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The variability of a newly discovered γ Doradus star, HD 108100

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Abstract. A coordinated photometric campaign at five observatories to monitor the suspected brightness variations of the early-F star HD 108100 was undertaken by the DSN (Delta Scuti Network) and WET (Whole Earth Telescope). 288 hours of high-quality observations during a 58 day time span led to the discovery of two frequencies of 1.32 and 1.40 c/d with V amplitudes of 0.010 and 0.007 mag. The detection of both frequencies is statistically significant with amplitude signal/noise ratios of 18 and 12. The light variations are accompanied by $v - y$ color variations of 0.005 and 0.003 mag, respectively.

The variability of HD 108100 is typical of the new class of γ Dor variables. We also derive amplitude ratios and phase differences between the light curves at different wavelengths. These are consistent with g-mode pulsation of $\ell = 1$, but not $\ell = 2$. The observed periods can be fit by two modes with successive radial orders of $n \sim 19$.

Studies of the δ Scuti star 4 CVn from 1970 to 1976 reported the existence of unusually low frequencies of 1.3 and 1.4 c/d. These frequencies can now be traced back to HD 108100, the single comparison star used in these studies. Consequently, 4 CVn should no longer be regarded as an example of a star exhibiting both δ Scuti type pulsation (acoustic modes of mixed character) and γ Dor variability (gravity modes of high order).

An analysis of unpublished data from 1970 to 1976 shows that the amplitudes associated with the two frequencies of HD 108100 are variable and that the two frequencies can appear to switch their power.

Key words: stars: variables: other – stars: oscillations – stars: individual: HD 108100 – stars: individual: 4 CVn

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1. Introduction

The γ Doradus variables are a newly discovered class of multiperiodic variable stars, found mainly among main-sequence stars at or near the cool border of the δ Scuti star instability strip. In the literature they have also been called slowly variable early F-type stars. These stars show periodic light variations with periods of many hours to days. Such periods are too long to be attributed to radial or p-mode pulsation.

Evidence for a new class of pulsating stars was presented by Balona, Krisciunas & Cousins (1994), who photometrically examined the star γ Doradus and found it to be a slowly variable multiperiodic star. Two attractive hypotheses to explain the variability of this new class of variable stars are spots rotating with the star and pulsation. The spot hypothesis can explain some multiperiodic behavior, e. g. two close periods could be caused by differential stellar rotation. However, for the star γ Dor, Balona, Krisciunas & Cousins found a period of 0.678 d in addition to the 0.757 and 0.733 d periods. The relative large difference between the values of the periods is not compatible with the spot hypothesis and therefore supports the interpretation in terms of nonradial gravity mode pulsation. Furthermore, for 9 Aur, Krisciunas et al. (1995a) found periods of 1.26 and 2.90 d. Aerts & Krisciunas (1996) interpret these two periods with a $\ell = 3$, $|m| = 1$ spheroidal mode and its toroidal corrections due to the rotation of the star.

The pulsational excitation of γ Doradus stars is caused by the κ mechanism operating in the HeII ionization zone, the same as for the δ Scuti stars, according to model calculations by Moskalik (private communication). These models predict that among A and F stars, there would be a separation in temperature between p-mode (δ Scuti) and g-mode (γ Doradus) pulsators. This separation would be similar to that found between the β Cep and

Table 1. Photometric measurements of HD 108100

Telescope	Observers	Filters	Number of nights (hours)	
			First analysis	Final analysis
McDonald Observatory, USA, 0.9m	Handler, Audard, Guzik	y, v	18 (124.7)	21 (140.6)
Xing Long, China, 0.85m	Li, Jiang, Liu, Zhou	V	0 (0)	11 (64.3)
Piszkéstető, Hungary, 0.5m	Paparo, Pikall, Stankov, Zima	V	4 (27.9)	6 (43.8)
Sierra Nevada Observatory, Spain, 0.9m	Garrido, Beichbuchner	$uvby$	7 (39.2)	7 (39.2)
Mt. Suhora, Poland, 0.6m	Krzesinski, Ogloza, Pajdosz, Zola	V	0 (0)	0 (0)
Total			29 (191.8)	45 (287.9)

The 44.5 hours of measurements obtained at Mt. Suhora Observatory, Poland, were of lower accuracy (about $\pm$ 0.01 mag per single measurement) than the measurements from the other sites. Although the Polish measurements covering nine nights were not included in the present analysis, they are useful since they confirm the variability of HD 108100.

SPB variables among the B stars. For the latter, we refer to model calculations by Gautschy & Saio (1993) and Moskalik (1995).

At the present time, less than thirty γ Doradus stars are known (e.g. see Krisciunas & Handler 1995). It is important to detect additional members of the class in order to understand the physical properties involved. Such searches are being undertaken. Examples are the systematic examinations of stars in the Hyades cluster (Krisciunas et al. 1995b) and NGC 2516 (Zerbi et al. 1997).

The star HD 108100 is a candidate for γ Doradus-type variability because of its spectral type, F2, and its main-sequence position in the H-R Diagram near the cool border of the δ Scuti star instability strip.

An additional motivation to test HD 108100 for variability arises from two unusually low frequency values found among the multiple frequencies of the δ Scuti variable, 4 CVn. These two frequencies, 1.327 and 1.402 c/d, appear in extensive series of unpublished photometric data (see Fitch 1980). If true, 4 CVn would be one the few stars exhibiting both short-period δ Scuti-type and long-period γ Doradus-type variability (Breger & Beichbuchner 1996). However, only a single comparison star, viz. HD 108100, was used in the Fitch study. An origin of the low-frequency variability in the comparison star is, therefore, possible.

2. Photometric observation and reduction techniques for periods around 1 day

Reliable detections and photometric studies of low-amplitude pulsation modes with periods in the range between about one-half and several days (frequencies, f, from about 0.25 to 2 c/d) are unusually difficult. On the one hand, multisite measurements from different continents are needed to decrease or eliminate the potentially serious daily aliasing effects, $\pm f \pm i$, where i is an integer. On the other hand, the photometers used during the multisite campaigns are on different instrumental systems. Even if the same comparison stars are measured at each observatory, a zero point problem still remains: the different instrumentation distorts the measured photometric differences between the variable and its comparison stars by several millimag. The standard method of photometric transformation by observing standard stars is ineffective at the millimag level and is not usually attempted.

The potential problem can be demonstrated by considering a frequency of, say, 1.05 c/d. If the observing campaign lasted for a week or less, different observatories spaced eight hours apart would cover systematically different phase ranges of the light curve. Linking the different observatories by similar averages would essentially destroy the intrinsic variation. A discussion of observational biasses leading to possible spurious low-frequency detections can be found in Breger & Beichbuchner (1996). Even if the frequencies were not as close to 1 c/d as in the example used above, the problem would still exist.

Two methods can be used to solve the difficulty of relating of the instrumental zero points:

(i) The observatories should be close enough in longitude to permit considerable overlap of data. The overlap allows the derivation of zero point shifts. In the present study such overlap is minimal and occurs only at large airmasses. The method could not be applied.

(ii) Each observatory should provide enough data from a large number of nights so that the observatory zero point can easily be fixed from taking an average of all the data from that observatory. In addition, one could use the final multifrequency solution for the variable as a fine adjustment. Four nights of homogeneous data with similar extinction and constant instrumentation appear to be a minimum requirement.

We adopt the second method for the present study.

Another problem associated with variable stars with periods of thirty minutes or longer concerns the correction for transparency changes and equipment drifts. For the present study the three-star technique (Breger 1993) was adopted, where the required high photometric accuracy and long-term stability are achieved by alternating measurements of the variable star with those of two carefully chosen comparison stars. It is important to note that the same photometric channel is used for the measurements of all three stars. The procedure can produce the required long-term stability of 2 mmag or better, but yields a variable star measurement only every five minutes. The technique is working well for periods between 30 minutes and several days.

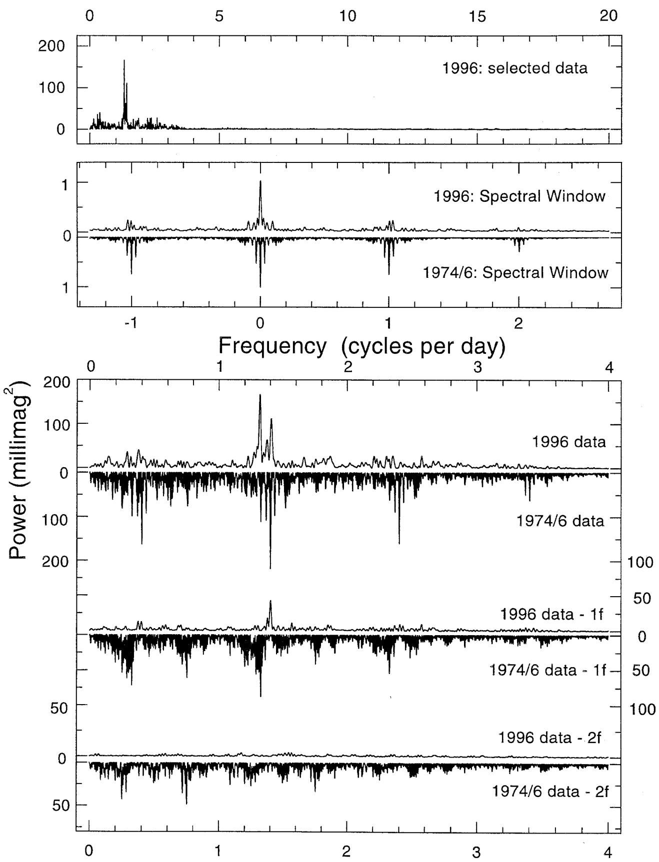

Fig. 1. Power spectra of HD 108100 using only the most homogeneous V and y photometry from three observatories obtained during 1996. The spectra are shown before and after applying multiple-frequency solutions. The diagram demonstrates that HD 108100 is variable. The inverted spectra also shown in the figure are based on residuals of (4 CVn - HD 108100) derived from unpublished b photometry from 1974 and 1976 (see Sect. 4)

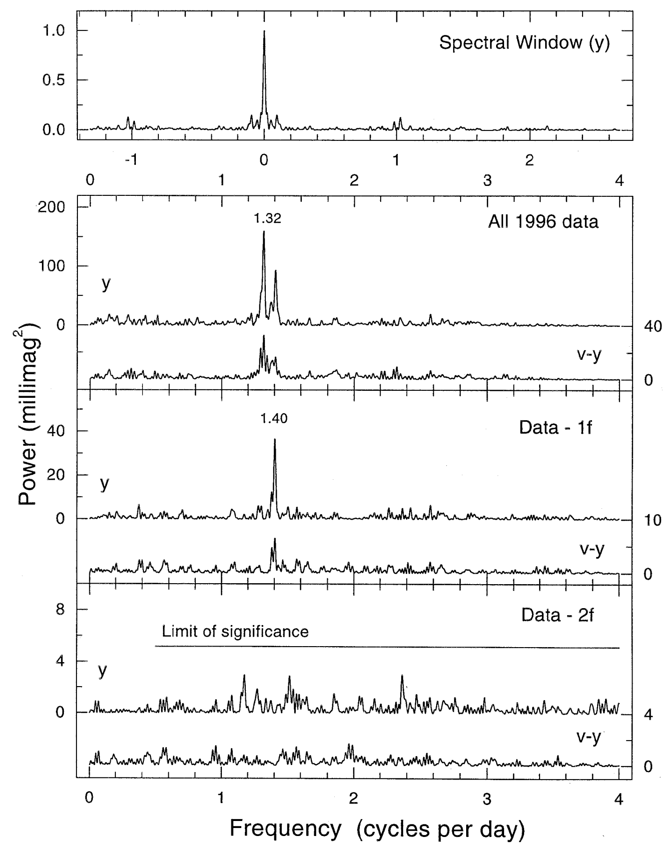

Fig. 2. Power spectrum of HD 108100 in the 0 to 4 c/d range using all data obtained during 1996 judged by us to be "good". Note the excellent spectral window. The variability of both y (=V) and the color, $v - y$, are analyzed. The power spectra are shown before and after applying multiple-frequency solutions.

3. New measurements

During 1996 February and March, HD 108100 was observed photometrically at five observatories (see Table 1). The two comparison stars used were HR 4843 (F6IV) and HR 4728 (G9III). Both stars have been used before as comparison stars for studies of the star 4 CVn and no evidence for any variability has been found.

The coverage of HD 108100 ranged from two-color observations about every 0.005 d at Sierra Nevada Observatory to about every 0.03 d at McDonald Observatory. Due to the long periods of HD 108100, averages of two successive measurements were computed for the observatories with high duty cycles. Three filters were used: the v and y filters of the narrowband $uvby$ system as well as the Johnson V filter. Since the magnitudes for the y and V filters are defined to be the identical, we can combine the y and V measurements. Our new measurements, therefore, can be regarded to consist of V measurements with some added color information.

To show that HD 108100 is intrinsically variable, it is necessary to avoid potential systematic errors caused by the zero point problem discussed in the previous section. Consequently, as an initial step we selected only the three observing runs with extensive y and V data of high photometric homogeneity and accuracy. We required that for all these nights the magnitude difference between the two constant comparison stars are constant within each observatory. This left 18 nights from McDonald Observatory, Texas, 7 nights from Sierra Nevada Observatory, Spain and 4 nights from Piszkéstető Observatory, Hungary.

An examination of these specially selected high-quality data showed the existence of light variability of HD 108100. To find the frequencies of this variability, a package of computer programs with single-frequency and multiple-frequency techniques (program PERIOD, Breger 1990a), which utilize Fourier as well as multiple-least-squares algorithms, was applied. The latter technique fits a number of simultaneous sinusoidal variations in the magnitude domain and does not rely on prewhitening. The analyses were performed using the traditional units of magnitude. We note that for the small amplitudes present in HD 108100 any differences between using intensity and magnitude variations are negligible.

The initial analysis shows that HD 108100 is variable and that two frequencies, 1.32 and 1.40 c/d respectively, are present in the data. In addition, the top panel of Fig. 1 shows that the variability of HD 108100 is restricted to low frequencies. A small band of power around 35 c/d (not shown) occurs beyond the Nyquist frequency and is a reflection of the low-frequency variability. Our subsequent analyses can now be restricted to the range from 0 to 4 c/d.

In order to examine the variability in more detail, we can now add data which did not completely fulfil the criteria listed above, viz. 11 nights from Xing-Long Observatory, China (lower accuracy of about 5 millimag per observation), 3 further nights from McDonald Observatory (uncertain photometric zero point), and 2 further nights from Piszkéstető Observatory (uncertain photometric zero point). For these additional data we have adopted the optimum zero points to give the best fits to the total data set and added the color information, $v - y$.

We have also examined the data for the existence of 2f terms, which could be a sign of nonsinusoidal light-curve shapes. The amplitudes of these 2f terms derived by least-squares fitting were smaller than 0.0010 mag and are indistinguishable from noise.

The power spectra are shown in Fig. 2, which demonstrates that the presence of two frequencies at 1.32 and 1.40 c/d, respectively, is confirmed in both V (=y) and $v - y$. Are there additional frequencies present in the data, i. e. after prewhitening, are the remaining peaks statistically significant? Due to the presence of nonrandom errors in photometric observations and because of observing gaps, the predictions by standard statistical false-alarm tests give answers which are considered by us to be overly optimistic. In a previous paper (Breger et al. 1993) we have argued that a ratio of amplitude signal/noise = 4.0 provides a useful criterion for judging the reality of a peak. Subsequent comparisons have confirmed that this restrictive limit of 4.0 cannot be lowered significantly for typical photometric data. This means that peaks below signal/noise values of 3.5 should be regarded with extreme suspicion.

To determine the noise level, the following approach was adopted: The amplitudes were calculated from the power spectrum, which oversampled the frequency range of 0.5 to 4 c/d by a factor of 20. An average value of these amplitudes was then determined and assumed to be the noise level. The limit of significance shown in Fig. 2 corresponds to an amplitude signal/noise ratio of 4. The power spectra show that, while more than two frequencies may be excited in the star, the remaining peaks in the power spectra are not statistically significant.

The observed variability and the two-frequency fit are shown in Fig. 3. The agreement is quite good with a standard deviation of ± 0.004 mag in y and ± 0.002 mag in $v - y$ per single measurement.

4. Variability of HD 108100 from 1970 to 1976

For the years 1970, 1974 and 1976, an observational study of the δ Scuti variable 4 CVn was undertaken by Fitch, Wisniewski and Bell and briefly discussed by Fitch (1980). For 1974, these data are quite extensive and cover 27 nights. We are grateful to W. Fitch for making the reduced data on 4 CVn available to us before publication.

Only one comparison star, HD 108100, was used in the study. This means that some of the measured brightness variations of 4 CVn could, in principle, originate in HD 108100 instead. Fitch (1980) listed a number of frequencies for 4 CVn. These included 1.327 and 1.402 c/d, which are very similar to the frequencies detected by us for HD 108100 in the present study.

Therefore, these two frequencies must have originated in HD 108100, not 4 CVn. Consequently, the star 4 CVn should no longer be regarded as an example of a star exhibiting both δ Scuti type pulsation (acoustic modes of mixed character) and γ Doradus-type variability (gravity modes of high order).

We can now use the residuals of the 4 CVn data by Fitch to study the variability of the comparison star, HD 108100, at low frequencies. This is possible because the variability of 4 CVn occurs at higher frequencies (5 to 9 c/d). Since the data were obtained at a single site, the unavoidable aliasing leads to some spectral leakage to low frequencies. This requires that the intrinsic variation of 4 CVn needs to be prewhitened before the low-frequency range is examined. The dominant frequencies of 4 CVn are well-determined, but the star also shows amplitude variations from year to year. For the years prior to 1974, the observational situation is unsatisfactory. However, for the years 1974 and 1976 the amplitudes of the dominant frequencies of 4 CVn are very well determined and the prewhitening appears to be reliable. The solutions given by Breger (1990b) have been used to prewhiten the Fitch data.

The Fourier spectrum of the combined 1974 and 1976 photometry, in which the variability of 4 CVn has been prewhitened, is shown in Fig. 1. The dominant two peaks are found at 1.327 and 1.402 c/d. For the 27 nights obtained during the year 1974 covering 123 days, the data can be fit well with b amplitudes of 0.008 and 0.013 mag, respectively. The frequencies detected in 1996 are the same as those found in the 1974/6 data, although the amplitudes associated with the two frequencies are different. The different noise or power levels left after prewhitening two frequencies in the 1974/6 and 1996 data are a reflection of the high accuracy of the new 1996 data.

When all the available data from 1970 to 1996 are analyzed together to increase the precision of the two values of the two frequencies, the problem with annual aliasing (± 0.003 c/d) cannot be solved. The third decimal places of the two frequencies cannot be determined with satisfactory solutions for all the years. This does not prove that the frequencies are variable, since there are a number of other possible explanations. These include:

(i) the Fitch data contain some nightly zero-point uncertainties, because no constant comparison star was available for the reductions,

(ii) the combined 1970-1996 data suffer from insufficient frequency resolution to separate the two frequencies within individual years. This is coupled with gaps covering up to two decades,

Table 2. Amplitudes of HD 108100

Year	Frequency resolution (c/d)	Filter	Mode at 1.32 c/d Amplitude mag	S/N	Mode at 1.40 c/d Amplitude mag	S/N	Comments
1996	0.026	y	0.010	17.8	0.007	12.3	Present data
		v	0.015	12.9	0.009	7.8	Present data
		$v-y$	0.005	10.6	0.003	5.3	Present data
1974	0.012	b	0.008	4.2	0.013	7.3	27 nights, 4 CVn residuals
Uncertain values							
1970	0.068	V	0.01	6	0.01	5	5 nights, 4 CVn residuals
1976	0.087	b	(0.01)	5	(0.02)	6	8 nights, 4 CVn residuals

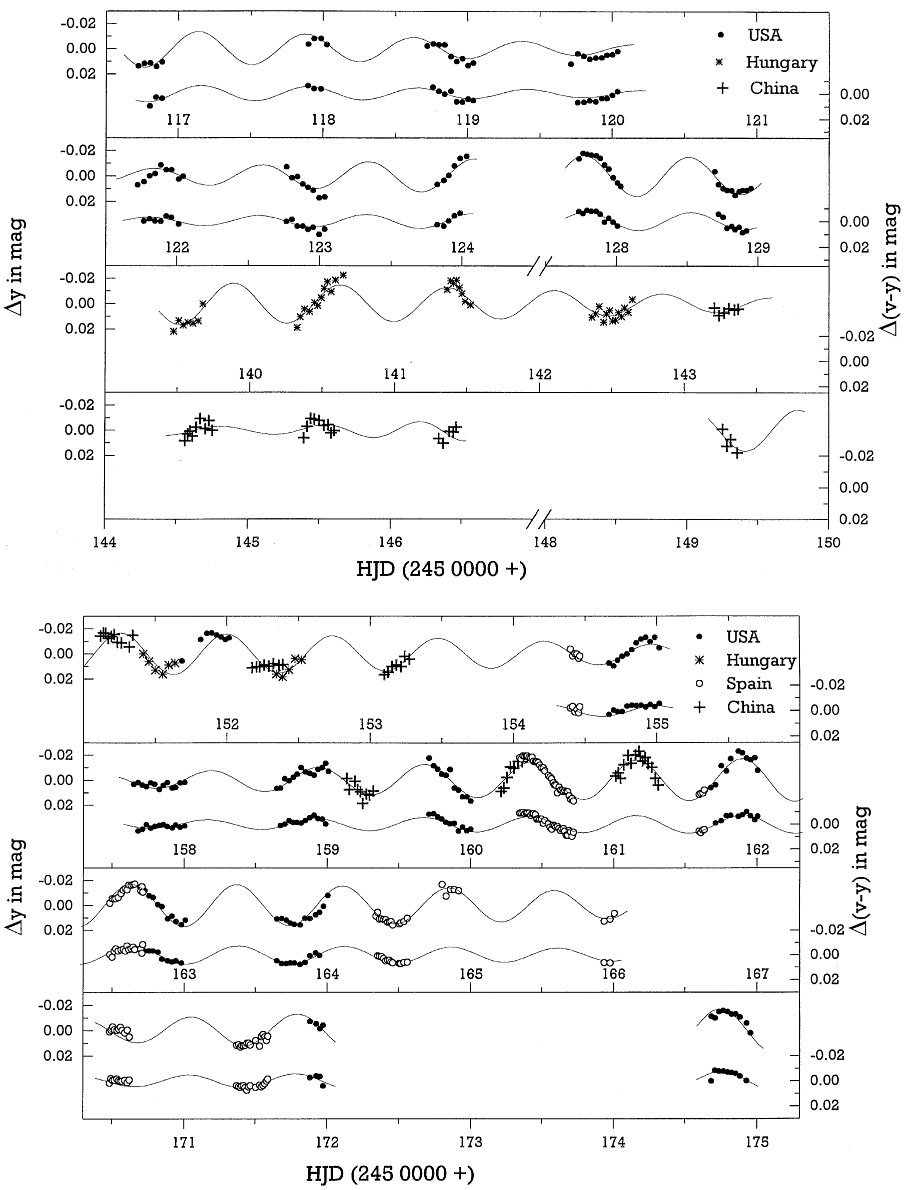

Fig. 3. Multisite photometry of HD 108100 obtained during the 1996 multisite campaign. Δy and $\Delta v-y$ are defined to be the magnitude differences (variable – comparison stars) normalized to zero. The fit of the two-frequency solution derived in this paper is shown as a solid curve

(iii) there may exist additional frequencies with low amplitudes, which remain undetected because of the limits of frequency resolution,

(iv) incorrect prewhitening of the 4 CVn variability, caused by reverse spectral leakage from low to high frequencies, is also a possibility. This explanation, however, is improbable: for the 1974 data of 4 CVn, we have carried out a simultaneous multi-frequency solution involving all the low and high frequencies. The solution confirmed our derived amplitudes and frequencies.

To minimize the effect of these uncertainties, we have performed separate solutions for the different years. The results can be found in Table 2. At this stage it appears prudent to comment on the uncertainties of the derived amplitudes. For the 1996 data, σ(amplitude) < 0.0005 mag. This estimate was derived by dividing the available data into two halves and comparing separate solutions. For the 1970 - 1976 data, the calculated internal errors severely underestimate the real uncertainties because of additional sources of error listed above. A cautious estimate of the 1974 data leads to an uncertainty of $\pm$ 0.002 mag for the derived amplitudes.

A comparison of the 1996 data with the 1970 – 1976 photometry shows that the amplitudes of HD 108100 have changed. The amplitude variation is very much larger than the estimated uncertainties in the derived amplitudes. In fact, the two frequencies appear to have switched their power. During 1974 the 1.40 c/d mode was dominant, while in 1996 the amplitude of the 1.32 c/d mode was about 50% higher than that of the other mode. This conclusion is not affected by the fact that different filters were used: in the photometric $uvby$ system, the b filter used in 1974 is intermediate in wavelength between the two filters (v, y) used in 1996, which show similar amplitude ratios between the two modes of pulsation.

Several pioneering studies of the δ Scuti star 4 CVn carried out from 1966 to 1970 (e. g. Shaw 1977) also used the new Gamma Doradus variable, HD 108100, as a comparison star. However, because of the amplitude variability of 4 CVn, the data are too few to investigate the variability of HD 108100 from the residuals of the 4 CVn data.

5. Discussion

The new γ Doradus variable, HD 108100, shows normal narrowband photometric values for its class: $b - y$ = 0.234, m_1 = 0.161, c_1 = 0.639. A new β value (2.705 $\pm$ 0.008) has been obtained by one of us (GH) as part of a larger, presently unpublished program. The $uvby\beta$ calibrations for F stars by Crawford (1975) give M_V = 2.38 with zero reddening. The δm_1 value of 0.012 indicates normal, solar abundances. The photometric calibration of Moon & Dworetsky (1985) gives $T_{\rm eff}$ = 6890 K, log g = 3.93. In the H-R Diagram, HD 108100 lies on the main sequence, just to the cool side of the instability strip border. This position is typical for a γ Doradus variable.

The values of the pulsation constants Q can be estimated from the following equation:

$$\log Q_i = -6.456 + \log P_i + 0.5 \log g + 0.1\, M_{\rm bol} + \log T_{\rm eff}.$$

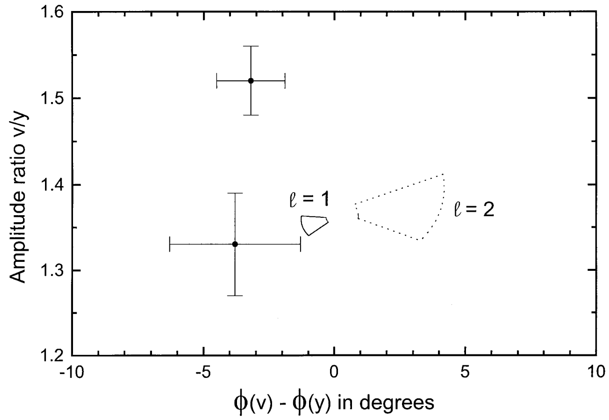

Fig. 4. Phase shifts versus amplitude ratios for $T_{\rm eff}$ = 6850 K, log g = 3.9, Q = 0.27 d. The computed loci for ℓ = 1 and 2 are indicated (see text). The observed points are plotted together with their uncertainties

Table 3. Amplitude Ratios and Phase Shifts for HD 108100

Frequency (c/d)	Period (hours)	Amplitude Ratio A(v)/A(y)	Phase Shift ϕ(v) – ϕ(y) (degrees)
1.321	18.17	1.52 $\pm$ 0.04	-3.2 $\pm$ 1.3
1.404	17.09	1.33 $\pm$ 0.06	-3.8 $\pm$ 2.5

Based on the results obtained for other γ Doradus stars (see Sect. 1), we interpret the variability in terms of nonradial, g-mode pulsation. We note, however, that for this star the spot model cannot be ruled out as an explanation for the variability.

The Q values of the two pulsation frequencies become 0.27 $\pm$ 0.03 d, and 0.29 $\pm$ 0.03 d. The uncertainties are estimated from the uncertainties of the photometric quantities and calibrations used. The Q values of HD 108100 are too high by a factor of at least 8 for the variability to be caused by p modes, since for these stars the fundamental radial mode has a Q value of 0.033 d. The most promising interpretation is in terms of high-order g modes.

Garrido et al. (1990) have shown that the phase shifts between the light curves in V and $v - y$ provide excellent indicators of the pulsational ℓ values. The observed values are shown in Table 3. The listed uncertainties are estimates calculated by dividing the available data in two halves and examining the agreement between the derived parameters.

However, the results listed by Garrido et al. are not fully applicable to HD 108100, because the large value of the pulsation constant, Q, derived for HD 108100, dramatically changes the expected amplitude, phase diagrams for the different ℓ values. Following the approach of Garrido et al., we have recomputed the expected phase shifts and amplitude ratios for Q = 0.27 d, $T_{\rm eff}$ = 6850 K, log g = 3.9. Because of the small pulsational amplitude in HD 108100, the adopted linear approximation used in these calculations should be valid.

Table 4. A g-mode model (ℓ = 1) for HD 108100

Mode	Frequency (c/d)	Period (hours)	Q (days)
g_{16}	1.786	13.44	0.250
g_{17}	1.663	14.43	0.268
g_{18}	1.554	15.44	0.287
g_{19}	1.456	16.48	0.306
g_{20}	1.369	17.53	0.323
g_{21}	1.291	18.59	0.345
g_{22}	1.220	19.68	0.366

Fig. 4 shows the loci where $90^o \leq \Phi^T \leq 135^o$ and $0.25 \leq R \leq 1$. We refer to Garrido et. al. (1990) for details. The results show that it is possible to distinguish between ℓ = 1 and ℓ = 2 on the basis of phase differences. At least for one of the two detected pulsation modes, both the observed phase difference and amplitude ratio agree with ℓ = 1. The second pulsation mode shows a slightly higher than predicted amplitude ratio, but we consider the disagreement to be minor, since the calculated amplitude ratio (but not the phase difference) is sensitive to the adopted atmospheric parameters.

We conclude that the observed phase shifts are in agreement with those expected for g modes with ℓ = 1, while ℓ = 2 is improbable.

The Q value can be used to estimate the radial overtones of the excited g modes. We have used an equilibrium model kindly supplied by A. Claret (see Claret 1995). This model (Table 4) corresponds to a slightly evolved star with 1.6 $M_\odot$, log $L/L_\odot$ = 0.896, log g = 4.03, log $T_{\rm eff}$ = 3.835, X_c = 0.261 and Z = 0.02. Nonradial g-modes were computed using a numerical code written by RG and is based on the formulation given in Unno et al. (1989). All the periods were calculated in the quasi-adiabatic aproximation, which gives values similar to those obtained by non-adiabatic calculations. The numerical values in Table 4 reach the asymptotic value ($n \gg \ell$) of

$$\Pi_{nl} = \frac{\Pi_o(n + l/2 + \delta)}{\sqrt{l(l+1)}} \quad \text{, with}$$

$$\Pi_o \equiv (\Pi_{n+1,l} - \Pi_{n,l})\sqrt{l(l+1)} = \frac{2\pi^2}{\int_0^{R_*} \frac{N}{r} dr}$$

where N is the Brunt-Väisälä frequency and δ a constant value depending on the stellar structure.

The comparison of the observed periods with the model shows a good agreement near a radial order, $n \sim 20$, while the Q values indicate $n \sim 18$. The small difference is caused by the fact that the model parameters are not exactly identical to the values derived above for HD 108100. These uncertainties are within those of the photometric calibrations used. Furthermore, the observed difference in period between the two modes corresponds to the expected difference of two successive radial orders of the model.

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