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Mode characterisation in δ Scuti stars[⋆]

I. ρ Pup, GN And, V1208 Aql and AV Cet

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Abstract. We present new spectroscopic observations of four bright δ Scuti pulsators. Line indices of the Balmer lines can be used to establish mode identifications using the ratio R between such line index amplitudes and photometric amplitudes. For the well known radial pulsator ρ Pup an absolute value of the amplitude ratio of the radial mode was found to $R = 0.43$, consistent with earlier values of $R \sim 0.5$ reported for other δ Scuti stars. In GN And we recover the recently reported newly excited mode, while the former dominant mode was not recovered. We confirm that V1208 Aql is a non-radial pulsator, containing two modes of different degree. In V1208 Aql we report a previously unseen mode behavior: the phases of both modes are reversed between the core and wings of the Hβ line, suggesting the presence of more undetected modes. For AV Cet we find that the dominant mode is a previously undetected one. We suggest the undertaking of new photometric observations of ρ Pup, GN And, V1208 Aql and AV Cet to determine the frequencies and amplitudes of the pulsations.

Key words. stars: oscillations – stars: variables: δ Sct – stars: individual: GN And – stars: individual: V1208 Aql – stars: individual: AV Cet – stars: individual: ρ Pup

1. Introduction

To gain insight into the physics of δ Scuti stars, one needs information about the eigenfunctions of the excited modes. Through extensive photometry we have very precise frequencies and photometric amplitudes of the modes of a large number of stars. It is however generally accepted that more information from either spectroscopy or multicolor photometry is needed in order to identify the modes. We have been applying a spectroscopic analysis involving line-indices of stellar absorption lines to a number of stars with great success (Dall et al. 2002a; Viskum et al. 1997). This analysis has so far only been applied in direct combination with simultaneous photometry, which restricted the degrees of freedom in the analysis, by determining accurate frequencies and amplitudes.

This paper presents results from short runs on a sample of bright δ Scuti stars (Table 1). All stars have been reported to pulsate in more than one mode, they have at least one well-known frequency, and the sample spans a wide range in $v \sin i$.

Despite of their relative brightness, to our knowledge, no new observations have been conducted on these stars for quite some time. The aims of our observations were to confirm the presence of pulsations in the line indices of the Balmer lines and to determine whether there is agreement with the frequencies found in the literature. As an additional aim, these mini-runs serve as excercises for the planning and implementation of future campaigns, both in terms of targets, instrumentation and of the diagnostic capabilities of the applied analysis.

The line indices applied in this paper are proportional to the equivalent width (EW), and thus sensitive to the temperature variations in the star. To calculate the line indices of the Balmer lines, $\Lambda^{\mathrm{H}i}, i = \alpha, \beta, \ \ldots$ we follow the procedure of Dall et al. (2002a): a line-index is similar to the Strömgren Hβ index, in that it integrates part of the flux in a line. The difference is that applying software filters, one can calculate any number and type of line index. In general a given Λ_i is characterized by the shape of the filter W_i^x used, where the integration is carried out over pixels (x-coordinate):

$$\Lambda_i = \sum_x \frac{C_x - S_x}{C_x} W_i^x, \qquad (1)$$

where S_x is the flux in pixel bins, and C_x is the continuum over the line.

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[⋆] Based in part on observations made with the Danish 1.5-m telescope at ESO, La Silla, Chile.

When simultaneous photometry and line index measurements exist, we can use the ratio of the amplitudes in line index and photometry to attempt a mode identification, following the investigation by Bedding et al. (1996) of the sensitivity of different absorbtion lines to pulsation modes with different ℓ. They showed that the Balmer lines have sensitivity similar to radial velocity measurements because of the strong limb darkening in these lines, while photometry has very weak center-to-limb variation. Thus the line indices of Balmer lines and the photometry show different response to spatial variations across the stellar disk (i.e. to the ℓ value), because the Balmer lines sample the centre of the disk stronger than the limb while photometry smear out spatial variations across the disk. Thus, the amplitude ratio

$$R = \frac{A(\Lambda^{\mathrm{H}\alpha})}{A(v)} \qquad (2)$$

(in units of mag^{-1}) between the amplitudes of $\Lambda^{\mathrm{H}\alpha}$ and photometry is an increasing function of ℓ, so that modes with different ℓ will be grouped in an amplitude ratio diagram. In Eq. (2) v and $\Lambda^{\mathrm{H}\alpha}$ are chosen as examples, but any photometric band and any Balmer line index can be used. The great advantage of this method is that it requires only modest spectral resolution and hence can be applied to stars that are too faint to be observed by high resolution techniques.

What has hitherto remained unanswered was which values of R to expect for a given ℓ. One approach is the statistical one of Viskum et al. (1997, 1998) and Dall et al. (2002a), who investigated the multi-mode pulsators FG Vir and BN Cnc respectively, basing the assignment of ℓ values on the clustering of modes with the same R. They assigned modes with the lowest values of R to radial pulsation, and higher values of R to higher degree modes. This seemed to work extremely well, as in both cases the results seem to be confirmed by independent studies. For both stars the amplitude ratio $R_{\ell=0}$ of the radial modes was around 0.5.

Another approach is taken in this paper: by investigating a well studied δ Scuti star with very accurately determined period and amplitude, and known to be a radial pulsator, one may calibrate $R_{\ell=0}$ to an absolute value. The star ρ Pup is a good example. It has only one well defined and stable period, and is generally agreed to be a radial pulsator (e.g. Baglin et al. 1973; Kurtz 1976). Hence it poses a good case for determining an expected value of $R_{\ell=0}$. However, ρ Pup is a metallic-line star, situated close to the red edge of the instability strip and hence not “typical”.

$R_{\ell=0}$ will depend on temperature and gravity, and some spread is expected when looking at a larger sample of stars. Large variations are not likely though, as limb darkening does not vary drastically among δ Scuti stars. Fast rotation, on the other hand, might change this simple picture.

Table 1. The program stars, also listing the observations presented in this paper. The parameters are taken from Rodriguez et al. (2000).

Name	V [mag]	$v \sin i$ [km s^{-1}]	Observations time [hours]	# of spec.
HR 3185 (ρ Pup)	2.81	15	8.03	605
HR 114 (GN And)	5.20	16	8.55	486
HR 7331 (V1208 Aql)	5.53	51	8.16	546
HR 401 (AV Cet)	6.21	141	3.92	92

2. Observations

The observations of the three fainter stars discussed here (GN And, V1208 Aql, AV Cet) have been done with the 2.54 m Nordic Optical Telescope (NOT) during periods of Technical Time. In all cases we used the same ALFOSC setup in echelle mode covering 8 spectral orders including the Balmer lines from Hα to Hδ with resolution around 4300. The detector is a Loral/Lesser 2K device with 15μ pixels, which we windowed to 820 by 2050 pixels. The full frame readout time is ~80 s and the window was read out in 35 s.

ρ Pup was observed with the Danish 1.54-m telescope at ESO, La Silla, as a secondary target during a campaign on the roAp star HR 1217. As HR 1217 set an hour before morning twilight, we used the remaining time for ρ Pup, with DFOSC in echelle mode, covering only three orders with Hα in the middle order, resolution around 4300.

Below follow details of the observations on each star.

Observations of ρ Pup

Observed for 20–60 min at the end of the nights of Nov. 30 to Dec. 13 of 1998, with integration times between 3 and 8 s. Generally good weather throughout the period.

Observations of GN And

The star was observed on 2000 Sep. 12 and Oct. 16, i.e. with a gap of 34 days in between. With integration times of 20–25 s on Sep. 12, and 50 s on Oct. 16, we achieved duty cycles of 40% and 58% respectively on the two dates. Clear weather and photometric conditions on both nights.

During the Sep. 12 observations, it was not possible to observe for approximately two hours when the star was passing within 4° of zenith, where it is impossible for the telescope to track. On Oct. 16, GN And was only the target for the first part of the night, with AV Cet observed during the second half.

Observations of V1208 Aql

Observed for 8.16 hours on 2000 Jul. 17. With integration times of 16–20 s we obtained a duty cycle of 34%. The night was clear with photometric conditions.

Observations of AV Cet Observed during the second half of the night of 2000 Oct. 16. The first half of the night was devoted to GN And. Integration times were between 105 and 120 s, giving an overall duty cycle of 76%. The weather was clear and conditions photometric.

3. Data reduction

All spectra were reduced in the same way using IRAF tools. After filtering out CCD cosmetics and doing overscan correction, all images had bias subtracted. The scattered light was removed before normalizing the master flatfield. After flatfielding, the orders were extracted and normalized with the Blaze function of the flatfield.

We chose to normalize the orders with the Blaze function of the flatfield instead of using the Blaze for the individual images, in order to use a constant normalization. This causes the spectral orders to be sloped because of the temperature difference between the flatfield lamp and the star. However, this does not influence the subsequent analysis. The advantage of this approach is the avoidance of errors introduced by trying to fit across the broad Balmer lines, which are more or less centered on the top of the Blaze.

Due to the fast readout mode chosen for the ρ Pup observations, we had to make one extra correction before extracting the orders: the two amplifiers of the DFOSC CCD controller each read out half of the image and the two halves were reduced separately. Even so, a small offset ($<$1%) remained which was corrected by simple scaling.

None of the extracted spectra were continuum normalized and no wavelength calibrations were done.

The software for calculating line indices is called *Ix* and has been described by Dall (2000).

4. Establishing the calibration: ρ Pup

The pulsation period of ρ Pup is known very accurately ($P = 0.14088$ d^{-1}). For all practical porposes it is a monoperiodic pulsator, although Mathias et al. (1997) found evidence for additional modes at a very low level. The main pulsation is generally agreed to be radial.

Since the individual data segments cover only a small fraction of the pulsation period, we have plotted the data only as a function of the pulsation phase in Fig. 1. As can be seen, the amplitude is found to be 32 promille[1] in $\Lambda^{\mathrm{H}\alpha}$. Assuming the pulsation to be stable, we can take the photometric amplitude $A = 75$ mmag found by Eggen (1956), and use Eq. (2) to obtain the amplitude ratio of this radial mode as $R = 0.43$. Note that there exist other measurements of the photometric amplitude, e.g. 90 mmag (Baglin et al. 1973) and 100 mmag (Kurtz 1976).

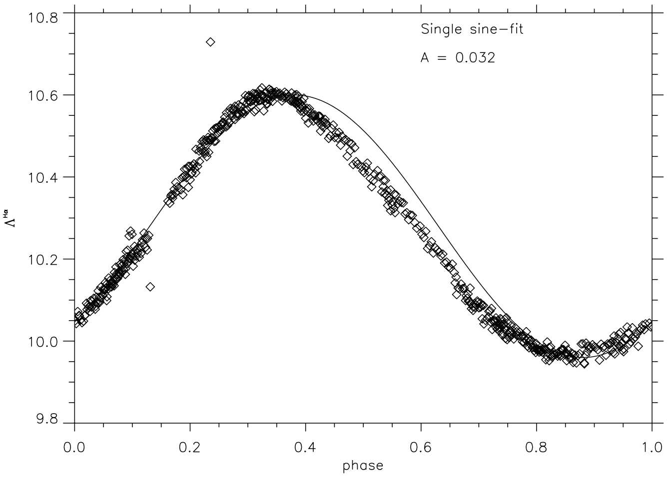

Fig. 1. ρ Pup: the $\Lambda^{\mathrm{H}\alpha}$ data plotted against the pulsation phase. The asymmetry of this curve closely resembles the photometric light curves.

This low R is consistent with the findings of FG Vir and BN Cnc that radial pulsation will have low amplitude ratios around 0.5. As mentioned earlier, we do not expect to find strictly the same value of R for radial modes. Fast rotation will not complicate the interpretation for ρ Pup, but the photometric amplitude is not precisely known. It may also be quite plausible that the peculiar metallicity may have an effect.

We conclude that the value $R_{\ell=0} = 0.43$ found here is sufficiently close to the expected value 0.5.

5. Analysis of GN And, V1208 Aql, and AV Cet

All three stars were subjected to the same analysis. First the line indices were calculated for the first four Balmer lines. In all cases Hδ was found to have very high noise due to the low efficiency of the cross-disperser grating, so this line was not included in our analysis. Hβ had in all cases the highest S/N, as this line is situated at the peak efficiency of the cross-disperser.

In all cases a fit to the time series was attempted using the reported frequencies, and using the fitting program Period98 (Sperl 1998). The uncertainty in the frequency determination is very high for such short series, so we merely want to confirm that the time series can be fitted using the known frequencies.

Below we present the details of the analysis and a discussion of the individual stars.

5.1. GN And: Analysis and discussion

The data from the two nights were taken with slightly different slitwidths, so we had to choose the filters so that the data from the two nights are directly comparable. This was done by assuring that the mean value in the two nights was the same for a given line, and that the set of filters for the two nights differed only by a simple scaling factor. The final time series of line indices contains 486 points.

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[1] Note that *promille* is parts-per-thousand and that 1 promille equals 1.086 mmag.

Table 2. The frequencies from Rodriguez et al. and the amplitudes found in the Hβ line index of GN And. Amplitudes are given in promille.

mode	frequency [d^{-1}]	amplitude	S/N
f_1	14.43	0.8	3.6
f_2	17.23	1.2	5.5

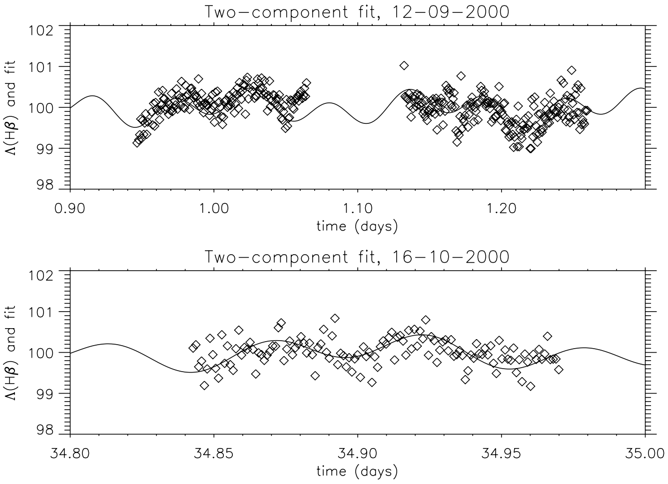

Fig. 2. Fit to the timeseries of GN And. The data have been scaled to an (arbitrary) average value of 100.

Because of the large separations between the two data sets and the relatively short length of each set, our goal was only to check the presence of the known mode at 14.43 d^{-1} (Rodriguez et al. 1993) and if possible verify the existence of the new mode at 17.23 d^{-1} reported by Rodriguez et al. (1998).

The data were decorrelated against external parameters such as the airmass and the slope of the continuum. These are measures of systematic errors from instrumental drifts, mainly spectrograph bending. We were able to remove these errors by simple linear fits.

The noise level in the time series is 4.5 promille for $\Lambda^{\mathrm{H}\alpha}$ and 2.7 promille for $\Lambda^{\mathrm{H}\beta}$, measured as the point-to-point scatter. This means that a 4σ detection in $\Lambda^{\mathrm{H}\beta}$ requires an amplitude of at least 0.9 promille. For the case of the better S/N of $\Lambda^{\mathrm{H}\beta}$ we have plotted a two component fit to the time series in Fig. 2. The components of the fit are listed in Table 2.

Detection of the f_1 mode can not be claimed, since its amplitude is only around or slightly below the detection limit. Rodriguez et al. (1998) find the photometric amplitude of f_1 to be 1.8 mmag, decreased by a factor of 19 between 1991 and 1996. That f_1 is not detected in our data could mean that its amplitude has decreased further to below our detection limit of 0.9 promille, which corresponds roughly to a photometric amplitude of 0.9 mmag. If the mode is indeed $l = 2$ as suggested by Rodriguez et al. (1993), then we expect it to have roughly equal amplitudes in photometry and Λ^{H}, favoring the scenario of a decreasing amplitude.

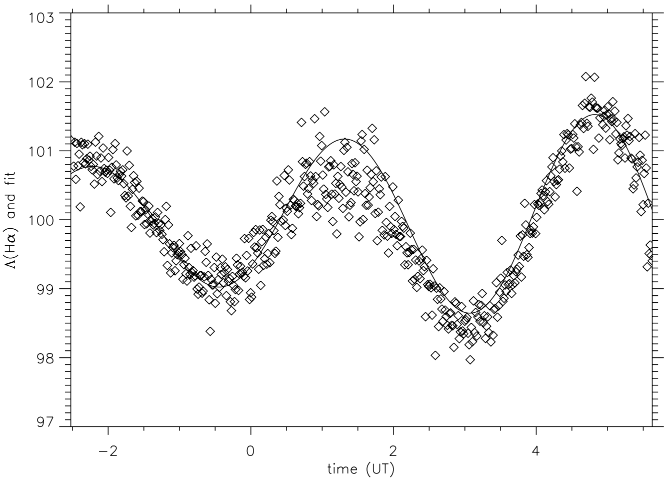

Fig. 3. V1208 Aql Hα time series and the fit using the known frequencies.

Table 3. The frequencies and amplitudes found in V1208 Aql for the three Balmer line-indices (in promille). Also listed are the photometric amplitudes (in mmag) from Wehlau & Wehlau (1995).

mode	frequency	amplitude of...			
	(d^{-1})	photometry	$\Lambda^{\mathrm{H}\alpha}$	$\Lambda^{\mathrm{H}\beta}$	$\Lambda^{\mathrm{H}\gamma}$
f_1	6.68	18.1	12.5	10.8	13.2
f_2	7.12	6.3	9.9	7.0	6.3
$S/N(f_1)$			60	64	46
$S/N(f_2)$			47	41	22

An alternative explanation is that the mode is radial, as suggested by Balona (1999). In this case we would expect the amplitude in Λ^{H} to be lower than in photometry. If that is the case, then the mode can have the same photometric amplitude of 1.8 mmag as in 1996, but still be well below our detection limit.

As is evident, new photometric time series are required to clarify the current pulsational content of GN And.

5.2. V1208 Aql: Analysis and discussion

The photometric variability of V1208 Aql was discovered by Breger (1969) and has been described by Reed & Welch (1988) and Wehlau & Wehlau (1995) as being multiperiodic. The latter give the two frequencies adopted here, and they note that there might be additional periods present. Our data set is too short to allow a search for extra periods, so our aim is merely to investigate the known oscillations using line indices of the Balmer lines.

With the two previously reported frequencies we obtain a satisfactory fit to the time series of the line indices of Hα, Hβ and Hγ, using filters with $FWHM \sim 30$ Å. The fit for $\Lambda^{\mathrm{H}\alpha}$ is shown in Fig. 3. The amplitudes of the two modes in the three series $\Lambda^{\mathrm{H}\alpha}$, $\Lambda^{\mathrm{H}\beta}$ and $\Lambda^{\mathrm{H}\gamma}$ are listed in Table 3. The noise in the three series, measured as the point-to-point scatter is 2.79, 2.27, and 3.86 promille respectively, yielding very high S/N.

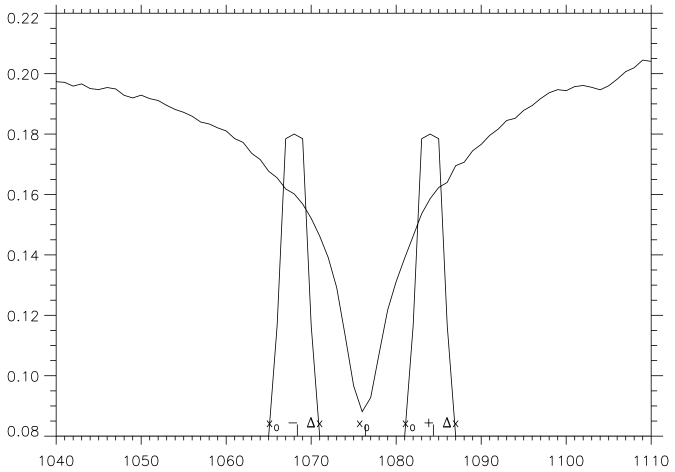

Fig. 4. A symmetrical filter to investigate different parts of the line by varying Δx.

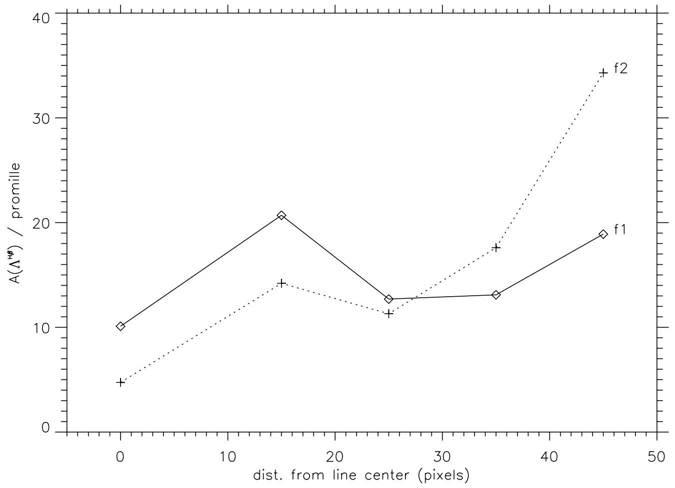

Fig. 5. V1208 Aql Hβ amplitudes in different parts of the line. See text for discussion and noise considerations.

The definition and the S/N in this series are so good that we can test several filters on the three Balmer lines. We have defined a series of filters consisting of two quite narrow filters ($FWHM \sim 10$ Å) on each side of the line center x_0 as shown in Fig. 4. Varying the distance Δx to the line center, we can then investigate the oscillations in different parts of the line. In Fig. 5 we show the amplitudes of the two modes as a function of Δx. Quite surprisingly, we find much larger amplitudes than in the broad filters used for Table 3 and Fig. 3. The noise increases smoothly from 1.84 promille in the center to 10 promille in the wings (point-to-point), which means that the modes are still very well defined at all points.

The explanation for this behavior is that both modes are changing their phase from the line center to the wings by at least 180°, as can be seen from Fig. 6. This phenomenon raises the question whether the amplitudes of line-index variations can be used as a reliable diagnostic tool for mode typing in δ Scuti stars, as used by Viskum et al. (1998) and Dall et al. (2002a). To investigate this, we applied the same filter sequence to the data of Viskum et al. and Dall et al. and found no such dramatic effects to be present.

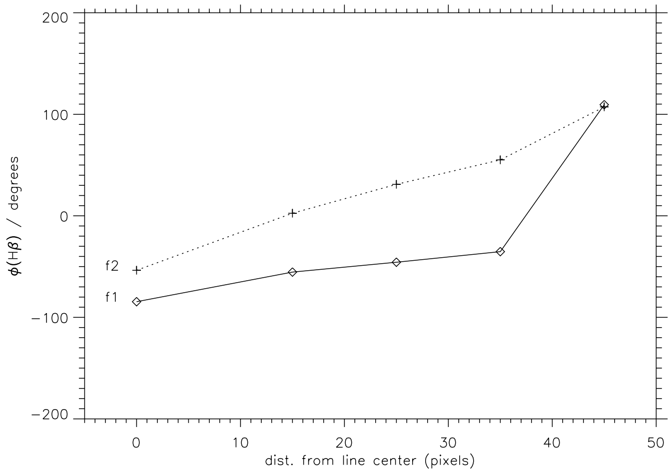

Fig. 6. V1208 Aql; the changing phase of the modes when going from the core to the wings in Hβ. At the center the formal errors are $\sim$1°, rising to no more than 3° in the wings.

A possible explanation of this effect could be that the single mode really consists of two or more modes which are very close together, and whose eigenfunctions are sampled differently in different depths of the atmosphere. If this is the case, then this method can be used to probe for the possible existence of modes that would otherwise remain undetected. In the present case the comment by Wehlau & Wehlau about the indications of more modes seem to support this hypothesis.

We find it very unlikely that this can be due to a node in the eigenfunction situated just right in the stellar atmosphere, since the typical modes in δ Scuti stars are of low order. Also, if this was the case, then we would expect the mode amplitude to be very low at some point in the line, but this is not observed.

The photometric amplitudes are at least six years old, but assuming that the amplitudes have not changed significantly in the past six years, we can attempt some general typing of the mode nature using the analysis outlined in Sect. 3. We will use the amplitudes of Λ^{H} listed in Table 3, noting that although the amplitude changes considerably over the extent of the line, the biggest change is in the wings where the contribution to the total EW is small. Moreover, it is a broad filter resembling very closely the EW that should be compared to the photometric amplitude, which is also an integrated quantity, with the important difference that we cannot freely choose the integration filter. Thus, the EW of the line should still reflect the geometric properties of a given mode, and hence be usable for the analysis based on amplitude ratios.

As noted also by Reed & Welch (1988) and by Peña & Warman (1979), the period ratio is inconsistent with two radial modes. For the dominant mode, we find an amplitude ratio R consistently and significantly below 1, while for the secondary the ratio is around or a little above 1. The two modes will then have different degree, with the

Table 4. The reported frequencies in AV Cet, this paper (DF) and from GB. Amplitudes are given in mmag for the photometry of GB and in promille for the Λ data. For the fit we have taken the frequencies of this work. Se text for discussion.

mode	frequency [d^{-1}]		amplitude	comments
	GB	DF	$\Lambda^{\mathrm{H}\beta}$	
f_1	14.59	9.6	1.8	A(GB) $\sim$ 10 mmag
f_2	19.19	21.9	1.9	
f_3	-	33.3	2.3	new mode?

low-ratio mode being the low-degree mode. The values of the ratios point towards non-radial modes, but the vintage of the photometric amplitudes disallows any firm conclusions. Hence, we suggest that the two modes (f_1, f_2) have one of the following possible ℓ-values: (0,1), (0,2), (1,2). This suggestion is in accordance with the suggestion of Reed & Welch, that both modes cannot be radial. With $v \sin i = 51\ \mathrm{km\,s^{-1}}$ we find it unlikely that R depends very much on the azimuthal number m. The difference in R of the two modes should thus reflect a different degree.

It is however very important to obtain new photometric time series for V1208 Aql to determine the current amplitudes of the known modes. Reed & Welch note the disagreement of the frequency content found in data sets from different years, and propose that the star may have undergone period changes, or more likely have experienced the excitation of new modes. So the frequency content also needs to be asertained. As this is a bright star, such a task can be carried out with a small telescope.

5.3. AV Cet: Analysis and discussion

The variations of AV Cet are rather poorly studied. Gonzalez-Bedolla (1990, hereafter GB) and Gonzalez-Bedolla et al. (1990) found a dominant frequency and some sign of additional frequencies from four nights of photoelectric observations in 1984. The characterization of this star as double- or multiperiodic is evident from the lightcurves of Gonzalez-Bedolla. From his Fig. 1 the amplitude seem to be ~10 mmag, although he keeps the quote of Jørgensen et al. (1971) of 20 mmag.

Our data set covers only around four hours, but shows also clear evidence for multiperiodicity. Of our three Balmer line indices, the Hα data are clearly noisier than the other two, thus for an estimate of frequencies and amplitudes we have considered only the combination $\Lambda^{\mathrm{H}\beta} + \Lambda^{\mathrm{H}\gamma}$.

The internal scatter in the series is ~1.1 promille, so amplitudes need to be of the order ~0.8 promille to claim a 4σ detection.

The combined Hβ and Hγ line indices and the fit corresponding to the frequencies f_1–f_3 of Table 4 are shown in Fig. 7. For the fit of Fig. 7, we have used the frequencies found by a period search (using Period98) in order to produce a more accurate fit. Due to the short time base these periods have very high uncertainties (± 3.9 d^{-1}), wherefore we do not claim these to be more correct than the periods found by GB. However, these do not fit the data very well, and only by inclusion of f_3 do we get a satisfactory fit. Even though f_3 can be explained by e.g. $f_1 + f_2$, we find it highly unlikely that such a combination would produce an amplitude this large.

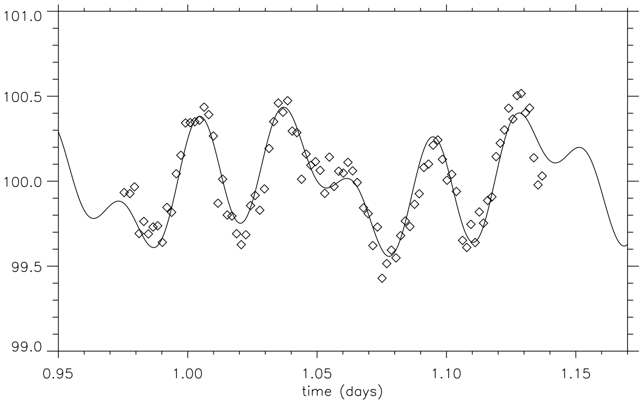

Fig. 7. AV Cet time series of the combined Hβ and Hγ line indices. The time is relative to the date at start of observations i.e. 1.00 is midnight.

Assuming that f_3 is indeed a real mode and noting the six minute sampling rate of GB, we are sure that this mode would have been detected in that data set, if it had been present in 1984. Thus, this might be a newly excited mode, which now seems to be the dominant one in AV Cet. However, new observations will be required to resolve this issue.

6. Discussion

In all three stars we have recovered the oscillations, although the frequency solutions did not match completely with previously published values. This can generally be ascribed to our very limited time base.

We have found evidence that new modes are being excited in GN And and AV Cet, demonstrating that such effects occur as a general rule in δ Scuti stars, both in slow and fast rotators. For both stars new photometric observations would be very welcome to obtain accurate frequencies and amplitudes for the modes and to confirm the presence of new modes. A multisite campaign was carried out on AV Cet in 2001 Oct.–Nov., involving both photometry and spectroscopy, thus we may hope soon to have a clearer picture of the pulsational content and the mode behavior of this star. This campaign has already established the multiperiodic nature of AV Cet confirming the presence of at least 5 frequencies (Dall et al. 2002b).

We also find evidence for amplitude variations in AV Cet, with a factor of at least 5 to the photometric amplitudes of Gonzalez-Bedolla (1990). The recent campaign of Dall et al. (2002b) confirms the present amplitude of the photometric variations.

The non-detection of the previously reported dominant mode at 14.43 d^{-1} in GN And can be explained either by amplitude variations, or by a radial nature of the mode. Thus, we have here the potential to distinguish between the two proposed mode identifications.

In V1208 Aql we have strengthened the case for non-radial pulsation, and confirmed that the two modes have different degree. The dominant mode is the low-degree mode and the assignments we suggest are (0, 1), (0, 2), (1, 2) to the two modes (f_1, f_2) at 6.68 d^{-1} and 7.12 d^{-1} respectively. However, new photometric amplitudes would be needed to make a clear assignment.

We have found a previously unseen mode behavior: in V1208 Aql both modes reverse their phases going from the center of the line to the wings. This effect is not seen in FG Vir or BN Cnc, suggesting that multi-mode pulsators do not in general show such behavior.

Even though new photometry is needed to establish reliable frequencies and amplitudes, we have successfully demonstrated the potential of the method. The instrumentation proved to be reliable, with consistently good results. The combination of intermediate resolution and a small telescope produce very high quality data, adequate for this kind of work, which is encouraging for the planning of future extended campaigns.

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