives the most robust results. The conclusion is that case A is preferred for EX Cnc due to the high number of frequencies found in a relatively narrow interval, while we use case B for EW Cnc. The results for these cases are printed in italics in Table 1.

4.4 Fourier analysis of EW Cnc and EX Cnc

For each site the light curves were high-pass filtered to remove slow trends. In this way we suppressed variations with frequencies below 80 µHz, corresponding to periods longer than ≃ 3.5 hours.
The pulsation frequencies are found mainly in the intervals from 200–600 µHz and 150–350 µHz for EW Cnc and EX Cnc, respectively. We used the PERIOD04 package by Lenz & Breger (2005) to fit the light curves in the frequency range 100–1000 µHz, as follows. The amplitude spectrum was calculated using the light curve from case B for EW Cnc and case A for EX Cnc (see Sect. 4.4). The highest peak was then selected and the frequency, amplitude and phase were fitted. This was done iteratively while in each step always improving the frequencies, amplitudes and phases of previously extracted frequencies.

We extracted 41 and 26 frequencies with S/N > 4 in the two stars, and the parameters are given in Tables 2 and 3. The uncertainties are based on simulations, as described in Appendix B. To determine the S/N of the extracted frequencies, we estimated the noise level in the amplitude spectrum around each frequency. This was done after cleaning the amplitude spectra so only peaks with S/N < 3 remained. The noise was calculated in bins with a width of 35 µHz and the noise estimate is the average of the three nearest bins for each frequency. The noise levels are marked by grey dashed lines in the residual spectra in Fig. 4.

In comparison with Gilliland & Brown (1992) detected 10 frequencies in EW Cnc and 6 frequencies in EX Cnc. We recovered these frequencies except one of their weaker modes at 423.2 µHz in EW Cnc and at 186.5 µHz in EX Cnc. Zhang et al. (2005) detected 4 frequencies in EW Cnc and 5 frequencies in EX Cnc. They used data from a single observatory, and this explains why some of their frequencies are offset from ours by ±1 c d⁻¹.

To check whether the frequencies we detected in the time-series analysis were reliable, we made the time-series analysis for both cases A and B. In both EW Cnc and EX Cnc we found that nearly all frequencies with S/N > 7 were detected in both cases, while this was not true for the weaker frequencies. Further, for the weaker frequencies that were detected in both cases there was sometimes an offset of 1 c d⁻¹. In those cases, we chose the solution for case A, which has the better spectral window. As an additional check we used the 20 days in the time series with the best coverage and were able to recover all frequencies with S/N > 6. We also used only the data set from La Silla (14 consecutive nights of observation) but found that for the weaker frequencies, the ±1 c d⁻¹ alias was often identified as the most significant frequency, which is not surprising given the high sidelobes from the single-site time series.

Several of the 41 frequencies found in EW Cnc are found to be linear combinations; examples are \( f_5 \approx f_{13} \approx 2 f_1 \) and \( f_{18} \approx f_5 - f_2 \approx f_{12} - f_{28} \). We searched for combinations within twice the resolution of the data set which is \( \Delta f = 2/T_{\text{obs}} = 0.63 \muHz \). The condition is expressed as \( f_i \approx n f_j + m f_k \) for any integer value \( n, m \in [-2; 2] \) and \( i, j, k \in [1; 41] \) and we found 13 combination frequencies. We compared this with 1 000 sets of 41 randomly distributed numbers in the same interval as the observed frequencies, and we found 18 ±6 combinations. Hence our detection of 13 linear combinations in EW Cnc is not surprising. However, none of the frequencies found in EX Cnc are found to be linear combinations. This is also the case for 1 000 simulations of randomly distributed frequencies. The reason for the different results for the two stars is that the frequencies in EX Cnc are found in a much narrower frequency interval than for EW Cnc.

### 4.5 Interpretation of the EX Cnc spectrum

In both cases A and B, we see a clear pattern of nearly equally spaced peaks for EX Cnc (Fig. 4). In the top panel we show the amplitude spectrum of EX Cnc (case A) in more detail. To guide the eye we indicate a comb pattern with a separation of 1 c d⁻¹ (11.574 µHz) with dashed vertical lines. In the bottom panel the frequencies detected in case A (listed in Table 3) are marked by vertical lines.

We note that each dominant peak in the comb pattern consist of several closely spaced peaks with remarkable similarity to what is seen for stochastically excited and damped oscillations, also called solar-like oscillations, which are driven by convection (Anderson, Duvall & Jefferies 1990). We investigated whether the observed regular pattern and the closely spaced lower amplitude peaks around each dominant peak could be explained by

(i) Stochastically excited and damped oscillations of equally spaced modes.
(ii) The spectral window (alias peaks).
(iii) Closely spaced modes.

(i) In \( \delta \)-Scuti stars, the oscillations are caused by the \( \kappa \)-mechanism (opacity driven) and are believed to be coherent, which will produce a single isolated peak for each oscillation mode in the amplitude spectrum. Although damped oscillations driven by convection might be present in some \( \delta \)-Scuti stars (Samadi, Goupil & Houdek 2002), the expected frequencies and amplitudes are very different from what we see in Fig. 5 which is consistent with opacity driven oscillations. The calculations by Samadi, Goupil & Houdek (2002) show frequencies in the range

| ID | \( f \) [µHz] | \( a \) [mmag] | \( \phi \) | S/N |
|---|---|---|---|---|
| 1 | 226.910(4) | 3.87(6) | 0.94(1) | 36.2 |
| 2 | 238.883(5) | 3.74(6) | 0.60(1) | 35.0 |
| 3 | 240.297(8) | 2.31(7) | 0.97(2) | 21.7 |
| 4 | 191.464(9) | 2.08(7) | 0.45(2) | 18.3 |
| 5 | 226.45(1) | 1.79(8) | 0.28(3) | 16.7 |
| 6 | 205.49(1) | 1.68(8) | 0.14(3) | 15.2 |
| 7 | 228.66(2) | 1.33(8) | 0.57(4) | 12.4 |
| 8 | 215.33(1) | 1.34(8) | 0.41(4) | 12.3 |
| 9 | 196.96(1) | 1.18(7) | 0.71(4) | 10.5 |
| 10 | 190.92(1) | 1.16(8) | 0.46(3) | 10.2 |
| 11 | 217.43(2) | 1.05(8) | 0.28(5) | 9.6 |
| 12 | 211.82(2) | 1.04(7) | 0.77(4) | 9.5 |
| 13 | 196.15(2) | 0.83(7) | 0.03(4) | 7.4 |
| 14 | 193.93(2) | 0.79(7) | 0.11(6) | 7.0 |
| 15 | 219.95(2) | 0.75(7) | 0.89(6) | 6.9 |
| 16 | 236.34(2) | 0.60(5) | 0.04(7) | 5.6 |
| 17 | 203.19(3) | 0.62(7) | 0.64(8) | 5.6 |
| 18 | 223.01(4) | 0.59(7) | 0.19(9) | 5.5 |
| 19 | 258.86(3) | 0.58(6) | 0.27(8) | 5.5 |
| 20 | 199.45(3) | 0.59(7) | 0.76(7) | 5.3 |
| 21 | 234.39(4) | 0.55(6) | 0.51(1) | 5.2 |
| 22 | 229.14(5) | 0.55(5) | 0.51(1) | 5.2 |
| 23 | 250.65(2) | 0.48(8) | 0.85(6) | 4.5 |
| 24 | 256.86(3) | 0.47(6) | 0.55(9) | 4.4 |
| 25 | 182.09(3) | 0.50(6) | 0.69(8) | 4.4 |
| 26 | 148.54(3) | 0.49(6) | 0.20(7) | 4.3 |

2 The S/N was measured for case B.
400–1200 µHz and amplitudes of roughly 100 ppm for their selected models. These values are consistent with what we found specifically for this star using the parameters in Table 5, a mass of 2 $M_\odot$, and the usual scaling relations to predict the characteristics of solar-like oscillations (Kjeldsen & Bedding 1995; Brown et al. 1991). We find the central frequency (maximum amplitude) to be $\nu_{\text{max}} \simeq 630$ µHz, amplitudes $\delta L/L \simeq 40$ ppm, and mean frequency separation $\Delta \nu_0 \simeq 40$ µHz). These properties of solar-like oscillations are clearly inconsistent with the observed amplitude spectrum.

(ii) Simulations showed that the regular pattern was unlikely to be the result of only two or three modes. To reproduce the observed amplitude spectrum required at least 4–5 modes, equally spaced by roughly 1 c d$^{-1}$. The low alias sidelobes, especially in case A, imply that the pattern is intrinsic to the star. Many of the lower amplitude peaks around each dominant peak seem to be separated by exactly 1 or 2 c d$^{-1}$ from a neighbouring peak. However, the strength of these lower amplitude peaks are in many cases higher than expected from the strength of the sidelobes in the spectral window.

(iii) Closely spaced peaks are not uncommon in $\delta$ Scuti stars (Breger & Bischoff 2002). Breger & Pamyatnykh (2006) noted that 18 pairs ($\Delta f < 1$ µHz) exist in the $\delta$ Scuti star FG Virginis (Breger et al. 2005). They found evidence for the frequency doublets being real. As seen in Fig. 5, we also detect several close pairs.

Table 4. Properties of the light curves and amplitude spectra of the observed BS stars in M67. Star ID from Sanders (1977) and ID, $V$, and $B - V$ from Montgomery, Marschall, & Janes (1993) are given. $N$ is the number of data points. The point-to-point scatter at the LaS and LOAO sites and the noise level in the amplitude spectrum in the range 350 ± 150 µHz and 760 ± 60 µHz are listed. The last column contains membership probabilities from Sanders (1977).

| Name   | Sanders | MMJ | $V$  | $B - V$ | $N$ | $\sigma_{\text{LaS}}$ [mmag] | $\sigma_{\text{LOAO}}$ [mmag] | $A_{350}$ [µmag] | $A_{760}$ [µmag] | $P_{\text{Member}}$ [%] |
|--------|---------|-----|------|---------|-----|-----------------------------|-----------------------------|-------------------|-------------------|---------------------|
| S1466  | 6511    | 10.60 | 0.34 | 13316   | 1.7 | 3.3                         | 66                          | 41                | 0                 |                     |
| S1434  | 6510    | 10.70 | 0.11 | 3312    | –   | 3.3                         | 372                         | 160               | 91                |                     |
| EX Cnc | S1284   | 6504 | 10.94 | 0.22 | 14660 | 1.9 | 2.9                         | 240                         | 65                | 95                 |                     |
| S1066  | 6490    | 10.99 | 0.11 | 16954   | 1.7 | 2.6                         | 46                          | 35                | 90                |                     |
| S1263  | 6501    | 11.06 | 0.19 | 17408   | 4.6 | 2.7                         | 89                          | 69                | 89                |                     |
| S968   | 6479    | 11.28 | 0.13 | 9851    | 1.5 | 2.9                         | 55                          | 37                | 95                |                     |
| S752   | 6476    | 11.32 | 0.29 | 3316    | –   | 2.8                         | 194                         | 120               | 95                |                     |
| EW Cnc | S1280   | 5940 | 12.26 | 0.26 | 15524 | 1.9 | 3.3                         | 188                         | 46                | 93                |                     |

Figure 5. The top panel shows the amplitude spectrum of EX Cnc for case A. The inset shows the spectral window on the same horizontal scale as the main Figure. The vertical dashed lines are separated by 1 c d$^{-1}$ (11.574 µHz). In the bottom panel the detected frequencies are marked by vertical lines.
In summary, damped oscillations driven by convection seems to be a very unlikely cause for the characteristic pattern we see in Fig. 3. We believe the pattern is most likely due to a nearly regular series of at least five modes (excited by the \( \kappa \) mechanism) which, due to a general spacing very close to 1 c d\(^{-1} \), shows a large number of small peaks around each dominant peak caused by the spectral window. This is further enhanced by the presence of lower amplitude modes close to the dominant modes (see bottom panel in Fig. 3). Our interpretation is supported by \( \text{Gilliland \& Brown} \) (1992) who found frequency separations of \( \sim 5 \mu \text{Hz} \) and \( \sim 10 \mu \text{Hz} \) in this star, and suggested that the latter might be due to rotational splitting.

### 4.6 A search for pulsations in six other BS stars

In addition to EW Cnc and EX Cnc, we observed six other BS stars in the instability strip as shown in Fig. 1. To search for pulsations in the stars we calculated the amplitude spectra in the range 0–1000 \( \mu \text{Hz} \), using weights as for case B (Sect. 4.3). In Table 4 we summarize the properties of the BS stars observed during the campaign. For completeness, EW Cnc (S1280) and EX Cnc (S1284) are included in the Table. We give the ID numbers from Sanders (1977) and Montgomery, Marshall & Janes (1993), and the \( V \) magnitude, \( B - V \) colour from the latter. The total number of data points \( N \) and \( \sigma_{\text{fit}} \) (Eq. A1) for the La Silla and LOAO (Mt. Lemmon Optical Astronomy Observatory) sites indicate the quality of the data. We note that La Silla had very good weather conditions during the campaign, while LOAO had worse conditions (for more details see Paper I). The mean level in the amplitude spectrum in the range where oscillations are expected is denoted \( A_{\text{350}} \) (200–500 \( \mu \text{Hz} \)), while that at slightly higher frequencies \( A_{\text{760}} \) (700–820 \( \mu \text{Hz} \)) is a measure of the white noise. In the last column, the membership probability from \( \text{Sanders} \) (1977) is given. We note that more recent radial velocity studies by \( \text{Girard et al.} \) (1989) and \( \text{Zhao et al.} \) (1993) are in agreement with this.

Two of the BS stars (S1434 and S752) were only observed by a few sites. Hence, for these stars the noise level in the amplitude spectrum is about a factor 4–6 higher than for the other stars. We find no significant peaks in the range 0–1000 \( \mu \text{Hz} \) above \( S/N \) of 4 in any of the BS stars except EW Cnc and EX Cnc.

Our results are in agreement with \( \text{Sandquist \& Shetrone} \) (2003) who looked for photometric variability in several BS stars in M67. Except for EW Cnc and EX Cnc they found no \( \delta \) Scuti pulsations in their sample, which included S752, S968, S1066, and S1263. The latter was also observed by \( \text{Gilliland \& Brown} \) (1992) who placed an upper limit of variation at 0.2 mmag (corresponding to \( \sim 5 \mu \text{mag} \) scatter in the time series) for frequencies above 130 \( \mu \text{Hz} \), in agreement with this study and \( \text{Sandquist \& Shetrone} \) (2003). We note that \( \text{Stassun et al.} \) (2003) reported unusually high scatter of up to 30 mmag in this star from a photometric \( BV I \) time-series study. The relatively high noise level for S1263 compared to the other BSs in our data (see \( \sigma_{\text{LaS}} \) in Table 4) is due to the star being blended (see Fig. 3).

### 5 THEORETICAL MODELS OF EW & EX CNC

To model EW Cnc and EX Cnc we used the stellar evolution code CESAM (More 1997). The effects of rotation are taken into account in the equilibrium equations as a first-order perturbation to the local gravity, while assuming rotation as a rigid body. The \( \text{CEFF} \) equation of state was used (\( \text{Christensen-Dalsgaard \& Daeger} \) 1992) and OPAL opacities were adopted (\( \text{Iglesias \& Rogers} \) 1996). A more detailed description of the input physics for the CESAM code was given by Casas et al. (2006).

We used the oscillation code FILOU (\( \text{Tran Minh \& Leung} \) 1995; \( \text{Suárez} \) 2002) to calculate the oscillation frequencies from the evolution models. We assume rigid-body rotation and the effects up to second order in the centrifugal and Coriolis forces were included. We note that Reese, Lignières & Ricouard (2006) found that this perturbation approach may be invalid even at moderate rotational velocities. Effects of near degeneracy are expected to be significant (Soufi et al. 1998) as was described in detail by \( \text{Suárez, Goupil \& Morel} \) (2006).

#### 5.1 Fundamental atmospheric parameters

The fundamental atmospheric parameters of EW Cnc and EX Cnc were estimated by Mathys (1991) and \( \text{Gilliland \& Brown} \) (1992) based on Strömgren photometry by Nissen, Twarog, & Crawford (1987) but applying different calibrations (Moon \& Dworetsky 1985; Philip \& Relfs 1979). We used the most recent calibration by \( \text{Napiwotzki, Schoenberner \& Wenske} \) (1993), while assuming the mean cluster reddening from Nissen et al. (1987). For EW Cnc we used Geneva photometry from Rufener (1976) and applied the calibration by \( \text{Kunzli et al.} \) (1997). Landsman et al. (1998) constrained \( T_{\text{eff}} \) of both stars based on UV measurements. We summarize the results in Table 5. Typical uncertainties on \( T_{\text{eff}} \) and \( \log g \) are 150 K and 0.2 dex and there is good agreement between the different calibrations.

| Star     | \( M/M_\odot \) | \( T_{\text{eff}} \) [K] | \( \nu_{\text{rot}} \) [km s\(^{-1}\)] |
|----------|-----------------|--------------------------|-----------------------------|
| EW Cnc   | 1.7             | 7930–8110                | 90, 150                     |
|          | 1.8             | 7900–8210                | –                           |
|          | 1.9             | 7900–8210                | –                           |
|          | 2.0             | 7940–8200                | –                           |
| EX Cnc   | 1.8             | 7450–7620                | 65, 120                     |
|          | 1.9             | 7470–7740                | –                           |
|          | 2.0             | 7480–7740                | –                           |
|          | 2.1             | 7470–7710                | –                           |
|          | 2.2             | 7480–7730                | –                           |
|          | 2.3             | 7630–7740                | –                           |

Table 5. Fundamental parameters of EW Cnc and EX Cnc.

Table 6. Parameters of theoretical pulsation models for EW Cnc and EX Cnc, which are inside the photometric error boxes shown in Fig. 6. For each mass the range of effective temperatures is given. For each star we computed models with two different rotational velocities given in the last column.
5.2 The model grid

We have calculated a grid of stellar models consistent with the fundamental parameters of EW Cnc and EX Cnc. A few evolution tracks are shown in Fig. 6 in the $\log g$ versus $T_{\text{eff}}$ diagram, where the solid and dashed lines correspond to rotational velocities of 65 and 120 km s$^{-1}$. The photometric error boxes are shown as grey squares. The center of each box is the $T_{\text{eff}}$ and $\log g$ from Landsman et al. (1998) and the half-widths are equal to the estimated uncertainties of 150 K and 0.2 dex. We have computed pulsation frequencies for the models inside the photometric error boxes. The mass ranges are 1.7–2.0 $M_{\odot}$ for EW Cnc and 1.8–2.3 $M_{\odot}$ for EX Cnc in steps of 0.1 $M_{\odot}$. Further details of the grid of pulsation models are given in Table 6.

Analyses of stellar spectra (Peterson, Carney & Latham 1984; Manteiga, Martinez Roger & Pickles 1989; Pritchet & Glaspey 1991) reveal moderate projected rotational velocities for EW Cnc and EX Cnc, and we have used average values of $v \sin i = 90$ and 65 km s$^{-1}$, respectively. However, the inclination angle is unknown, and therefore we calculated models and corresponding oscillation frequencies for the minimum and a moderate value of $v_{\text{rot}}$ for each star. The values in the last column in Table 6 correspond to inclination angles of $i = 90^\circ$ and $45^\circ$.

5.3 Comparison of observed and theoretical frequencies

In Fig. 7, we show the number of modes as a function of frequency, in bins of 50 $\mu$Hz. The black histograms are for the observed frequencies for EW Cnc (left panels) and EX Cnc (right panels), which are listed in Tables 2 and 3. The solid histograms are for frequencies from pulsation models and the colours indicate how high angular degree, $l$, we have included. The top and bottom panels are for models with high and low mass. The low-mass models both have a mass 1.8 $M_{\odot}$, while the high-mass models correspond to the evolution tracks that graze the photometric error boxes, i.e. 2.0 and 2.3 $M_{\odot}$ for EW Cnc and EX Cnc, respectively. We used the $T_{\text{eff}}$ adopted for the centres of the photometric error boxes in Fig. 6.

By inspecting the histograms for the models in Fig. 7, one can see that the number modes increase when increasing the mass or decreasing $T_{\text{eff}}$. Histograms for models with different rotational velocities are nearly identical since the frequency shifts are relatively small ($\approx$ few $\mu$Hz) for these moderate velocities. The histograms of all pulsation models within the photometric error boxes are in agreement with the observations, but only when including modes with degrees $l \leq 0$, 1, and 2. However, if the masses are lower than 1.7 and 1.8 $M_{\odot}$ for EW Cnc and EX Cnc, respectively, it will require lower temperatures, which are outside the photometric error boxes. In other words, if a more accurate $T_{\text{eff}}$ becomes available we can put a lower limit on the mass.

In EW Cnc the detected frequencies are evenly distributed over a wide interval, while in EX Cnc they are concentrated in a narrow band. The horizontal bars labeled “A” in Fig. 7 indicate where most observed frequencies are found. In these frequency intervals we estimate that we have detected 40–60% of the modes in EW Cnc and 70–100% in EX Cnc. These results rely on the assumptions that the considered ranges in mass and $T_{\text{eff}}$ are realistic and that only $l \leq 2$ modes have detectable amplitudes.

To further investigate the distribution of peaks and search for recurring patterns we computed autocorrelations for the frequencies from the observations and the pulsation models. This method can in principle be used to extract important quantities for asteroseismic modeling like the large and small separation and rotational splitting. This would enable us to constrain the mass and temperature of the stars. Since we have no information about the relative amplitudes of the theoretical frequencies, each frequency is represented by a Gaussian of unit height and with a FWHM equal to twice the formal frequency resolution of the data set. To be able to compare the autocorrelations of the observed and theoretical frequencies, we follow the same procedure for the observations, i.e. only using the frequencies and not the observed amplitudes. We use the frequencies from the regions where the majority of the frequencies are observed. These regions are marked by horizontal bars labeled “A” in Fig. 7.

In the top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top panel only radial modes are included. The results for EX Cnc shows the large separation at $\approx 23 \mu$Hz for the model with high mass, while for the less massive model there is a low peak at twice the large separation (see top
Figure 7. Histograms showing the number of frequencies in EW Cnc (left panel) and EX Cnc (right panel) in frequency bins of 50 µHz. The filled histograms are for pulsation models and the colour describes how high angular degree is included. The thick black lines are for the observations. The top and bottom panels are for pulsation models with high and low mass with the adopted \(T_{\text{eff}}\). The models in the bottom panels both have mass 1.8 \(M_\odot\), slightly different \(v_{\text{rot}}\), and quite different \(T_{\text{eff}}\). The horizontal bar marked "A" marks the region used for the autocorrelation in Sect. 5.3.

Figure 8. Comparison of the autocorrelations of frequencies from pulsation models and the observed frequencies in EW Cnc (left panels) and EX Cnc (right panels). In the top panels we included only radial modes while in the middle panel we included modes with \(l = 0, 1,\) and 2. We show results for the same models as in Fig. 7. The bottom panels are the autocorrelations of the observed frequencies. In the middle panel we included all model frequencies with \(l = 0, 1,\) and 2; the higher number of modes makes the interpretation of the autocorrelation much more difficult. In the bottom panels we show the autocorrelations of the observed frequencies. There is an intriguing similarity between the autocorrelation of the observed frequencies in EX Cnc and the model with high mass (the middle and bottom right panels in Fig. 8). However, we are extremely cautious not to over-interpret the only marginally significant autocorrelation peaks at 2, 6, 12, and 24 µHz.

Although there appears to be qualitative agreement between the observations and the theoretical models, we cannot at this stage use the method to determine which combination of mass, evolutionary stage, or rotational velocity best describes the observations. To make progress and make a detailed comparison of the ob-
erved frequencies with theoretical models would require that we have identified at least some of the dominant modes. This can be achieved from the study of line-profile variations or from comparison of phase shifts of the frequencies in different photometric filters (Daszyńska-Daszkiewicz, Dziembowski & Pamyatnykh 2003). We cannot apply the latter method since most of our observations were done in the $V$ band with only a few nights of data in $B$.

6 CONCLUSION

We have analysed a new photometric data set of eight BS stars in M67. Only in the two known variable stars EW Cnc and EX Cnc do we find $\delta$ Scuti pulsations. We detect 41 frequencies in EW Cnc and 26 frequencies in EX Cnc. Compared to the previous multisite campaign by Gilliland & Brown (1992) we have detected four times as many frequencies in these two stars, and the number of frequencies is comparable to the best-studied field $\delta$ Scuti stars.

The frequencies with the highest amplitudes in EX Cnc are separated by roughly 1 d$^{-1}$ (see Fig. 3) and our extensive multisite data are therefore essential to study the pulsations in this star. We have made simulations of the light curves which show that the frequencies are recovered in all cases (see Appendix B). We repeated the Fourier analyses on subsets of the data to confirm that the same frequencies were extracted. Thus, we claim that the observed pattern cannot be due to the spectral window, but represents a real property of the distribution of frequencies in EX Cnc. Additional support for this claim is the fact that a similar pattern is not seen in EW Cnc.

We computed a grid of theoretical pulsation models that take the effects of rotation into account, which were not included in earlier models (Gilliland & Brown 1992). We find general agreement between the observed and computed frequencies when comparing their distribution in histograms. We can claim to have detected non-radial modes and in the range where most of the frequencies are observed, and at least 40% and 70% of all low-degree ($l \leq 2$) modes are excited in EW Cnc and EX Cnc, respectively. This is perhaps the most important result of the current study, since in the past decade of observational work on $\delta$ Scuti stars only a tiny fraction of the frequencies expected from theoretical models were in fact detected. A reasonable explanation is that high S/N and good frequency resolution is needed to be able to detect the weakest modes as was suggested by Breger et al. (2005) and Bruntt et al. (2007).

The autocorrelation of the observed frequencies does not show any significant peaks in any of the stars. However, autocorrelations of the frequencies from theoretical pulsation models show that if indeed modes with degree $l = 0$, 1, and 2 are observed, we cannot expect to unambiguously detect the large separation from such an analysis. This result was obtained while assuming that all amplitudes are equal, since no amplitude information is available for the theoretical models.

To improve on the interpretation of the rich frequency spectra of EW Cnc and EX Cnc, and other well-observed $\delta$ Scuti stars in general, we see two possibilities:

- On the theoretical side, it would be very helpful to have estimates of the amplitudes of the modes. If relative amplitudes could be reliably estimated from theory the autocorrelation might be a useful method for measuring the separation between radial modes and hence constrain the density of $\delta$ Scuti stars.

- On the observational side we need to be able to identify the degrees of at least the main modes. This can in principle be done by comparison of phases and amplitude ratios for different narrow-band filters as has been attempted for other $\delta$ Scuti stars (Moya, Garrido & Dupret 2004; Daszyńska-Daszkiewicz et al. 2005).

We have too few observations in the $B$ filter to follow the latter suggestion, and multi-filter (eg. Strömgren $by$) observations should be considered for similar campaigns in the future. The points mentioned here also apply when planning ground-based support for the CoRoT (Michel et al. 2006) and Kepler (Basri, Borucki, & Koch 2005) satellite missions. These missions will provide photometric time series with long temporal coverage of several $\delta$ Scuti stars, but only in a single filter.

On request we would gladly provide the light curves presented here.

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APPENDIX A: DATA POINT WEIGHTS

This Appendix contains a detailed description of how we calculated weights using an ensemble of reference stars (cf. Sect. 4.1). The reference stars were chosen from the most isolated stars, i.e. stars with a maximum of 10% flux from neighbouring stars within their
photometric apertures. Furthermore, we required that their point-
to-point scatter was close to the theoretical limit as determined by
photon noise. The observations from LOAO had the greatest field-
of-view with a total of 358 stars. For this site we used \( M = 65 \)
reference stars. For the site with the smallest CCD we used only
40 reference stars. In Fig. A1 we show the average point-to-point
scatter (\( \sigma_{\text{int}} \), see Eq. A1 below) for the stars at the LOAO site plotted
together against \( V \) magnitude. The solid grey line marks the fiducial
\( \sigma_{\text{int, fiduc}} \) that represents the typical scatter for the best stars at a
given magnitude. The reference stars are marked with filled circles,
and the inset shows the location of the stars in the colour-magnitude
diagram.

A1 Determination of scatter weights: \( W_{\text{scat}} \)

For each reference star we calculated the internal standard deviation

\[
\sigma_{\text{int}}^2 = \sum_{k=1}^{N} (m_k - m_{k+1})^2 / [2(N - 1)],
\]

(A1)

where \( m_k \) is the magnitude of the \( k \)th measurement and \( N \) is
the number of data points. For each reference star \( r \) and for each data
point \( k \), we measured how much the data point itself and the two
neighbouring data points \((k - 1 \text{ and } k + 1)\) deviated from zero, as

\[
\delta_r = \frac{|\Delta m_{k+1}| + |\Delta m_k| + |\Delta m_{k-1}|}{3 \sigma_{\text{int, fiduc}}},
\]

(A2)

where \( \Delta m \) is the deviation from zero and \( \sigma_{\text{int, fiduc}} \) is the fiducial scatter (cf. solid curve Fig. A1). Thus, \( \delta_r \) is a measure of the actual
scatter normalized by the expected scatter for a star of that magnitude.

\footnote{The neighbouring data points were required to be within a certain
time limit, set arbitrarily to ten times the median time step between frames (for
a given telescope). If there was only one neighbouring data point, we used
only this to compute the deviation \( \delta_r \). If there were no neighbouring data
points within the time limit (rarely the case), we assigned a weight that was
the mean of the weights of data points just before and after the point in
question.}

A2 Determination of outlier weights: \( W_{\text{out}} \)

We want to assign low weight to data points that deviate signifi-
cantly from the mean magnitude. We calculated the outlier weight
for each data point for the \( r \)th reference star as

\[
W_r = \left\{ 1 + \left( \frac{\Delta m_r}{\sigma_t} \right)^{b} + \left( \frac{\Delta m_r}{\sigma_f} \right)^{b} \right\}^{-1},
\]

(A4)

and the final outlier weight for the target star is the average value
\( W_{\text{out}} = \sum_{r=1}^{M} W_r / M \) using all \( M \) reference stars. In Eq. A3
\( \Delta m_r \) is the deviation from zero for the target star and \( \sigma_t \) is an esti-
mated scatter. Likewise, \( \Delta m_r \) and \( \sigma_f \) are the corresponding values
for the \( r \)th reference star. The values of \( \sigma_t \) and \( \sigma_f \) determine how
much a data point must deviate before the outlier weight becomes
significantly smaller than 1. For the target star we used \( \sigma_t = 3 \)
and for the reference stars we used \( \sigma_f = 2 \). Thus, data points that lie
within \( 3 \sigma \) for the target star, and within \( 2 \sigma \) for the majority of the
reference stars will not get low outlier weights. The exponent \( b \) de-

Figure A2. The top panel shows the light curve of a reference star from
WFI. The grey points have scatter weights \( W_{\text{scat}} < 25\% \). The bottom
panel shows the scatter weight found using all the reference stars. The
dashed horizontal line marks the 25\% level.

Figure A3. The light curve of a reference star is plotted versus a target star
(EW Cnc) for data from WFI. The large black dots have outlier weights
\( W_r < 0.5 \). We plot the “3 \( \sigma \) ellipse” in grey colour (see text for details).

Based on all \( M \) reference stars, we then computed the average deviation of the \( k \)th data point as \( \langle \delta \rangle = \sum_{r=1}^{M} \delta_r / M \), and calcu-
lated the scatter weight as

\[
W_{\text{scat}} = \frac{1}{(\langle \delta \rangle + \delta_{\text{floor}})^{2}},
\]

(A3)

where we used \( \delta_{\text{floor}} = 1 \text{ mmag} \) to avoid that a few very good
stars dominate. The optimal choice of the exponent \( n \) is discussed in Sect. 4.3.

In Fig. A2 we show the light curve versus data point number
for one reference star in the top panel. These data are from the
Wide-Field Imager (WFI) at Siding Spring, Australia. In the bottom
panel we plot the derived scatter weights normalized so that the
highest weight equals 1. The dashed horizontal line marks the limit
for data points with scatter weights \( W_{\text{scat}} < 25\% \). These points
are plotted with grey symbols in the top panel as well.
scribes how steeply $W_r$ decreases from one to zero. We used the value $b = 4$. To estimate the scatter $\sigma$ in Eq. A1 for the target and reference stars, we use the scatter weights $W_{\text{scat}}$ from Sect. A1. We approximate $\sigma = \sigma_{\text{int}} \cdot \eta$, where $\sigma_{\text{int}}$ is computed from Eq. A1 and $\eta = \langle W_{\text{scat}} \rangle / W_{\text{scat}}$, where $\langle W_{\text{scat}} \rangle$ is the average scatter weight over the entire series. Thus, $\eta$ is a measure of the relative change in scatter from frame to frame.

To illustrate the process we have plotted the light curve of a reference star versus the target star EW Cnc in Fig. A3. The grey ellipse has half-major and half-semi-major axes corresponding to $3 \sigma_{\text{int}}$ for each star. Intuitively, there are too many points outside this “3 $\sigma$ ellipse”. If the noise were Gaussian, the fraction of points that would fall outside the $3 \sigma$ limit would be only $P_{\text{Gaus,3$\sigma$}} (2D) = 1.1\%$. This corresponds to only 24 out of 2150 data points from WFI, while about 100 are found in the data. The large black dots in Figure A3 have outlier weights $W_r < 0.5$ and small points have $1 \geq W_r \geq 0.5$.

In Fig. A4 we show the light curves of EW Cnc and the same reference star as in Fig. A3. For the reference star (top panel) the filled circles mark data points with low outlier weights, i.e., $W_r < 0.5$. The data points of the target EW Cnc are shown in the bottom panel in Fig. A4. We have marked the points with final outlier weights $W_{\text{out}} < 0.5$ with filled squares$. It is interesting to note that several data points are not obvious outliers. In fact some of the marked outliers have $\Delta m < 2 \sigma$, where $\sigma$ is the local rms scatter. The reason for these points having $W_{\text{out}} < 0.5$ is that they were outliers in most of the reference stars.

APPENDIX B: LIGHT CURVE SIMULATIONS

Simulating the light curves has two goals:

- To measure our ability to extract the inserted modes for cases A and B and decide which one is optimal.
- To measure the uncertainty on the frequency, amplitude, and phase.

The simulated light curves were constructed to have the same noise characteristics as for the observations. To measure the properties of the noise in the observations, we first subtracted the detected frequencies before computing the amplitude spectrum. We used two components to describe the white noise and the drift noise:

1. The white noise was measured as the mean level in the observed amplitude spectrum the frequency range 1000–1500 $\mu$Hz.
2. The drift noise leads to an increase in the noise level towards low frequencies. This “$1/f$” noise was measured by fitting a fiducial spline function to the observed increase in noise in the amplitude spectrum.

Since each site had a different white noise component and a different shape of the $1/f$ noise we constructed the light curve site by site before adding the data as we did for the actual observations.

In practice we created an evenly sampled light curve covering the time span of the observed time series, but with an over-sampled grid in time by a factor five. Each light curve consist of random numbers with different seed number. The mean is zero and the numbers have a point-to-point scatter corresponding to the noise level found in step (1). Firstly, we take the Fourier transform of the light curve to the frequency domain, and multiply the result by the fiducial spline fit found in step (2). We then take the Fourier transform to return to the time domain, and pick the synthetic data points closest in time to the observed data points. Finally, we add the frequencies detected in the star. For each star 50 simulations were realized.

We made a Fourier analysis of each simulation as we did for the observed data (see Sect. 4.3). In Fig. B1 we show how often each inserted frequency was recovered in the simulations versus S/N. The top and bottom panels are for EW Cnc and EX Cnc, respectively. In each panel open and solid symbols correspond to cases A and B (Sect. 4.3). For EW Cnc it is seen that in both case A and B all frequencies with S/N $> 5$ are recovered. We prefer case B for EW Cnc since it has a significantly lower residual noise level (see Table I). For EX Cnc we chose case A because it shows a much better recovery rate than case B.

The uncertainties on frequency, amplitude, and phase given in Tables 2 and 3 are computed from the rms scatter in the simulations. We plot the uncertainties versus the amplitude for EW Cnc (case B) and EX Cnc (case A) in Fig. B2. The dashed lines are theoretical lower estimates of the uncertainties using the expressions from Montgomery & O’Donoghue (1999), which are valid for uncorrelated noise, i.e., for data with only a white noise component. For real data one must multiply the uncertainty by the square root of the estimated correlation length (Montgomery & O’Donoghue 1999). We found this by calculating the autocorrelation of the residual amplitude spectrum after the mean value has been subtracted. The intersection of the autocorrelation function with zero is a measure of the correlation length, $D$. For both EW Cnc and EX Cnc we find $D = 3.2 \pm 0.1$ or $\sqrt{D} = 1.79 \pm 0.06$. The resulting estimates of the uncertainties are marked by the solid lines in Fig. B2.

In general we find an acceptable agreement with the estimated uncertainties from Montgomery & O’Donoghue (1999). For most parameters the estimated uncertainties are too low, especially so for the frequencies and phases in EX Cnc. This is likely because the frequencies lie closer in EX Cnc compared to EW Cnc. The

$^6$ Note that the stellar oscillations were subtracted before calculating outlier weights.

$^7$ Recall that $W_{\text{out}}$ is the mean of $W_r$ for all reference stars $r$. 

Figure A4. In the top panel the light curve of a reference star is shown, where filled circles have reference star outlier weights $W_r < 0.5$. The light curve of the target star (EW Cnc) is shown in the bottom panel, where filled boxes have final outlier weights $W_{\text{out}} < 0.5$ (see text for details).
uncertainties on the amplitudes in EW Cnc are close to the estimate for uncorrelated noise.

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