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On the relationship between the δ Scuti and γ Doradus pulsators

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ABSTRACT

We searched for δ Scuti-type pulsations amongst known and candidate γ Doradus stars. The motivations for such a project come from the need to understand the relationship of these two classes of pulsator better, from the present poor knowledge of the hot border of the γ Doradus phenomenon, and from the exciting prospects for asteroseismology should stars be found which have both types of pulsation excited. We acquired 270 h of observations and monitored a total of 26 stars. One target, HD 209295, turned out to be a member of both classes of pulsating star, but this object is peculiar in the sense that it is a close binary. We classify six of our targets as new bona fide γ Doradus stars, whereas nine more are good γ Doradus candidates, and three turned out to be ellipsoidal variables. One of our programme stars was found to be a δ Scuti star, with no additional γ Doradus variations. Furthermore, one star was already known to be a bona fide γ Doradus star, and we could not find an unambiguous explanation for the variability of five more stars. The analysis of our data together with improved knowledge of stars from the literature enabled us to revise the blue border of the γ Doradus phenomenon towards cooler temperatures. This new blue edge is much better defined than the previous one and extends from a temperature of about 7550 K on the ZAMS to 7400 K one magnitude above it. Five bona fide γ Doradus stars we observed are located inside the δ Scuti instability strip, but none of them exhibited observable δ Scuti pulsations. We therefore suggest that γ Doradus stars are less likely to be δ Scuti pulsators compared with other normal stars in the same region of the lower instability strip. In addition, we show that there is a clear separation between the pulsation constants Q of δ Scuti and γ Doradus stars. The γ Doradus stars known to date all have $Q > 0.23$ d.

Key words: techniques: photometric – stars: oscillations – δ Scuti – stars: variables: other.

1 INTRODUCTION

The relationship between the γ Doradus and δ Scuti stars is not yet clear. Although the two classes of pulsator share a similar parameter space in the HR diagram and even partly overlap (Handler 1999), the γ Doradus stars are high-radial-order gravity (g)-mode pulsators (Kaye et al. 1999a), whereas the δ Scuti stars are believed to be mostly low-radial-order pressure (p)-mode pulsators (e.g. Breger 2000). The driving mechanism of the two classes should be different because of the different types of modes excited. Hence, there should be different thermal time-scales in the driving regions. Indeed, δ Scuti pulsations are known to be driven by the κ-mechanism (Chevalier 1971), whereas the only presently feasible driving mechanism for the γ Doradus stars is similar to convective blocking (Guzik et al. 2000, 2002). The latter mechanism is also expected to weaken or even exclude the driving of δ Scuti-type pulsations.

Several open questions still remain. Is the presence of δ Scuti- and γ Doradus-type pulsations mutually exclusive? Is there an overlap or a separation between these pulsators? Are there stars that show both types of oscillation? What determines the type of mode that a particular star pulsates in? To tackle those questions, we decided to observe a large number of γ Doradus candidates located within the δ Scuti instability strip to search for short-period pulsations.

In addition, this allows us to check whether these γ Doradus candidates are indeed pulsators. This is important as most of these candidates were identified from *Hipparcos* photometry (ESA 1997), the quality of which is poor compared with ground-based work and which contains no time-series colour information. Furthermore, there is usually strong aliasing in amplitude spectra of *Hipparcos* photometry caused by a pseudo-sampling frequency near 12 cycle day^{-1} (see Eyer & Grenon 1998), which often leads

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to difficulties in period determinations. For instance it is often not possible to distinguish a δ Scuti star with a 2-hour period from a γ Doradus candidate from *Hipparcos* photometry only. We conclude that these technical facts make a good assessment of the presence of γ Doradus pulsations from *Hipparcos* data alone difficult: γ Doradus stars can easily be confused with spotted stars, ellipsoidal variables and δ Scuti stars (see Kaye et al. 1999a and Handler 1999 for more extensive discussions).

Our ground-based observations introduced above are probably the most effective way to assess the relationship between the γ Doradus and δ Scuti stars: about one third of all non-Am and non-Ap stars in the lower instability strip are indeed δ Scuti stars (Breger 2000 and references therein) and Am and Ap stars are rare (or even absent) amongst the γ Doradus stars (Handler 1999). Consequently, a statistical assessment of the incidence of δ Scuti pulsations in γ Doradus stars becomes possible. We note that Breger & Beichbuchner (1996) already looked for possible γ Doradus pulsators among δ Scuti stars in the literature, but their results were largely inconclusive because of observational selection effects, the small number of γ Doradus stars then known and because the incidence of observable γ Doradus pulsations among stars with basic parameters in the γ Doradus star domain is as yet unknown.

The results to be expected from our search are manifold.

(i) The number of known bona fide γ Doradus stars is still small (<20). Discovering more of these stars will aid the understanding of the class as a whole.

(ii) If both types of pulsation could be identified in the same star, this would be exciting news for asteroseismology: the δ Scuti pulsations in such hypothesized stars could be used to determine (at least) accurate basic parameters, which can then aid in identifying the γ Doradus modes and in probing the deep stellar interior. It would also mean that in stellar models in which γ Doradus-type modes are driven, δ Scuti oscillations must not be damped.

(iii) If no such ‘hybrid’ stars are found, the reason for their absence can be examined, and some observational discriminants may be found. Of course, the driving mechanism for the γ Doradus stars will also need to explain such a result.

(iv) An improved assessment of the hotter candidate γ Doradus stars may also enable us to locate the currently poorly-defined blue edge of the γ Doradus region better in the HR diagram (Handler 1999); pulsational models must explain it. The location of the red edge of the δ Scuti instability strip can also be better examined.

Hence, whatever the implications of the present survey, the driving mechanism for the γ Doradus pulsations will be observationally much better constrained.

2 OBSERVATIONS

As mentioned in the Introduction, we selected known candidate γ Doradus stars located within the overlap region of the lower instability strip (adopted from Breger 1979) and the domain of the γ Doradus stars in the HR diagram (Handler 1999). All stars observable from intermediate Southern geographical latitudes were included in our survey, and we chose two comparison stars for each. In addition, we included further γ Doradus candidates (regardless of their position in the HR diagram) which were located within eight degrees of the main targets into the observing sequence whenever practical to examine the physical nature of these stars as well. Finally, we also decided to monitor a few more candidates that seemed to be of special astrophysical interest.

Our measurements were acquired as differential photoelectric photometry at the 0.5-m and 0.75-m telescopes at the Sutherland station of the South African Astronomical Observatory (SAAO) and at the 0.6-m telescope (see Shobbrook 2000 for a description) at Siding Spring Observatory (SSO) from 1999 October to 2001 October. We used the Johnson B and V filters with a total integration time of about one minute in each filter as a compromise between good time resolution and optimum colour information, but we sometimes added the Cousins I_c if deemed necessary (possible reasons will be listed below). A few runs obtained on the SAAO 0.5-m telescope were taken as high-speed photometric observations through the BVI_c filters, with comparison star observations every 30–45 min, which also results in some long-term photometric stability (Breger & Handler 1993). For all runs, apertures of 30–45 arcsec on the sky were chosen. Sky measurements were taken depending on the brightness and proximity of the Moon.

Observing sequences were chosen for both good coverage of possible short-period δ Scuti pulsations and for best long-term stability. We adopted the sequences C1-C2-V-C1-C2-V... (the Cs denote the comparison stars and the Vs the variables) for SAAO observations and C1-V-C2-V-C1... for SSO measurements (where it was more difficult to move the telescope from one star to the next) in case one programme star was in the group. This resulted in one programme star measurement about every 7 min. If we had two variables in a group, the sequence C1-V1-C2-V2-C1-V1... was chosen, yielding a variable star measurement about every 15 min. These duty cycles apply to BV observations.

We attempted to observe each target star for at least two half nights to check them for δ Scuti-type variability and in order not to be susceptible to beating phenomena (negative interference from multiple pulsation modes). With this strategy, long-term variability is often detected in one night, and the second run will fulfil the same aim whilst making it possible to check for light variations from night to night as well. The data were reduced as soon as possible after they had been obtained in order to judge their quality and to be able to make decisions about future observing strategies and the scientific content of our data. This would for instance result in a change of the observing sequence or in the inclusion of the I_c filter or in a decision of whether to follow the star up or not.

Data reduction was performed in a standard way: correction for coincidence losses, sky background and extinction was followed by calculating differential magnitudes between the comparison stars, and if these were judged to be constant, construction of the differential target star light curve. Finally, the time base of our observations was converted to Heliocentric Julian Date (HJD). We summarize our observations in Table 1; the data are available at http://www.saao.ac.za/~gerald/delgamscudor in electronic form.

3 ANALYSIS

3.1 Results on the individual stars

Before proceeding to the astrophysical implications of our survey as a whole, the individual stars also need to be discussed, as a wide variety of behaviour was detected. We also need to make clear which criteria we use to distinguish between the different types of variable to be found in the region of the HR diagram under consideration.

We classify a star as a δ Scuti variable if it shows a variability time-scale that leads to pulsation constants Q of 0.04 d or less. The

Table 1. Journal of the differential photometric observations. We normally used the Johnson BV filters, but runs marked with one asterisk also utilized the I_c filter; those with two asterisks were high-speed photometry BVI_c with occasional comparison star measurements.

Target star(s)	Site	Run start JD − 245 0000	Run length, h
HD 10167	SAAO	1457.40	4.1
	SSO	2111.19	3.1
	SSO	2112.16	1.6
	SSO	2131.16	2.6
HD 12901	SAAO	1460.38	4.1
	SAAO	2154.48	2.0**
	SAAO	2155.47	4.5**
HD 14147	SAAO	1463.39	3.0
HD 27093	SAAO	1461.25	3.7
	SAAO	1466.48	2.2
HD 40745 and	SSO	1549.96	5.4
HD 41448	SSO	1554.96	1.9
	SSO	1555.95	5.1
HD 65526	SAAO	1576.30	3.5
	SAAO	1581.30	3.7
HD 81421	SAAO	1577.32	2.3
	SAAO	1578.31	6.2
	SSO	1578.95	7.0
	SAAO	1579.30	7.3
	SAAO	1581.57	1.0
	SAAO	1582.54	1.7
	SSO	1588.93	4.0
	SSO	1589.96	5.6
	SSO	1590.97	4.7
HD 85693 and	SAAO	1580.30	3.8
HD 86371	SAAO	1582.33	5.0
HD 110606 and	SAAO	1576.46	2.9
HD 113357	SAAO	1580.45	0.4
	SAAO	1581.46	2.7
	SSO	1621.12	4.1
	SSO	1630.00	2.6
	SSO	1631.96	2.9
HD 139095	SAAO	2045.29	1.6
	SSO	2102.85	6.1
	SSO	2110.86	6.2
	SSO	2111.86	5.1
HD 167858	SAAO	2045.44	5.4
	SAAO	2051.54	3.1
BD+8 3658	SSO	2105.01	1.6
	SSO	2130.90	4.3
	SSO	2134.94	3.2
	SSO	2140.88	2.6*
HD 173794	SSO	2131.87	8.3
	SSO	2133.12	1.0
	SSO	2135.09	2.6
	SSO	2135.87	7.7*
	SSO	2140.99	3.0*
	SSO	2144.88	7.1*
HD 181998	SSO	2146.87	1.4
	SAAO	2154.33	3.4**
	SAAO	2155.24	5.6**
HD 188032 and	SAAO	1458.26	2.5
HD 189631	SSO	2107.10	1.9
	SSO	2113.03	5.2
	SAAO	2192.23	2.9*
	SAAO	2193.30	0.6*
HD 198528 and	SAAO	1461.25	1.1
HD 201985	SAAO	1462.25	3.6
	SAAO	1466.26	3.6
	SSO	2119.10	4.1
	SSO	2119.95	6.3
HD 207223	SAAO	1463.25	3.2
HD 207651	SAAO	1463.25	3.2
	SAAO	2191.26	3.0**
HD 209295	SAAO	1464.33	4.2
	SAAO	1465.25	6.5

Table 1 – *continued*

Target star(s)	Site	Run start JD − 245 0000	Run length, h
	SSO	1467.03	2.3
	SSO	1468.91	6.4
HD 211699	SAAO	1468.25	1.1
	SAAO	1469.26	4.5
	SAAO	2176.26	2.1*
	SAAO	2190.26	4.2**
HD 221866	SAAO	1466.41	1.6
	SAAO	1467.28	4.6
Total			269.5

pulsation constant Q is calculated as

$$\log Q_{\rm i} = C + 0.5 \log g + 0.1 M_{\rm bol} + \log T_{\rm eff} + \log P_{\rm i}, \qquad (1)$$

adopting $T_{\rm eff,\odot} = 5780$ K, $\log {\rm g}_\odot = 4.44$, $M_{\rm bol,\odot} = 4.75$ (Allen 1976) and thus $C = -6.456$. The units of the quantities in the right-hand side of this equation are dex, magnitudes, kelvins and days, respectively. Our limit on Q follows from the fundamental radial mode of a δ Scuti star having $Q = 0.033$ d, and we allow for some 18 per cent error in its determination from the uncertainties of the physical parameters derived for the star (see Breger 1989 for a discussion). These parameters can be determined from calibrations of Strömgren photometry (Crawford 1975, 1979) and model atmosphere predictions (Kurucz 1991). Bolometric corrections were taken from Drilling & Landolt (2000).

There are also possibilities for separating γ Doradus stars, ellipsoidal variables and rotationally-modulated chemically peculiar objects. The latter two types of variable will only have one or two dominant periods in a frequency analysis based on Fourier spectra and sine-wave fitting (which are our main tools for the analysis), and if there are two periods, they will be harmonically related. In that respect, residualgram analysis (Martinez & Koen 1994) can become powerful. This method performs a least-squares fit of a sine wave with M harmonics to the measured time series and evaluates the residuals at each trial frequency, where M can be chosen. For rotationally-modulated light curves or those of ellipsoidal variables, $M = 2$ is usually the best choice, and is used throughout this paper.

Returning to the discrimination between the different types of slow variables, we note that multiperiodic γ Doradus stars can be easily identified if the different periods of variability are not harmonically related. However, if only a single period can be determined from the measurements, unravelling the cause of the variability of the star under consideration becomes more difficult.

A further diagnostic can be obtained from relative amplitudes and phases of the measured signals in different photometric filters. Ellipsoidal variables or eclipsing binaries of the W UMa-type show little colour modulation (B/V amplitude ratios less than 1.05) as their light variations are dominated by geometrical effects. The latter two types of variable can be distinguished by their light-curve shape; those of the W UMa-type have typical flat maxima and sharp minima. The light curves of rotationally-modulated Ap stars, on the other hand, often show quite large colour variations and in case of double-wave light modulations, phase shifts between the different filters can become quite large (e.g. see Kurtz et al. 1996). Colour amplitude ratios for γ Doradus pulsations will be quite similar to those of δ Scuti stars. For instance, typical B/V amplitude ratios for γ Doradus stars pulsating with photometrically detectable modes (spherical degree $\ell = 1$ or 2) would, according to model calculations (e.g. Garrido 2000), be between 1.2 and 1.35. The latter range is also expected for radial δ Scuti pulsation. Phase shifts between different filters are not a good indicator of pulsations in the present case, as our data sets are generally too small to obtain significant phase shifts.

We caution, however, that amplitude ratios could be misleading, in particular in cases of insufficient phase coverage of the orbital period of an ellipsoidal variable or of the rotation period of an Ap star. Both types of variable can then show colour-amplitude ratios similar to those of pulsating stars. Consequently, this diagnostic alone is not sufficient for a clear distinction; all the information available on the stars needs to be combined carefully to arrive at a safe classification.

3.1.1 HD 10167

The variability of this star was discovered by Eyer & Aerts (2000) in Geneva photometry. These authors could however not pinpoint the physical nature of the star. Our measurements show very little variation during the individual nights and night-to-night variations of a few hundredths of a magnitude. The *B*/*V* colour-amplitude ratio (1.24 ± 0.12) suggests pulsation as the cause for these variations. No δ Scuti-type variability is detected within a limit of 0.9 mmag in the *V*-filter amplitude spectrum. We classify HD 10167 as a γ Doradus candidate.

3.1.2 HD 12901

Handler (1999) suggested that this star could be a γ Doradus variable, but aliasing in the *Hipparcos* photometry also left the possibility that it could be a δ Scuti star. Eyer & Aerts (2000) clarified the situation by means of Geneva photometry and suggested that HD 12901 is a γ Doradus star. Our observations confirm their conclusion; no δ Scuti pulsations are detected (within 1.2 mmag) and the *B*/*V* and V/I_c colour-amplitude ratios (1.29 ± 0.02 and 1.9 ± 0.1, respectively) for the dominant period of the slow variations (0.8227 d, Eyer & Aerts 2000) in our data confirm that they are caused by pulsation of the star. Supported by the results of Eyer & Aerts (2000), we classify HD 12901 as a bona fide γ Doradus star.

3.1.3 HD 14147

This star was classified as a δ Scuti star with a period of 6.48 h by the *Hipparcos* group (ESA 1997). However, a re-analysis of these data reveals that HD 14147 is in fact an ellipsoidal variable with an orbital period of 12.95 h (Fig. 1). One can suspect low-amplitude δ Scuti variations with a period of about 1.5 h ($Q = 0.04$ d) being superposed on our single night of observation and the *Hipparcos* light curve.

3.1.4 HD 27093

From the time-resolved *Hipparcos* photometry alone it was not clear whether this star is a δ Scuti or a γ Doradus star (Handler 1999). However, the more rapid time sampling of our ground-based observations clearly shows that HD 27093 is a δ Scuti star; a combined analysis of both data sets results in a dominant frequency of $14.51\,837 \pm 0.00\,006$ cycle day^{-1}, corresponding to $Q = 0.018$ d. Semi-amplitudes of 18 ± 2 mmag in the *Hipparcos* H_p-band, 15 ± 1 mmag in the *B* filter and with 11.8 ± 0.6 mmag in

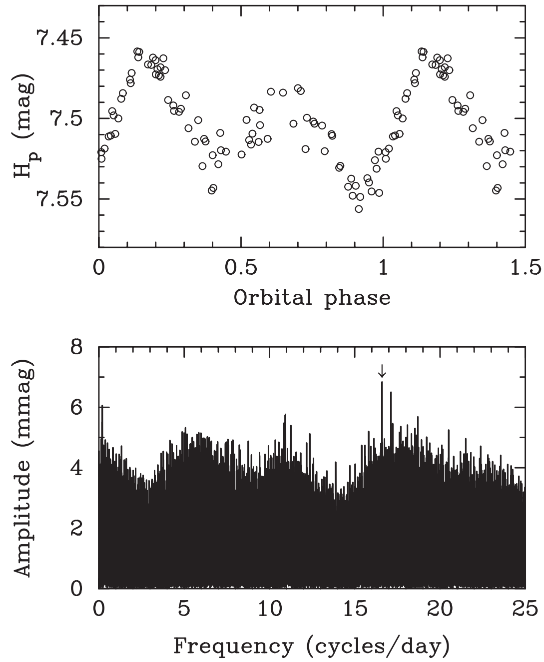

Figure 1. Upper panel: phase diagram of the *Hipparcos* photometry of HD 14147 folded with a frequency of 1.8528 cycle day^{-1}. Ellipsoidal variability of this star is strongly implied. Lower panel: residual amplitude spectrum of this star's *Hipparcos* photometry after removing the orbital modulation. A possible signal near 16.6 cycle day^{-1} can be suspected.

V could be determined (error estimates were derived from the formulae of Montgomery & O'Donoghue 1999). Some evidence for more δ Scuti periods is seen, but no long-term variations are detected within a limit of 2 mmag.

3.1.5 HD 40745 and HD 41448

These two stars could be observed in one group due to their proximity in the sky. Both are slow variables, with *B*/*V* colour-amplitude ratios (1.25 ± 0.21 for HD 40745 and 1.31 ± 0.12 for HD 41448) indicative of pulsation. These amplitude ratios were derived by fitting their dominant *Hipparcos* frequency to our data, in which these frequencies are also detected. In accordance with published frequency analyses of the *Hipparcos* data of the stars, we also find evidence for multiperiodicity for the slow variations of both. On the other hand, no δ Scuti-type variability is detected within a limit of 3.0 mmag (HD 40745) and 2.7 mmag (HD 41448), respectively. Because of the rather large errors on the colour-amplitude ratios, we can only confirm both stars as prime γ Doradus candidates.

3.1.6 HD 65526

For this prime γ Doradus candidate (Handler 1999), we obtained two nights of observation which were of excellent quality. The *B*/*V* colour-amplitude ratio in our data (1.19 ± 0.04) implies pulsation as the cause of the slow multiperiodic light variations of HD 65526. No δ Scuti variations are detected at a limit of 0.5 mmag in the amplitude spectrum. Thus HD 65526 is reclassified as a bona fide γ Doradus star.

3.1.7 HD 81421

This is one of the most difficult cases we encountered in our

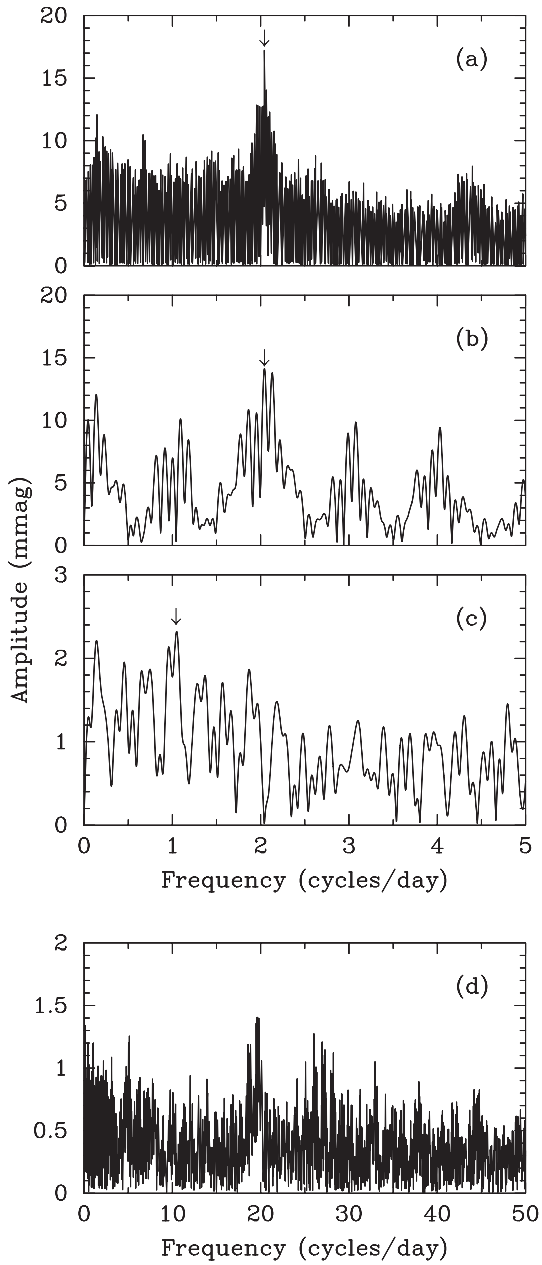

Figure 2. (a) Amplitude spectrum of the *Hipparcos* photometry of HD 81421; the frequency in these data is indicated with an arrow. (b) Amplitude spectrum of our ground-based *V*-filter observations; the *Hipparcos* period is confirmed. (c) Amplitude spectrum of our measurements after prewhitening of the *Hipparcos* frequency. Residual variation near 1 cycle day^{-1} is suspected. (d) Amplitude spectrum of our measurements after prewhitening of the *Hipparcos* frequency and its subharmonic. A wider range is chosen to show the suspected presence of δ Scuti pulsations.

survey; we must comment on this star in more detail. The star is classified as a periodic *Hipparcos* variable (ESA 1997), and its period is 11.75 h (see also Fig. 2(a)). This means that for consecutive nights of ground-based measurements practically the same phase of its light curve is always observed. For this reason, we coordinated the observations of this star from both sites to overlap and we attempted to cover a time baseline longer than usual.

Regrettably, these attempts were somewhat unlucky as our combined observations always covered the same branch of the light curve with the exception of one night where we could observe it from both sites, albeit with a 1.6-h gap in between. As we had no overlap between SSO and SAAO, we transformed the instrumental magnitude differences to the standard system to homogenize the data as much as possible. This procedure pointed us to a zero-point problem just in the single SSO night taken in between two nights of SAAO data, which has to be kept in mind as well.

The frequency analysis of our data corroborated the *Hipparcos* period (cf. Fig. 2(b)), and the amplitudes in our $B - (19.0 \pm 0.4) -$ and $V - (14.9 \pm 0.3) -$ filter data suggest that this variability is due to pulsation. However, after prewhitening this variation from the data, some residual amplitude near 1.0 cycle day^{-1}, half the dominant frequency, remains. Such a variation can of course also be caused by a problem with the nightly zero-points or by imperfect extinction corrections etc. However, an examination of the SAAO data only (which show excellent long-term stability as judged from the measurement of the constant comparison stars) suggests that this 1.0 cycle day^{-1} variation could be intrinsic to HD 81421. It could therefore be a subharmonic of the 11.75-h period, indicative of ellipsoidal variation, but our data are insufficient to confirm or reject this idea.

A search for δ Scuti pulsations of this star proved to be difficult as well. Although a short-period variation with a time-scale of about one hour seemed to be superposed on the slow variability of the star, and although the rms scatter of the nightly light curves of HD 81421 after removing the long-term trends is higher than that of the difference of the comparison stars, we cannot prove its presence. An amplitude spectrum of all our data after prewhitening the *Hipparcos* frequency and its suspected subharmonic (Fig. 2(d)) shows evidence for low-amplitude δ Scuti variability, but the signal-to-noise ratio is too small for a definite detection.

On the basis of our data and those by the *Hipparcos* satellite we can therefore still not pinpoint the physical nature of HD 81421. It could be a γ Doradus pulsator or an ellipsoidal variable, and it could additionally be a δ Scuti star. More observations of the star are needed. Photometric measurements with a suitable time distribution and/or time series spectroscopy are required to understand this object.

3.1.8 HD 85693

Although the *Hipparcos* photometry suggests variability with a light range in excess of 0.1 mag, this star showed only very-small-amplitude slow variability during our observations. Therefore, the error in the *B*/*V* colour-amplitude ratio is too large to allow us to pinpoint the cause of the light variations. We retain the star as a γ Doradus candidate and place an upper limit of 0.8 mmag on the presence of δ Scuti pulsations in our light curves.

3.1.9 HD 86371

We are unable to recover the *Hipparcos* period suggested by Handler (1999) in our photometry, but the complicated light curves and our measured *B*/*V* colour-amplitude ratio (1.20 ± 0.03) suggest pulsation as the reason for this star's variability. Our upper limit for δ Scuti variability of this star is 0.8 mmag. The multiperiodicity from the *Hipparcos* photometry, which is confirmed with a residualgram analysis, and the colour-amplitude ratio derived above lead us to classify HD 86371 as a bona fide γ Doradus star.

3.1.10 HD 110606 and HD 113357

The light curves of both stars appear quite complicated. Neither the *Hipparcos* data nor our observations allowed the detection of a dominant period, which suggests the presence of multiperiodic γ Doradus pulsations. The *B*/*V* colour-amplitude ratios in our data are 1.26 ± 0.06 for HD 110606 and 1.34 ± 0.07 for HD 113357, further supporting this idea. No δ Scuti variability is present within a limit of 1.0 mmag in either of the stars. We cautiously classify HD 110606 and HD 113357 as prime γ Doradus candidates, but we think that further observations can easily prove they are bona fide members of the group.

3.1.11 HD 139095

We suggest that this is a bona fide γ Doradus star. The *Hipparcos* and the ground-based light curves are multiperiodic, and the *B*/*V* colour-amplitude ratio is 1.23 ± 0.02, typical for pulsational variability of a late A/early F star. There is no evidence for δ Scuti-type variability within a limit of 1.1 mmag in the amplitude spectrum.

3.1.12 HD 167858

The *Hipparcos* data of the star imply it is a multiperiodic γ Doradus pulsator of quite high amplitude. This is confirmed with our ground-based data, and the *B*/*V* colour-amplitude ratio (1.29 ± 0.06) implies pulsation as the cause for these light variations. The search for δ Scuti pulsations of HD 167858 in two nights yielded a null result, with no variation detected within 1.0 mmag in the second night of our measurements, which was of much better quality than the first one. We classify HD 167858 as a bona fide γ Doradus star.

3.1.13 BD+8 3658

In his search for multiperiodic variability among *Hipparcos* variables, Koen (2001) found one frequency typical for γ Doradus variations (1.00064 cycle day^{-1}) and a second one suggesting δ Scuti variability of BD+8 3658. This star was therefore of considerable interest for us. Weak δ Scuti modulations with a peak-to-peak amplitude of about 0.01 mag at a time-scale of 2.5 h ($Q =$ 0.035 d) and evidence for multiperiodicity are indeed present in our data. However, we cannot identify the cause of the slow variability with certainty. Our ground-based measurements show almost no slow variability, a combined result of the *Hipparcos* period being very close to 1 d and of insufficient phase sampling. Therefore we cannot calculate meaningful colour-amplitude ratios. However, the phase diagram of the *Hipparcos* photometry relative to the long period (Fig. 3) is not typical for pulsational variability. More observations of this star are needed, including standard Strömgren photometry and spectroscopy.

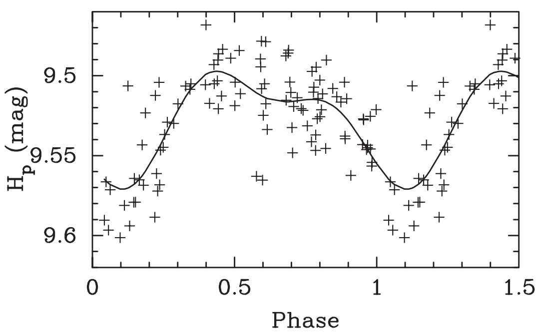

Figure 3. The phase diagram of the *Hipparcos* photometry of BD+8 3658 relative to a frequency of 1.00064 cycle day^{-1}. The solid curve is the result of a two-harmonic fit to these data. The light curve shape is not indicative of pulsational variability.

3.1.14 HD 173794

Handler (1999) could not decide whether this star shows variations close to 1.5 d or of one or two hours because of the aliasing problem in the *Hipparcos* data mentioned in the Introduction. In fact, both types of variation are present, as already seen from our first ground-based light curve (Fig. 4a). There are clear

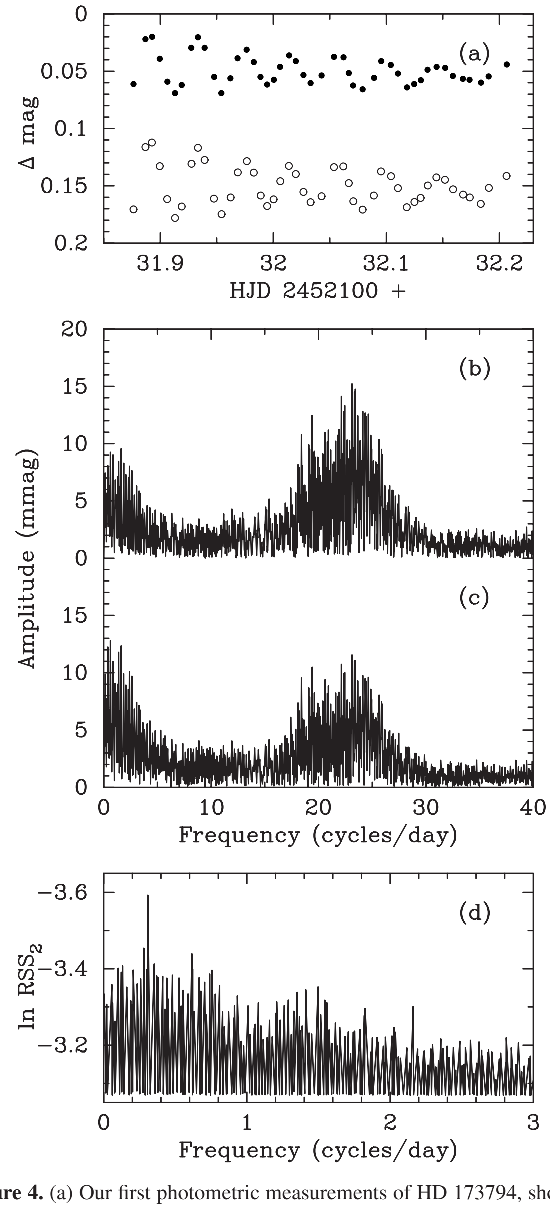

Figure 4. (a) Our first photometric measurements of HD 173794, showing both multiperiodic δ Scuti pulsation and a slow drop in mean magnitude (about 0.02 mag during this run). Filled circles are *V*-filter data, open circles the *B*-filter measurements. (b) Amplitude spectrum of all our ground-based *B*-filter observations. (c) Amplitude spectrum of all our *V*-filter measurements. Note that the δ Scuti pulsations have higher amplitude in the *B* filter, whereas the slow variability has slightly higher amplitude in *V*. (d) Residual sum of squares spectrum of a 2-harmonic fit (RSS_2) to the *Hipparcos* photometry of HD 173794.

multiperiodic δ Scuti pulsations superposed on slow variations which have very similar amplitude in the *B*- and *V*-bands (cf. Figs 4b and c). This raises the suspicion that HD 173794 is an ellipsoidal variable with a δ Scuti component. We therefore re-analysed the *Hipparcos* photometry of that star with the residualgram method; the result is shown in Fig. 4(d). The dominant peak in this plot is at 0.3078 cycle day^{-1}, exactly 1/2 the frequency found by Fourier analysis (Handler 1999). The phase diagram of the *Hipparcos* photometry relative to this frequency is typical for an ellipsoidal variable, and the corresponding frequency solution explains all the slow variability in these data.

These two frequencies also explain the slow variability in our data. We have therefore fitted them to our measurements, adopting the *Hipparcos* frequencies as definite and performed a frequency analysis of the residuals to examine the δ Scuti variability in more detail. The short-period pulsations turned out to be quite complicated, at least five frequencies in the range 19–26 cycle day^{-1} appear to be excited. We refrain from quoting exact values because of the aliasing problem. In any case, the short-period pulsations are quite interesting. All evidence, the *Hipparcos* parallax of the star, its spectral classification (A3 III-IV, Houk 1978) and the long period of the ellipsoidal variation, suggests it is rather evolved and thus pulsates in quite high radial overtones ($Q \approx 0.006, k \approx 10$).

3.1.15 HD 181998

We suggest that this star is a bona fide γ Doradus star. Our two longer nights of observations show slow variability that is not singly-periodic, consistent with the complicated amplitude spectrum of its *Hipparcos* photometry. These results combined with the colour-amplitude ratios ($B/V = 1.22 \pm 0.03$, $V/I_c = 1.68 \pm 0.03$) in our data show that the slow variations of HD 181998 are due to pulsation. An upper limit of 1.1 mmag is placed on the presence of δ Scuti pulsations.

3.1.16 HD 188032

The analysis of the *Hipparcos* data of this star (Handler 1999) left some doubt about its being a good γ Doradus candidate or a more rapid variable. In our ground-based observations, only slow variations with an amplitude below 0.02 mag are detected. From these we infer a B/V colour-amplitude ratio of 1.25 ± 0.1, suggestive of pulsation. Short-period variability in the δ Scuti domain remains undetected within 0.9 mmag. We classify this star as a γ Doradus candidate.

3.1.17 HD 189631

This star was found to be slowly variable within individual nights, but we are unable to determine the time-scale of the light variations. The colour-amplitude ratios ($B/V = 1.36 \pm 0.04$, $V/I_c = 1.82 \pm 0.12$) imply pulsation as the cause of this variability, which reached a peak-to-peak amplitude in excess of 0.05 mag from night to night. We conservatively classify HD 189631 as a γ Doradus candidate and note the absence of δ Scuti pulsation within an upper limit of 0.9 mmag.

3.1.18 HD 198528

We found slow variations with amplitudes of several hundredths of a magnitude in our four longest observing runs. However, only very small colour variability (B/V amplitude ratio < 1.04) was noted as well, raising the suspicion that the star is an ellipsoidal variable. A combined analysis of the *Hipparcos* photometry (with the decisive clue coming from residualgram analysis, see Fig. 5) and our new observations confirmed this interpretation. We found that a double-wave light curve (inconsistent with W UMa-type variability) corresponding to an orbital period of 0.807 d satisfactorily explains all the data. The period given by Handler (1999) based on Fourier analysis of *Hipparcos* photometry only is therefore incorrect, probably owing to the small number of observations (49 measurements distributed over 3 yr). No δ Scuti variation is detected within a limit of 1.5 mmag in the amplitude spectrum, although we note that a very weak 45-minute variation seemed to be present in both filters in our best data.

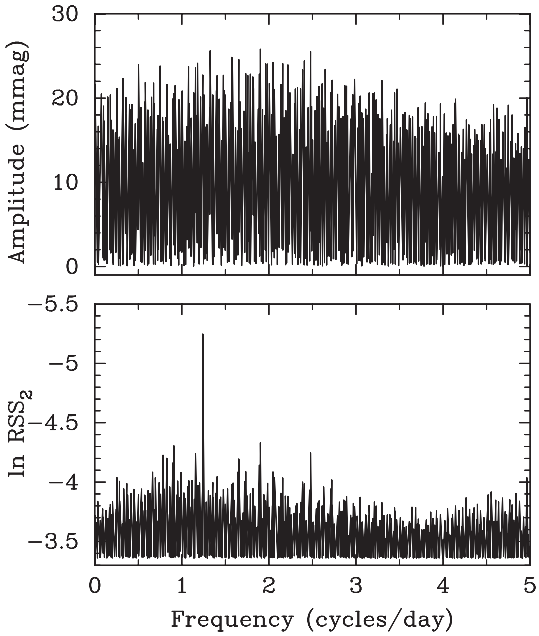

Figure 5. Upper panel: amplitude spectrum of the *Hipparcos* photometry of HD 198528. No periodicity can be found. Lower panel: residual sum of squares spectrum of a 2-harmonic fit (RSS$_2$) of the same data. The correct frequency of light variation is now quite clear.

3.1.19 HD 201985

This star remains unsolved. Although the *Hipparcos* photometry implies a range of variability of a few hundredths of a magnitude, little variation was seen during our observations (a few millimagnitudes at best), with one exception: during the first run from SAAO, the star was 0.15 mag fainter than on the other nights. An instrumental problem or misidentification on the sky is ruled out, as the star's mean $(B-V)$ colour on that night was the same as on the other four within fractions of a millimagnitude, and as the relative zero-points of the other three stars in the ensemble were consistent with the other nights. We note that little colour variability seems to accompany the magnitude changes, and we can place an upper limit of 2.0 mmag to the presence of δ Scuti pulsations. HD 201985 could be an eclipsing binary.

3.1.20 HD 207223

This is a singly-periodic bona fide γ Doradus star (Aerts & Kaye 2001) located close to HD 207651 in the sky. We tested HD 207223 for δ Scuti variability in a single night. None was detected within a limit of 1.5 mmag in the amplitude spectrum (cf. Kaye et al. 1999b).

3.1.21 HD 207651

The *Hipparcos* photometry seemed to indicate two frequencies of 1.4 and 6 cycle day^{-1} (Handler 1999), whereas our runs show a dominant δ Scuti variation with a time-scale of 1.5–2 h with superposed long-term modulations. The associated colour amplitudes corroborate the δ Scuti interpretation, but are inconclusive with respect to the slower variability. Estimating the absolute magnitude of the star from its *Hipparcos* parallax results in $M_v = -0.4 \pm 0.5$, but Strömgren photometric calibrations (Crawford 1979) yield $M_v = +0.8 \pm 0.3$. This may be an indication of binarity. In any case, we are unable to pinpoint the nature of the star on the basis of our data alone; more observations are needed. The Q values of the δ Scuti pulsations are 0.007 and 0.015 d for the two absolute-magnitude values, respectively.

3.1.22 HD 209295

This is our only detection of both δ Scuti and γ Doradus pulsations in the same star. It was already clear from the analysis of the *Hipparcos* photometry (Handler 1999) that multiperiodic γ Doradus variability is present in the star's light curves, and multiperiodic δ Scuti pulsations were clearly detected in our first nights of observation as well (Fig. 6). HD 209295 was studied in great detail by Handler et al. (2002), and we refer to this paper for more information. For the present purposes, we only note that these authors present evidence that the γ Doradus pulsations of HD 209295 are tidally excited. The star should therefore not be considered a normal γ Doradus star.

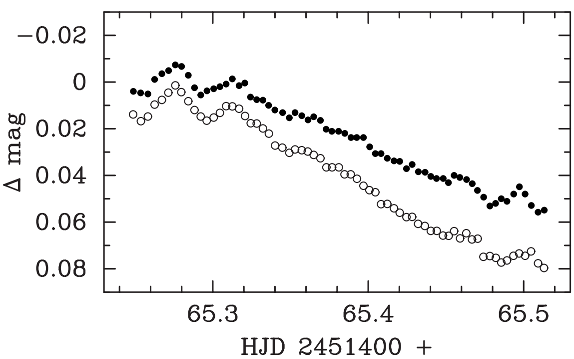

Figure 6. An example light curve of HD 209295. Filled circles are *V*-filter data, open circles the *B*-filter measurements. Multiperiodic δ Scuti pulsations are superposed on a gradual decline in brightness. Note the higher amplitude of the slow variations in the *B*-filter data, confirming their pulsational origin.

3.1.23 HD 211699

This prime γ Doradus candidate (Handler 1999) showed very little variability during our individual nights of observation, which may be due to the dominant period of light variation being close to one day. However, we were able to detect changes in the mean magnitude from night to night, whose *B*/*V* colour-amplitude ratio (1.29 ± 0.09) suggests that pulsations are causing them. We therefore retain this star as a γ Doradus candidate and we also note the absence of δ Scuti pulsations within an upper limit of 0.8 mmag.

3.1.24 HD 221866

Classified as a prime γ Doradus candidate by Handler (1999), this star showed clear evidence of slow variability. The *Hipparcos* period fits our data and results in a *B*/*V* colour-amplitude ratio of 1.18 ± 0.02, consistent with pulsation. δ Scuti-type variability remains undetected within a limit of 0.9 mmag in the amplitude spectrum. We conservatively retain this star as a γ Doradus candidate because of the rather low colour-amplitude ratio.

3.1.25 Variable comparison stars

Out of the 40 comparison stars used in this study, two turned out to be variable as well. The first, HD 86301, was a comparison star in the HD 85693/HD 86371 group. It is located near the hot luminous border of the δ Scuti instability strip and was found to be a very-low-amplitude variable. The light curve appears multiperiodic with a time-scale of 3.8–6 h and a total amplitude of about 0.01 mag. Our period estimate yields a range of $0.035\,\mathrm{d} < Q < 0.054\,\mathrm{d}$. We tentatively classify HD 86301 as a new δ Scuti star.

The second variable comparison star was HD 183452, chosen for the HD 181998 group. During our first short run on this group, it already showed conspicuous magnitude changes. After realizing the star was classified as variable from measurements with the *Tycho* satellite (ESA 1997), we added another comparison star into the sequence, but continued to monitor HD 183452 as well. The total amplitude of its light variations is in excess of 0.1 mag, but there is very little colour variation. We thus suspect that HD 183452 is an ellipsoidal variable. A double-wave light curve assuming a preliminary orbital period of 0.692 d fits our data very well.

Table 2. Programme star classifications. Objects indicated with an asterisk are δ Scuti stars in addition to their main type of variability, whereas stars indicated with two asterisks have suspected additional δ Scuti variations.

γ Doradus/δ Scuti 'hybrid'	*Bona fide* γ Doradus stars	γ Doradus candidates	Ellipsoidal variables	δ Scuti stars	Unsolved variables
HD 209295	HD 12901	HD 10167	HD 14147**	HD 27093	HD 81421**
	HD 65526	HD 40745	HD 173794*		HD 86593
	HD 86371	HD 41448	HD 198528**		BD+8 3658*
	HD 139095	HD 110606			HD 201985
	HD 167858	HD 113357			HD 207651*
	HD 181998	HD 188032			
	HD 207223	HD 189631			
		HD 211699			
		HD 221866			

3.2 Summary of survey results

We performed photometric monitoring of a total of 26 stars that seemed to be related to the γ Doradus phenomenon. One of them, HD 209295, turned out to be both a γ Doradus and a δ Scuti pulsator, but this object is peculiar, as its g-mode pulsations appear strongly coupled to its binary orbit (Handler et al. 2002).

We believe that six of our targets are new γ Doradus pulsators, and nine more stars are probable γ Doradus stars. We discovered three ellipsoidal variables and one δ Scuti star. The classifications of our target stars are summarized in Table 2. The detection limits we achieved for δ Scuti pulsations compare well with those of other ground-based variability surveys (starting with Breger 1969), to which our results are to be compared. Of course, the presence of very-low-amplitude δ Scuti pulsations in some of our targets cannot be ruled out. Such variability has been detected down to limits of 0.4 mmag with the help of extensive multisite campaigns (Handler et al. 2000), and space missions are expected to decrease these limits considerably.

4 THE HOT BORDER OF THE γ DORADUS PHENOMENON

As already mentioned in the Introduction, it is not quite clear up to what effective temperatures γ Doradus pulsations can be excited. With our new results added to those available in the literature, we can take a closer look at this problem. We show all the presently known γ Doradus stars and suspects (taken from the on-line catalogue by Handler & Kaye 2001) in a colour–magnitude diagram in Fig. 7.

Even a brief glance at Fig. 7 suggests that the blue edge of the γ Doradus instability region as outlined by Handler (1999) requires revision. (We again exclude HD 209295, the hottest bona fide γ Doradus star from the discussion because of its close-binary nature.) The three hottest stars referred to by Handler (1999) were HD 152569 (Kaye 1998), 57 Tau (Paparó et al. 2000) and M34 UVa 144 (Krisciunas & Patten 1999). HD 152569 was reclassified as a δ Scuti star (Kaye et al. 2000); thus it is not plotted in Fig. 7.

57 Tau is also a δ Scuti star, but it exhibits slow, apparent multiperiodic, variability with an amplitude of a few mmag (Paparó et al. 2000) in addition; the period of the highest-amplitude slow variation is 1.246 d. However, Kaye (1999) showed that 57 Tau is a spectroscopic binary with an orbital period of 2.486 d, almost exactly twice the value from the photometry. As there seems to be very little colour variation in the slow variations noted by Paparó et al. (2000), we think that 57 Tau is in fact an ellipsoidal variable. Therefore we do not any longer consider the star a good γ Doradus candidate.

The star UVa 144 in the open cluster M34 is a multiperiodic slow variable. However, the two periods found by Krisciunas & Patten (1999), 1.52 and 1.28 cycle day^{-1}, could be harmonics of each other allowing for some aliasing ambiguities. In any case, the $(b - y)$ colour of this star adopted by Handler (1999) is erroneous, as he was unaware of the measurements by Canterna, Perry & Crawford (1979) showing the star to be redder than previously thought.

Consequently, a revision of the blue boundary of the γ Doradus region in the colour–magnitude diagram is in order. The new blue edge is already included in Fig. 7. Compared to the original one by Handler (1999), it is about 150 K cooler on the ZAMS and about 75 K cooler one magnitude above it. There are now four stars that define it, the bona fide variable HD 218396 (Zerbi et al. 1999), as well as HD 41448 (Eyer 1998; Handler 1999; and this work), HD 211699 and HD 221866 (Handler 1999; and this work). As the evidence for the γ Doradus nature of all these stars is quite good, we think that another shift of this blue edge towards redder colours is no longer possible.

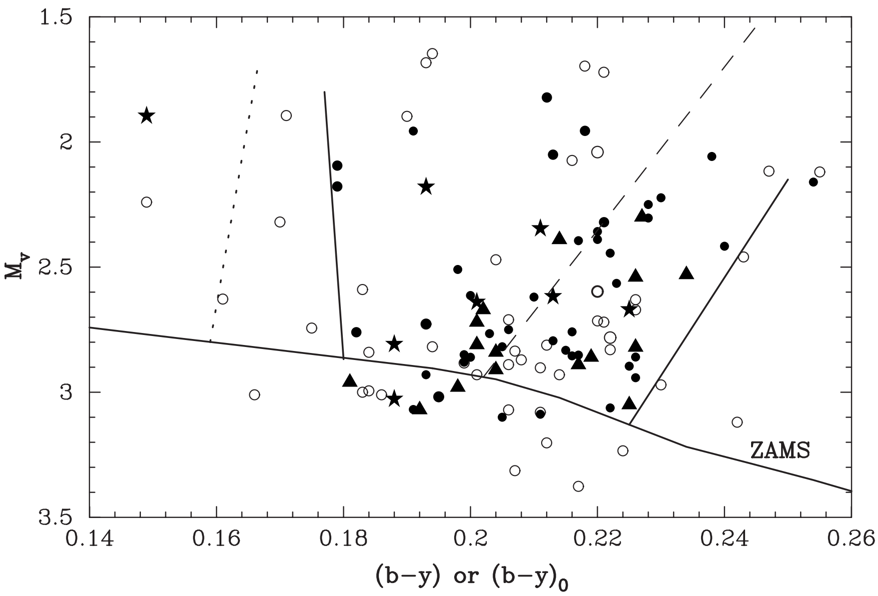

Figure 7. The domain of the γ Doradus pulsators in the colour–magnitude diagram. Star symbols denote bona fide γ Doradus stars observed by us and filled triangles are bona fide γ Doradus stars from the literature. The filled circles are prime γ Doradus candidates and the open circles are other γ Doradus candidates (including our unsolved variables). Ellipsoidal variables have been omitted. The approximately horizontal line is the Zero-Age Main Sequence (ZAMS)(Crawford 1975, 1979), and the dotted line is the blue boundary of the γ Doradus region derived by Handler (1999), which is superseded by this work. The lines almost normal to the ZAMS are the presently known boundaries of the γ Doradus region. The dashed line almost normal to the ZAMS represents the red edge of the δ Scuti instability strip (Rodriguez & Breger 2001). The γ Doradus star outlying far to the blue is HD 209295.

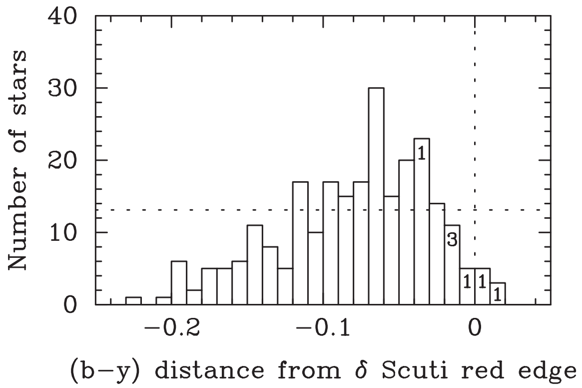

Figure 8. The number of δ Scuti stars as a function of $(b-y)$ distance from the red edge of the lower instability strip (vertical dotted line). In this diagram, the blue edge is located at $\Delta(b-y) = -0.19$ on the ZAMS and at $\Delta(b-y) = -0.23$ at the luminous end of the δ Scuti strip. The horizontal dotted line is the average number of stars per bin for $-0.19 < \Delta(b-y) < 0$. The numbers inside some of the bins are the number of bona fide γ Doradus stars tested for δ Scuti variability corresponding to their $\Delta(b-y)$.

5 THE INCIDENCE OF δ SCUTI PULSATIONS AMONGST γ DORADUS STARS

With the exception of the unusual variable HD 209295, we have observed five bona fide γ Doradus stars located inside the δ Scuti instability strip (HD 12901, HD 65526, HD 86371, HD 167858 and HD 181998) adopting the red edge for δ Scuti pulsations by Rodriguez & Breger (2001)[1]. Another star, HD 139095, falls on this red edge.

We did not find δ Scuti pulsations in any of these stars. Does this mean that, except under special circumstances such as the close binarity of HD 209295, γ Doradus stars cannot be δ Scuti pulsators at the same time?

As mentioned in the Introduction, the average incidence of photometrically detectable δ Scuti pulsations of chemically normal stars located inside the lower instability strip is 1/3. However, the γ Doradus star domain only overlaps with a region close to the cool edge of the δ Scuti instability strip. Hence it is quite possible that the incidence of δ Scuti pulsations in that overlap region is generally smaller than, for instance, in the middle of the δ Scuti strip.

To examine this idea, we assume that all stars tested for δ Scuti pulsations so far are uniformly distributed over $(b-y)$. We selected all 249 δ Scuti stars from the recent catalogue of Rodriguez, López-González & López de Coca (2000), for which uvbyβ photometry is available and determined their distance from the red edge of the δ Scuti instability strip, as defined by Rodriguez & Breger (2001). We then determined the number of stars in strips 0.01 mag wide in $(b-y)$, which are parallel to the red edge, and we show the number of bona fide γ Doradus stars we observed in those bins (Fig. 8).

As suspected, the number of δ Scuti stars decreases towards the red edge; stars near this red edge have an incidence of δ Scuti pulsation that is lower than average. We need to take this into account if we want to examine the significance of the absence of δ Scuti pulsation in the bona fide γ Doradus stars we observed.

Thus, the probability that we do not find δ Scuti pulsations in any of our observed bona fide γ Doradus stars inside the δ Scuti strip, results in 18 per cent. This suggests that γ Doradus stars are less likely to be δ Scuti pulsators than non-γ Doradus stars in the same domain of the colour–magnitude diagram. Obviously, more stars need to be observed to strengthen this conclusion.

[1] This revised red edge only became available near the end of this work and could therefore not be adopted for target selection (Section 2).

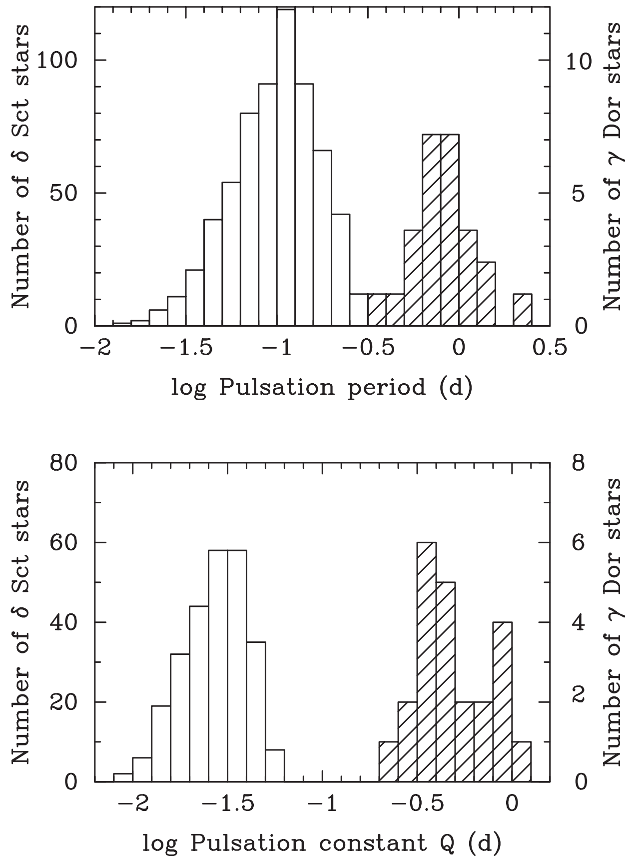

Figure 9. Upper panel: the number of δ Scuti (open histogram bars) and γ Doradus (hatched histogram bars) stars within certain ranges of pulsation period. The two groups of pulsator almost overlap in this diagram. Lower panel: the distribution of the pulsation constants of δ Scuti (open bars) and γ Doradus (hatched bars) stars. There is a clear separation between the two.

6 PULSATION PERIODS AND PULSATION CONSTANTS

The longest pulsation periods of δ Scuti stars listed in the catalogue of Rodriguez et al. (2000) are around 6.5 h; the possible δ Scuti stars AC And (Fernie 1994) and V823 Cas (Antipin 1997) even have periods of 17 and 16 h, respectively. The shortest pulsation periods of γ Doradus stars found so far were around 7.5 h (Handler 1999; Henry et al. 2001). This may lead to the suspicion that there might be an overlap in the pulsational behaviour of those two classes of pulsator, making a distinction hard for certain stars.

However, as the γ Doradus stars are so far only found on the main sequence, and as the long-period δ Scuti stars all seem to be evolved, this overlap is not a physical one. To support this suggestion, we compared the distribution of the pulsation periods of 636 δ Scuti stars in the catalogue of Rodriguez et al. (2000) to that of the bona fide stars (except HD 209295) listed by Handler & Kaye (2001). We show it in the upper panel of Fig. 9. As implied by the previous discussion, there is almost an overlap between the two groups.

On the other hand, if one uses the pulsation constant Q (calculated with equation 1 and the method described in Section 3.1) to discriminate between δ Scuti and γ Doradus stars, the ambiguity is removed (lower panel of Fig. 9, 262 δ Scuti stars from Rodriguez et al. 2000 for which pulsation constants could be calculated). There is a clear gap between the two groups. Thus we confirm that δ Scuti and γ Doradus stars can be separated via their pulsation constants; all bona fide γ Doradus stars known to date have $Q > 0.23$ d.

7 CONCLUSIONS

We performed a photometric search for δ Scuti pulsations among candidate γ Doradus stars to examine the interrelations between these two groups of pulsators. We observed altogether 26 stars, of which 65 per cent turned out to be bona fide γ Doradus stars or excellent candidates. However, none of these objects exhibited δ Scuti pulsations with the exception of the close binary HD 209295 (Handler et al. 2002), which is therefore anomalous.

Our results indicate that γ Doradus stars are less likely to be δ Scuti pulsators than non-γ Doradus stars in the same temperature range. This conclusion is not yet definite because of the small number of bona fide γ Doradus stars inside the δ Scuti domain investigated so far. This situation can be improved by performing a similar project in the Northern Hemisphere and by more extensive observations of the γ Doradus candidates we already examined, in order to prove their γ Doradus nature.

We were also able to locate the blue edge of the γ Doradus domain in the colour–magnitude diagram more accurately. Finally, we showed that the δ Scuti stars and the γ Doradus pulsators are clearly separated by the values of their pulsation constants Q; the known γ Doradus stars all have $Q > 0.23$ d.

Although we are still at the beginning of understanding the whole extent of the γ Doradus phenomenon, we think we now have the basic data for quantitative comparisons between observations and model calculations. Acceptable models for γ Doradus pulsators must be able to reproduce the observed constraints on pulsational instability in temperature, luminosity, metallicity and period.

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GH thanks Eloy Rodriguez for making an ASCII version of his δ Scuti star catalogue available and Chris Koen for his support of this project and for carefully proofreading a draft version of this paper. Michel Breger, Laurent Eyer and Tony Kaye also commented on a draft version of this work. We appreciate the constructive comments of the referee, Joyce Guzik.

NOTE ADDED IN PRESS

As pointed out to the authors by G. W. Henry, the star HD 221866 is located incorrectly in our Fig 7. Its measured $(b-y)_0$ is 0.151, which would place it near HD 209295. However, we doubt the correctness of the published $(b-y)_0$ as it is inconsistent with measurements of its $B-Y$ and $V-I$ colours. We suggest that new standard Strömgren photometry of HD 221866 be obtained.

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