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Long-term multicolour photometry and high-resolution spectroscopy of the two γ Doradus stars HD 12901 and HD 48501*

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Abstract. We gathered long-term multicolour Geneva $UB_1BB_2V_1VG$ photometric and high-resolution ($R = 40\,000$) spectroscopic data of the two γ Doradus stars HD 12901 and HD 48501. The photometry reveals three frequencies for each of the two stars: $f_1 = 1.21563\,\mathrm{c\,d^{-1}}$, $f_2 = 1.39594\,\mathrm{c\,d^{-1}}$ and $f_3 = 2.18636\,\mathrm{c\,d^{-1}}$ for HD 12901 and $f_1 = 1.09408\,\mathrm{c\,d^{-1}}$, $f_2 = 1.29054\,\mathrm{c\,d^{-1}}$ and $f_3 = 1.19924\,\mathrm{c\,d^{-1}}$ for HD 48501. The photometric amplitude is each time largest in the Geneva B_1 filter and the variations in all the different filters are perfectly in phase within the measurement errors. Mode identification points out that the six modes are all $\ell = 1$ modes and that the non-adiabatic temperature variations are extremely small, in contradiction to current theoretical predictions. Our spectra show that all the observed frequencies are intrinsic to the stars and cannot be due to binarity. We detect clear line-profile variations at low amplitude ($<1\,\mathrm{km\,s^{-1}}$) due to the oscillations of both targets. The estimated $v \sin i$ from the spectra are $\sim 53\,\mathrm{km\,s^{-1}}$ for HD 12901 and $\sim 29\,\mathrm{km\,s^{-1}}$ for HD 48501. It is at present unclear if the triplet-like structure for HD 48501 is the consequence of rotational splitting or of the large separation expected for high-order gravity modes in the asymptotic regime.

Key words. stars: variables: general – stars: oscillations – stars: individual: HD 12901, HD 48501 – line: profiles

1. Introduction

The γ Doradus stars constitute a recently-discovered class of (multiperiodic) non-radial gravity-mode oscillators with periods in the range 0.5−3 days. They are situated along the main sequence in the HR diagram, just below the classical instability strip (Handler 1999). Krisciunas (1998) and Zerbi (2000) review respectively the history of the discovery and the current observational status of this group of variables. The cause of the excitation of the modes is still controversial (cf. Guzik et al. 2000 versus Löffler 2002). It is therefore of utmost importance to explore observationally the details of the pulsational behaviour in as many γ Doradus stars as possible.

As the γ Doradus stars have very long beat-periods, of the order of months or even years, it is a non-trivial observational task to discover them, let alone to obtain detailed reliable results on their frequency content (for a recent example illustrating the difficulties, see Poretti et al. 2002). Many new members of the class were found from the HIPPARCOS photometry (Eyer 1998; Aerts et al. 1998; Handler 1999). Meanwhile, large (follow-up) photometric ground-based discovery campaigns have also been organised (e.g. Eyer et al. 2002; Henry & Fekel 2002; Handler & Shobbrook 2002). All these efforts have led to a total number of 30 *bona fide* members and many more candidates (Handler 2002). Extensive spectroscopic campaigns are being carried out by Fekel et al. (2003) and by Mathias et al. (2003).

Members of the Institute of Astronomy of Leuven University set up a large multicolour photometric search campaign with the old Swiss 0.70 m telescope at La Silla in 1996, well before most of the class members were found from HIPPARCOS data. They monitored 11 F0–F9 stars with a high dispersion in the Geneva database that fitted the observational

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* Based on observations gathered with the Swiss 0.7 m telescope equipped with the photometer P7 and with the Swiss 1.2 m Euler telescope equipped with the spectrograph CORALIE, both situated at La Silla, Chile. Reduced data available upon request from the first author.

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window of a few 3-weeks runs. Eyer & Aerts (2000) reported on these data and found that three of the stars are intrinsically variable.

Our current study presents more extensive Geneva photometry and high-resolution spectroscopy of two of these γ Doradus stars, HD 12901 (HIP 9807, $m_V = 6.8$ mag, F0V) and HD 48501 (HIP 32144, $m_V = 6.1$ mag, F2V), to perform detailed frequency analysis and mode identification. The third new γ Doradus star discovered by Eyer & Aerts (2000) has a visual magnitude of 8.2, which is why it was omitted for the follow-up high-resolution spectroscopic study.

In Sect. 2 we present the new data for the two stars. The period analysis and the photometric mode identification based upon the multicolour photometry are described in Sect. 3 while Sect. 4 is devoted to the analysis of the spectroscopy. We end with conclusions and future plans in Sect. 5.

2. Description of the data

We analysed 174 and 184 photometric measurements for HD 12901 and HD 48501. These were obtained with the photometer P 7 attached to the 0.7 m Swiss telescope situated at La Silla Observatory. P 7 measures in the Geneva seven-colour photometric system. Each datapoint is the result of averaging three consecutive exposures of 40 s. We kept only those measurements with an accuracy below 5 mmag in each of the seven filters. The Geneva database consists of thousands of measurements gathered at La Silla between 1973 and 1997 which underwent a very accurate global calibration by means of standard star measurements taken over 25 years. The system is so stable that data taken decades apart can easily be combined (see, e.g., De Cat & Aerts 2002; Aerts et al. 2003 for examples). The photometric data of our two target stars have a total timespan of 18−20 years, with typically very few old measurements taken many years ago and dedicated measurements taken over 800 days between 1995−1997. We kept the old data in the analyses as they are fully consistent with the dedicated measurements.

The spectroscopic data were gathered with the CORALIE échelle spectrograph attached to the 1.2 m Swiss Euler telescope at La Silla. We have obtained 43 and 34 high-resolution spectra for respectively HD 12901 and HD 48501. The spectra have a total timebase of about three years and were taken from 1998−2002. The obtained signal-to-noise ratio is about 100 for integration times of approximately 45 min.

The distribution of the dedicated data in time is presented in Table 1.

Table 1. Logbook of the dedicated measurements of HD 12901 and HD 48501. The Heliocentric Julian Dates (HJD) are given in days with respect to 2 450 000 and N denotes the number of measurements.

	Photometry			Spectroscopy		
Star	HJD		N	HJD		N
	Begin	End		Begin	End	
HD 12901	1.7	20.7	54	1144.6	1149.6	4
	45.6	63.6	36	1472.5	1477.6	8
	386.7	407.6	24	1761.9	1773.9	3
	744.6	764.6	29	1816.8	1829.8	26
	786.6	805.6	28	2582.7	2582.8	2
HD 48501	2.8	17.8	8	1145.8	1154.8	3
	45.8	63.8	43	1471.9	1479.9	7
	108.6	127.7	54	2626.8	2637.9	24
	389.8	407.9	18			
	744.8	763.8	28			
	786.8	805.8	29			

3. Photometric variations

3.1. Frequency analysis

We performed period analyses on the Geneva data with different methods, such as PDM (Stellingwerf 1978), Lomb-Scargle (Scargle 1982), CLEAN (Roberts et al. 1987). We accepted frequencies only when they were found by at least two methods. We chose each time the test frequencies in the interval $[0, 8]\,\mathrm{c\,d^{-1}}$ in steps of $10^{-5}\,\mathrm{c\,d^{-1}}$. This choice is based on the error estimates for the frequencies (for an expression, see e.g. Cuypers 1987). To determine the errors we took into account the time span of the dedicated observations only, which is about 800 days. This results in uncertainties between 3 and $8 \times 10^{-5}\,\mathrm{c\,d^{-1}}$ for the amplitudes (see Table 2).

3.1.1. HD 12901

For HD 12901, two of the three frequency analyses lead to the three significant frequencies $f_1 = 1.21563 \pm 0.00003\,\mathrm{c\,d^{-1}}$, $f_2 = 1.39594 \pm 0.00006\,\mathrm{c\,d^{-1}}$ and $f_3 = 2.18636 \pm 0.00006\,\mathrm{c\,d^{-1}}$. The error estimates were derived from the amplitudes in the B_1 filter. We show the Scargle periodograms for the Geneva B filter in the region $[0, 3]\,\mathrm{c\,d^{-1}}$ after subsequent prewhitening stages, as well as the window function, in the left panels of Fig. 1. The CLEANed spectrum of HD 12901 for the B_1 filter is shown in the left panel of Fig. 2. The dotted lines represent the results from the Scargle and PDM analysis. In CLEANing we have used a gain factor of 0.5 for 100 iterations. We see that the two first frequencies found from the Fourier analysis are also identified as high peaks after CLEANing. However, the CLEANing does not lead to f_3, but rather to two additional candidate frequencies: $0.11342\,\mathrm{c\,d^{-1}}$ and $1.17606\,\mathrm{c\,d^{-1}}$ (these are indicated as dashed line in Fig. 2). The latter is close to the one-day alias of f_3. The occurrence of aliasing problems from our data sets is not surprising as we are dealing with low-frequency gravity modes and single-site data with a limited time sampling (see Table 1).

In order to check the reality of the frequencies we have determined the amplitudes (in mag) and phases for several combinations of three frequencies. The result for the combination f_1, f_2, f_3 can be found in Table 2. We compared this fit to those resulting from taking different aliases (both daily and yearly) of these three frequencies. We can be sure of the reality of f_1 and f_2 because fits with their aliases give worse results than the one listed in Table 2 (besides the fact that all frequency

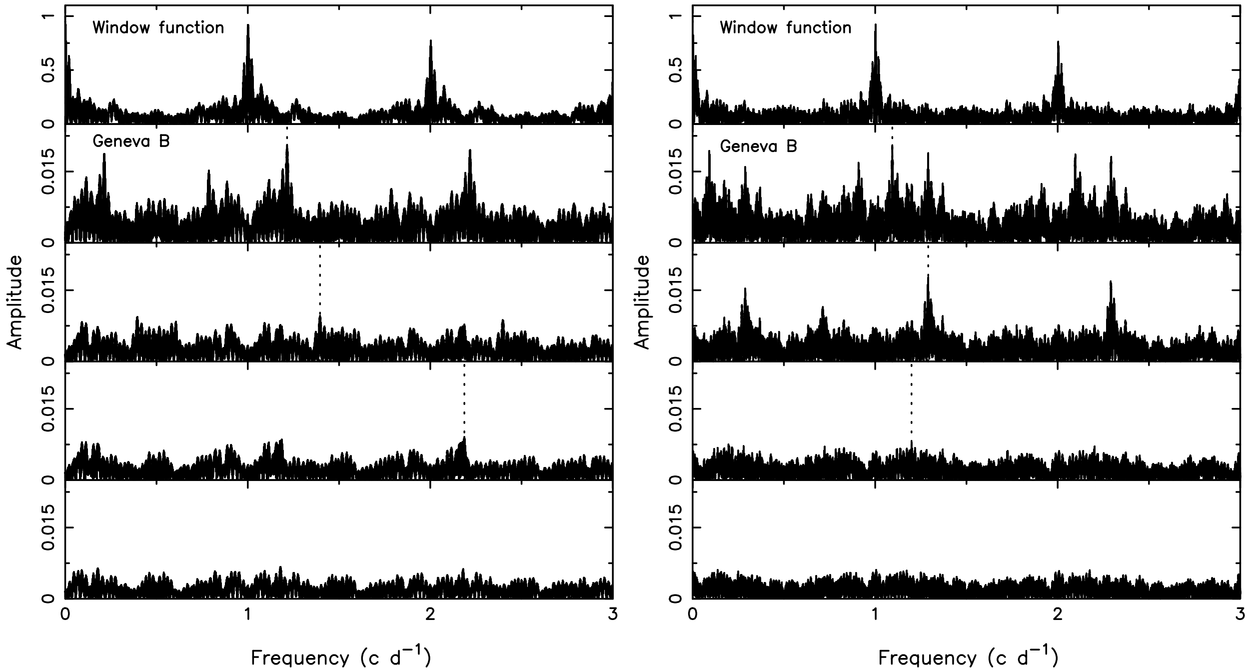

Fig. 1. Scargle periodograms of the Geneva B data of HD 12901 (*left*) and HD 48501 (*right*). The amplitude is expressed in magnitude and is rescaled to 1 for the window function (upper panel). The significant frequencies at subsequent stages of prewhitening are indicated by the dotted lines.

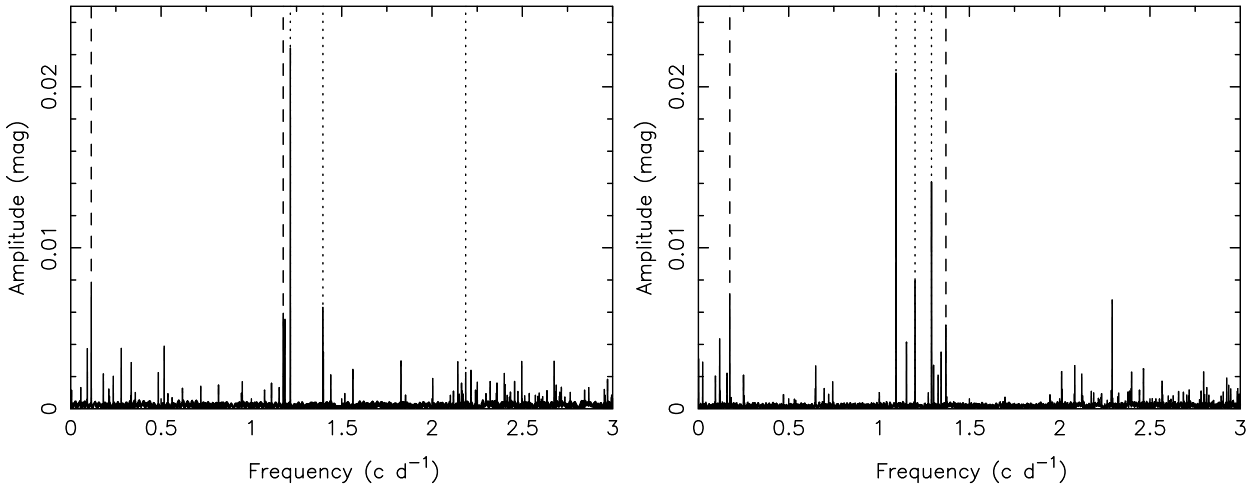

Fig. 2. CLEANed frequency spectra determined from adopting a gain factor of 0.5 during 100 iterations for the B_1 filter data of HD 12901 (*left*) and HD 48501 (*right*). The three frequencies found to be significant from the Scargle periodograms are indicated as dotted lines. Additional candidate frequencies are discussed in the text and are represented by the dashed lines.

analyses methods agree on them). As for the fits with f_1, f_2 and the one-day alias of f_3 near $f_3 - 1$ on the one hand and with f_1, f_2 and 0.11342 c d^{-1} on the other hand, these both lead to the same amplitudes as those listed in Table 2 within the error bars, but with a 4% lower variance reduction. We therefore do not find any reason to prefer $f_3 - 1$ or 0.11342 c d^{-1} above f_3.

For completeness, we note that Handler (1999) suggested HD 12901 to be a candidate δ Scuti star, although he listed an uncertain period of 2.18 d for this star in the HIPPARCOS data. Our ground-based higher-accuracy data do not lead to short-period variability, conform the earlier findings of Eyer & Aerts (2000). Based on this earlier result, Handler & Shobbrook (2002) already classified HD 12901 as *bona fide* γ Doradus star.

3.1.2. HD 48501

The frequency analysis for HD 48501 is even less ambiguous. We find again three frequencies: $f_1 = 1.09408 \pm 0.00004$ c d^{-1}, $f_2 = 1.29054 \pm 0.00003$ c d^{-1} and $f_3 = 1.19924 \pm 0.00005$ c d^{-1}. These results are derived by all three frequency search methods (see right panels of Figs. 1 and 2). The CLEANing indicates three additional well-marked peaks: at 0.17391 c d^{-1}, at 1.37026 c d^{-1} and at the one-day alias of f_2 (see right panel of Fig. 2). The amplitudes for the triperiodic fit with f_1, f_2, f_3 are listed in Table 2. We have again checked carefully whether fits with aliases of the three frequencies lead to better results but this is not the case. In addition, we determined fits with the four

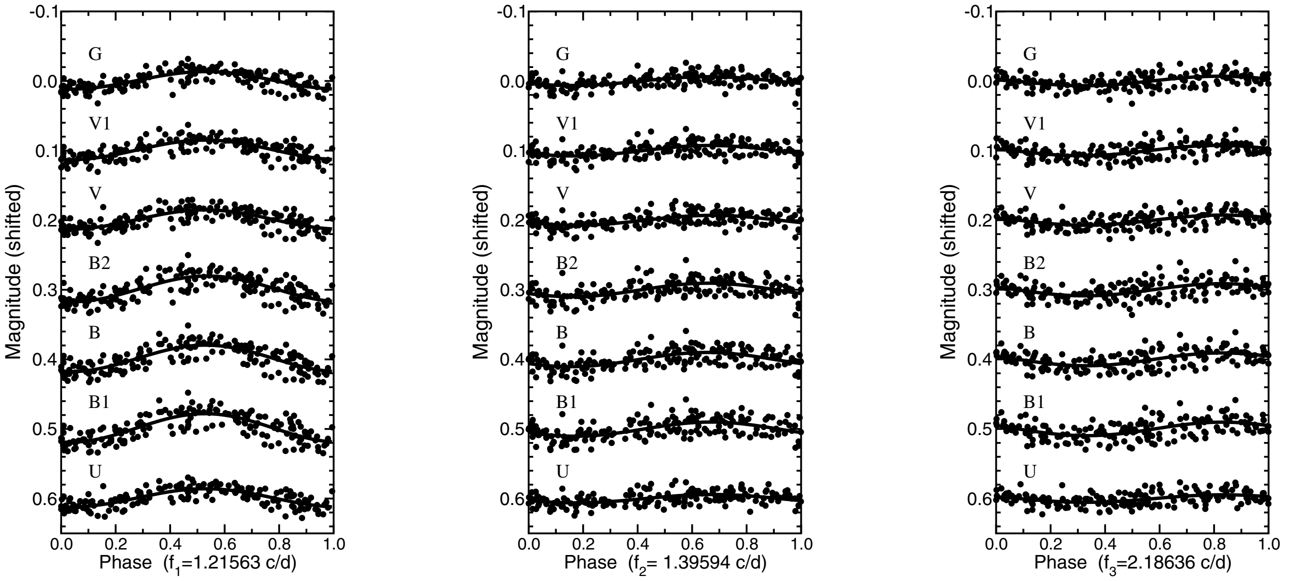

Fig. 3. Phase diagrams of the seven-colour photometry of the γ Doradus star HD 12901 for the indicated frequencies.

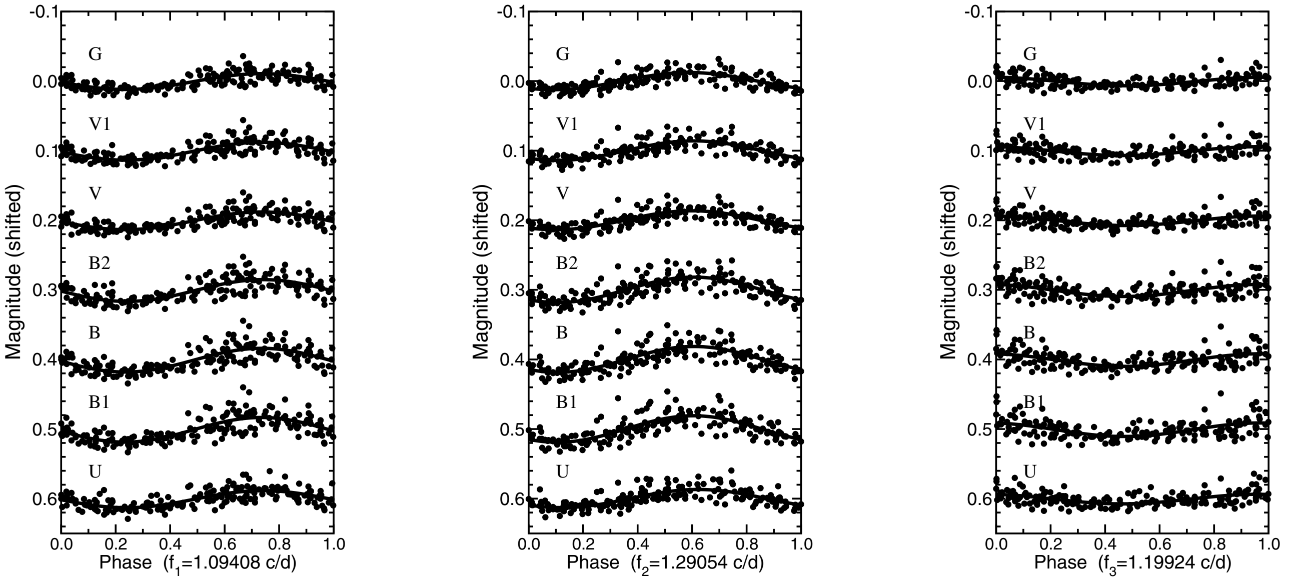

Fig. 4. Phase diagrams of the seven-colour photometry of the γ Doradus star HD 48501 for the indicated frequencies.

frequencies f_1, f_2, f_3 and either 0.17391 c d^{-1} or 1.37026 c d^{-1}. Such fits lead to a 3% increase in variance reduction and an amplitude of 6 mmag (in B) and of 4 mmag (in V) for the fourth frequency, without altering the values for the phases and amplitudes of the three main frequencies. We tentatively decline accepting those two additional frequencies, because they are only found from CLEANing and because the increase in variance reduction is only marginal.

Eyer & Aerts (2000) reported a second frequency of 1.2903 c d^{-1} besides the main frequency 0.0912 c d^{-1}. The latter is an alias of f_1, as they indicated might be the case. Our current data leave no doubt that f_1 is the true frequency and that f_2 is indeed present.

The three frequencies of HD 48501 may be part of a frequency multiplet with a separation of about 0.1 c d^{-1} (see Fig. 2). We test this hypothesis below by means of the spectra.

3.1.3. Phase behaviour as a function of wavelength

We show in Figs. 3 and 4 the phase diagrams for the three frequencies of HD 12901 and HD 48501 for the data obtained in the seven Geneva filters. Visual inspection of the phase diagrams demonstrates that the amplitude is each time largest in the B_1 filter. For both stars we also checked explicitly the frequency behaviour of the colours and find exactly the same three frequencies as the ones occurring in the passbands.

A most important observation is that the variations in all the different filters are *in phase* within the errors for f_1, f_2, f_3 of both HD 12901 and HD 48501. The largest phase difference occurs for the U and G passbands in comparison with the B and V bands for f_2 of HD 48501. The phase difference $\phi_B - \phi_V$ between the B and V lightcurves for f_1, f_2, f_3 amount to 0.0° ± 0.4°, −7° ± 7°, 0° ± 2°, for HD 12901 and to 0° ± 4°, +3° ± 3°, −3° ± 8°, for HD 48501. These results are very robust,

Table 2. Results of harmonic fits to the Geneva lightcurves and to the radial velocity variations of HD 12901 and HD 48501. A stands for the amplitude (expressed in millimagnitude for the light variations and in km s^{-1} for the radial velocity) and ϕ for the phase (expressed in units of 2π radians). The reference epoch for the phase is HJD 2 443 560.0. For the values of the frequencies we refer to the text.

		U	B_1	B	B_2	V_1	V	G	$V_{\rm rad}$
					HD 12901				
f_1	A	14.0 ± 1.3	21.9 ± 1.8	20.4 ± 1.7	19.7 ± 1.8	15.0 ± 1.4	14.8 ± 1.4	13.5 ± 1.3	1.04 ± 0.28
	ϕ	0.120 ± 0.001	0.119 ± 0.001	0.120 ± 0.001	0.128 ± 0.001	0.120 ± 0.001	0.120 ± 0.001	0.121 ± 0.001	0.764 ± 0.042
f_2	A	6.3 ± 1.1	10.7 ± 1.5	10.6 ± 1.3	10.2 ± 1.4	7.8 ± 1.2	7.4 ± 1.2	6.6 ± 1.1	1.30 ± 0.37
	ϕ	0.799 ± 0.028	0.796 ± 0.022	0.780 ± 0.020	0.786 ± 0.022	0.792 ± 0.024	0.799 ± 0.025	0.786 ± 0.026	0.406 ± 0.050
f_3	A	5.9 ± 1.3	10.6 ± 1.8	10.0 ± 1.7	9.5 ± 1.7	8.1 ± 1.4	7.9 ± 1.4	7.5 ± 1.3	–
	ϕ	0.089 ± 0.008	0.088 ± 0.006	0.086 ± 0.006	0.082 ± 0.008	0.071 ± 0.009	0.086 ± 0.007	0.078 ± 0.008	–
var.red.		64.1%	71.5%	72.2%	68.9%	67.2%	66.3%	65.0%	49.3%
					HD 48501				
f_1	A	12.9 ± 1.3	18.5 ± 1.4	17.9 ± 1.3	16.4 ± 1.2	13.4 ± 1.0	13.3 ± 1.0	11.9 ± 0.9	0.43 ± 0.12
	ϕ	0.980 ± 0.013	0.975 ± 0.012	0.976 ± 0.012	0.981 ± 0.012	0.976 ± 0.012	0.976 ± 0.012	0.976 ± 0.012	0.710 ± 0.026
f_2	A	13.3 ± 1.0	19.3 ± 1.4	18.9 ± 1.3	18.5 ± 1.3	14.2 ± 1.0	13.8 ± 1.0	12.5 ± 1.0	0.77 ± 0.12
	ϕ	0.998 ± 0.011	0.980 ± 0.011	0.982 ± 0.010	0.980 ± 0.010	0.979 ± 0.011	0.974 ± 0.011	0.964 ± 0.012	0.928 ± 0.028
f_3	A	7.0 ± 1.2	10.1 ± 1.4	9.4 ± 1.4	9.0 ± 1.3	6.6 ± 1.0	7.1 ± 1.0	6.3 ± 1.0	–
	ϕ	0.271 ± 0.024	0.279 ± 0.023	0.280 ± 0.023	0.277 ± 0.023	0.276 ± 0.025	0.288 ± 0.024	0.290 ± 0.025	–
var.red.		72.5%	77.0%	77.7%	77.1%	76.2%	77.7%	76.3%	75.7%

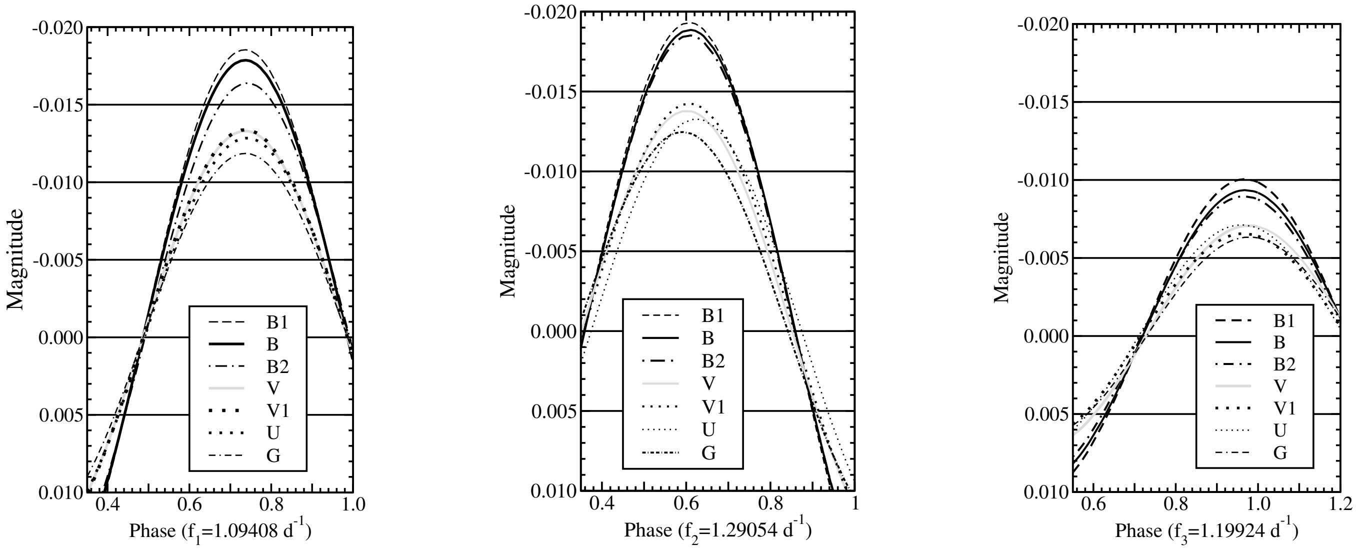

Fig. 5. The upper part of the theoretical fit to the observed phase diagram shifted to the same constant in the seven filters of the γ Doradus star HD 48501 for the indicated frequencies. No phase difference occurs for the different wavelengths, except for the U and G filter for the frequency f_2.

as they also hold if we make fits with aliases of the frequencies. The phase behaviour of HD 48501 is graphically depicted in Fig. 5. For brevity we omit a similar plot for HD 12901, for which the phase differences in the different passbands are smaller – see Table 2. This result is one of the main findings of our study, as it puts severe constraints on the non-adiabatic behaviour of the gravity-mode oscillations in the outer atmosphere of the two stars. Any future theoretical description of convection in the outer layers needs to be compatible with this observational result of null or very small phase shifts.

3.1.4. Amplitude and phase variability in time

We examine whether the amplitudes are stable in time or not. We made fits with f_1, f_2, f_3 for each of the two stars to parts of the data. We split the data in the same way for both stars: we considered the first two and the last two dedicated

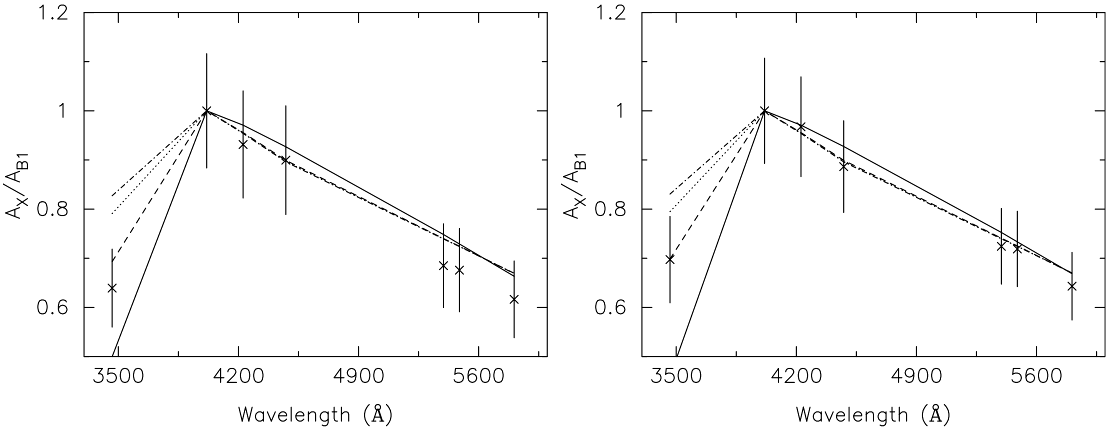

Fig. 6. Theoretically derived amplitude ratios versus observed ones with respect to the B_1 filter in case of the main frequency and for $\ell = 1$. We display the ratios for four different values of $f_T = 0.0$ (full line), 0.1 (dashed line), 0.2 (dotted line) and 0.3 (dot-dashed line). *Left panel*: HD 12901; *right panel*: HD 48501.

photometric observing runs. Each of these has a time span of about 2 months, about 1.9 years apart, and between 50 and 90 datapoints.

The results for HD 12901 of such triperiodic fits to both parts of the dataset lead to amplitudes and phases within the error bars of those listed in Table 2 for f_1 and f_2. However, the amplitude of f_3 increases by a factor 2.5 (from 7 to 15 mmag in B) in 2 years in all the filters. This result remains valid if we take an alias of f_3. The amplitude variability of the mode with f_3 is probably the reason why this frequency is less clearly present in the overall dataset compared to the two others.

For HD 48501 we find no sign of amplitude or phase variability when we compute the fits for the smaller data sets taken two years apart. All results agree with those given in Table 2 within the listed errors.

3.2. Mode identification

Multicolour photometric data offer the possibility to identify the non-radial oscillation modes from the amplitude ratios and the phase differences (e.g. Garrido 2000, for a detailed outline of the method). This method has mainly been applied to δ Scuti stars, for which accurate amplitude ratios and phase differences have been measured. We refer to e.g. Breger et al. (1999) for an application to the star FG Vir and to Breger et al. (2002) for the recent mode identification in the star BI CMi. In these mode identifications, the position of the observed amplitude ratio v/y versus $\phi_v - \phi_y$ for the Strömgren passbands is compared to theoretical predictions of these quantities for different values of the degree of the oscillation modes. These so-called theoretical regions of interest, however, largely overlap for modes of different degree ℓ and so accurate amplitude ratios and phase shifts have to be measured for the method to discriminate between the different degrees of the modes.

Very little is known about the observational phase behaviour as a function of wavelength of the gravity-mode oscillations in γ Doradus stars as most long-term monitoring campaigns focused so far on the discovery of new members and were often limited to only one or two filters. The lack of accurately measured phase shifts in γ Doradus stars is in contrast with the well-documented phase behaviour of the shorter-period pressure modes in the neighbouring δ Scuti stars, where phase differences are prominently present and provide a powerful diagnostic to identify their oscillation modes. A notable exception to the single-filter observations is decribed in the detailed study by Breger et al. (1997) for the star HD 108100. The negative phase shifts $\phi_v - \phi_y = -3.2° \pm 1.3°$ and $-3.8° \pm 2.5°$ (Strömgren filters) for the two detected frequencies of this star seem to point towards $\ell = 1$ modes as positive phase shifts are predicted by theory for the $\ell = 2$ modes for the stellar parameters of HD 108100 (see Fig. 4 in Breger et al. 1997).

Dupret et al. (2003) have recently proposed a new version of the mode-identification method based upon the amplitude ratios with a specific accurate treatment of the non-adiabatic behaviour of the oscillations in the outer atmosphere. These authors have mainly applied their method to the pressure modes in β Cep stars and to the gravity modes in slowly pulsating B stars and showed that their new treatment allows very good discrimination between the different degrees of the modes. As we did not obtain significant phase differences as a function of wavelength for our two γ Doradus stars, we have applied the new method by Dupret et al. (2003) to our lightcurves of HD 12901 and HD 48501 for each of the three frequencies listed in Table 2.

In the case of γ Doradus stars, no reliable theory of the interaction between convection and pulsation has been proposed until now and the characteristics of the thin convective envelope are not known well enough to fix the non-adiabatic effective temperature variation f_T, in contrast to the situation occurring for B stars (see Dupret et al. 2003). We hence kept the amplitude f_T and phase of the non-adiabatic temperature eigenfunction as respectively a free and a constant parameter for all wavelengths. We determined theoretical amplitude ratios under these conditions for $\ell = 1, \ldots, 4$ using the formalism recently proposed by Dupret et al. (2003). For all the three frequencies of the two stars we searched for the value of f_T that best corresponds to the observed amplitude ratios with respect to the

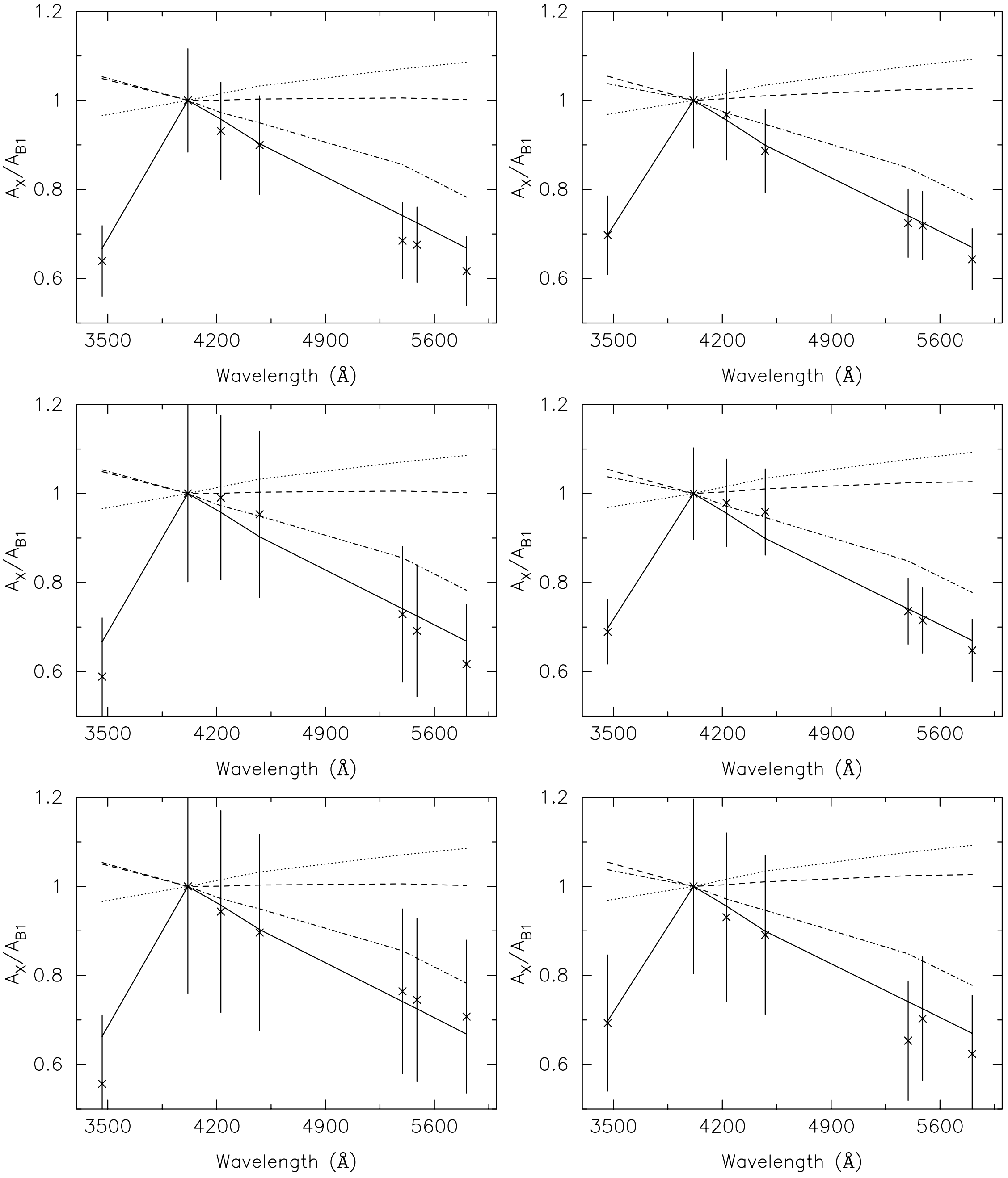

Fig. 7. Theoretically derived amplitude ratios versus observed ones with respect to the B_1 filter for $\ell = 1$ (full line), 2 (dashed line), 3 (dotted line) and 4 (dot-dashed line). *Left panel*: HD 12901 with $f_T = 0.05$; *right panel*: HD 48501 with $f_T = 0.1$. The upper, middle and lower panels are for respectively f_1, f_2, f_3.

B_1 filter. As an example we show this procedure for the main mode of both stars and for the $\ell = 1$ case in Fig. 6. The results are very similar for the other two frequencies and for the other ℓ-values of the modes and lead to consistent values of $f_T = 0.07, 0.04, 0.02$ for the modes f_1, f_2, f_3 of HD 12901 and of $f_T = 0.1$ for the three modes of HD 48501. Such values of the local effective temperature variations for a normalised radial displacement are much lower than those expected for gravity modes dominated by transversal motions, as also occurring for example in slowly pulsating B stars (Dupret et al. 2003). They are unexplained with current knowledge of non-radial oscillations in F-type main-sequence stars. We note that the amplitude ratios are almost insensitive to f_T towards wavelengths redder than B_1, while A_U/A_{B_1} is very sensitive to the value of f_T. The U filter therefore provides a very powerful tool to derive accurate f_T-values of the gravity modes of γ Doradus stars.

Subsequently, we determined the theoretical amplitude ratios for the best fitting f_T values and for different ℓ. We took $f_T = 0.05$ as average good values for HD 12901 and 0.1 for HD 48501. The results are shown in Fig. 7. While the uncertainties on the observed amplitude ratios are large, it is found that only an $\ell = 1$ mode is able to explain the observed ratios for the three frequencies for the two stars for all wavelengths.

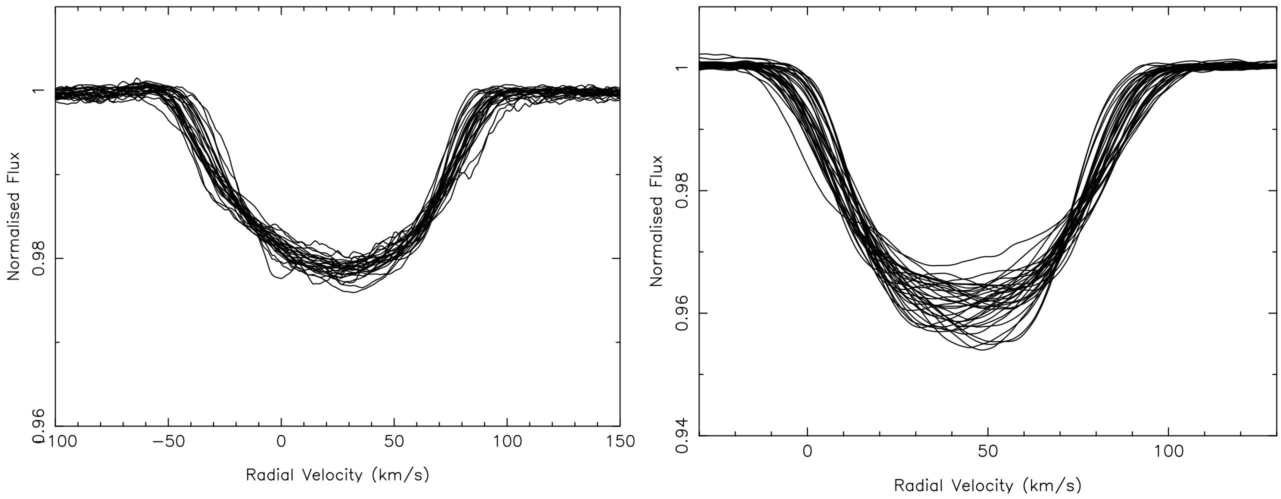

Fig. 8. Cross-correlation functions of HD 12901 (*left*) and of HD 48501 (*right*).

The mode identification supports the suggestion of a triplet for HD 48501, but we need to compare this result with the spectroscopic data, which will be done in the following section.

4. Spectroscopic data

The two stars do not show any Ca H and K emission, so there is no evidence of chromospheric activity. As we are searching for low-amplitude velocity variations at the stellar surface, we used a cross-correlation technique to derive the radial velocities of the two stars with the highest possible precision. We used the standard mask of an F0V star available in the CORALIE software package for the calculation of the cross-correlation function $C(v)$, which is defined by Baranne et al. (1996):

$$C(v) = \sum_{l} \sum_{x,o} p_{l,x,o} f_{x,o} \tag{1}$$

for each velocity point v. In this expression, $f_{x,o}$ is the value of the 2-dimensional spectrum for order o at pixel position x and $p_{l,x,o}$ is the fraction of the lth line of the mask which falls into the pixel (x, o) at velocity v. Subsequently, the cross-correlation function is normalised and shifted to the heliocentric reference frame.

In Fig. 8 we show our time series of the cross-correlation functions for the two stars. The profile variations due to the oscillations are readily seen from this plot and are very typical for high-order gravity modes (see, e.g., De Cat & Aerts 2002, for a comparison with line-profile variations due to gravity modes of slowly pulsating B stars). Both time series of the cross-correlation functions immediately rule out a binary nature as the origin of the detected multiperiodic variability of the stars.

The best estimate of $v \sin i$ is derived from the sharpest cross-correlation function, as the pulsational broadening is minimal for such a profile. We obtain $53 \pm 3\,\mathrm{km\,s^{-1}}$ and $29 \pm 2\,\mathrm{km\,s^{-1}}$ for respectively HD 12901 and HD 48501.

We subsequently derived the time series of radial-velocity variations by calculating the centroid of the cross-correlation functions. A period search on these radial velocities does not lead to clear frequencies due to the limited number of spectra. We therefore determined harmonic fits to the radial velocities, imposing the frequencies f_1 and f_2 found in the multicolour photometry. The amplitudes found in this way are only marginally significant. They are also listed in Table 2. They are very low compared to the amplitudes of several $\mathrm{km\,s^{-1}}$ due to high-order gravity modes in slowly pulsating B stars (De Cat & Aerts 2002). The frequencies f_1 and f_2 have about equal contributions to the amplitude for HD 12901, while the frequency f_2 is clearly dominant in the radial-velocity variations for HD 48501. We show in Fig. 9 a comparison between the phase behaviour of the Geneva B and radial-velocity data for f_1 of HD 12901 and for f_2 of HD 48501.

The average spacing in the triplet-like frequency structure of HD 48501 is $0.097\,\mathrm{c\,d^{-1}}$. Should this be due to rotational splitting of an $\ell = 1$ mode, this estimate has to be equal to $|m(1 - 1/\ell(\ell + 1))\Omega|$ with Ω the rotation frequency of the star. Using the radius estimate of 1.1 $R_\odot$ determined by Eyer & Aerts (2000) then leads to an equatorial rotation velocity of some $11\,\mathrm{km\,s^{-1}}$. At first sight, this is incompatible with our observationally determined estimate of $v \sin i$ because the pulsational and intrinsic broadening is much less than $27(=\sqrt{29^2 - 11^2})\,\mathrm{km\,s^{-1}}$. It would therefore be tempting to conclude that the three frequencies of HD 48501 cannot be the components of one $\ell = 1$ mode due to rotational splitting in the case of rigid rotation, but that they must be $\ell = 1$ modes of different radial order. This would also lead to the acceptance of the frequency $1.37026\,\mathrm{c\,d^{-1}}$ as the one with the next radial order. As we are dealing with high-order gravity modes of low degree, this would imply that the observed splittings give us a direct measure of the integral of the Brünt-Väisälä frequency (weighted with $1/r$) over the depth within the star. However, it has been found recently that the estimate for $v \sin i$ from high-resolution spectra is a significant overestimate of the true equatorial rotation velocity in some selected β Cep stars for which detailed seismic interpretations from frequency multiplets are available (Aerts et al. 2004; Handler & Aerts 2003). Moreover, it was shown that the rotation need not be rigid inside a star more massive than the Sun (Aerts et al. 2003) and so one

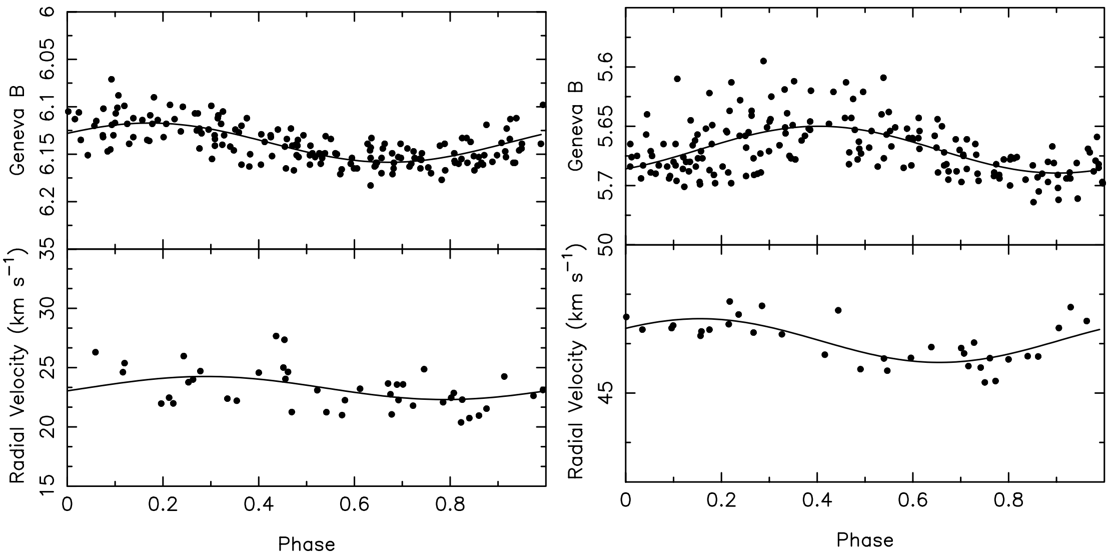

Fig. 9. Phase diagrams of the Geneva B and radial velocity data of HD 12901 for its f_1 (*left*) and of HD 48501 for its f_2 (*right*). The reference epoch of the different data sets was taken equal.

cannot use the simple estimate from the Ledoux shift while assuming a constant rotation frequency to make definite conclusions. It hence does not seem justified to exclude rotational splitting from the $v \sin i$ estimate without further evidence.

We find a phase difference between the Geneva B data and the radial-velocity data of 128° ± 15° for f_1 and of +135° ± 25° for f_2 of HD 12901. The corresponding values for HD 48501 are +96° ± 14° for f_1 and +19° ± 14° for f_2. The gravity modes in slowly pulsating B stars clearly follow a phase lag of $\simeq -90°$ (De Cat & Aerts 2002) and are much better determined than those of γ Doradus stars. However, the values listed by Mantegazza et al. (1995) for the γ Doradus star HD 224638 seem secure and are very different from those we find for HD 12901 and HD 48501. We caution overinterpretation of our results, however, because the bulk of the spectra only have a time base of two weeks for the two stars and so the phases are quite inaccurate. Moreover, the radial-velocity curves are noisy. Therefore, the derived phase differences need further observational confirmation before we can use them to model the outer convection properties of both stars in detail.

We have at present too few spectra to perform an independent spectroscopic mode identification as none of the modes is really dominant over the other ones in the spectroscopic variability. We plan to do this in the future, after several more years of spectroscopic monitoring. A detailed abundance analysis for the two stars studied here, as well as for 35 additional (candidate) γ Doradus stars will be published elsewhere.

5. Conclusions

We have disentangled three frequencies in the observed multicolour light variations of the γ Doradus stars HD 12901 and HD 48501. These frequencies are typical for high-order g-modes in such stars. The photometry and the high-resolution spectra rule out any extrinsic cause of the multiperiodic behaviour. The amplitudes are largest in the B wavelength range and decrease towards the U and V wavelengths.

The amplitude ratios of HD 12901 and HD 48501 are only compatible with dipole modes and with non-adiabatic temperature eigenfunctions of extremely low amplitude. Moreover, the phase difference in the different colours from U to G are insignificant. This observational result is of importance for any future efforts to model the amplitude ratios and phase differences in terms of the physical conditions in the thin surface convection layers of F-type stars and could give strong constraints on the characteristics of such layers. Theoretical studies of the interplay of convection and pulsation are urgently needed to obtain better knowledge of the excitation mechanism of the γ Doradus stars and to understand the amplitude and phase variability of the gravity modes in such cool stars.

We plan to perform long-term follow-up spectroscopy for the two stars, as well as for a few additional stars selected from the sample analysed by De Cat et al. (in preparation), who have monitored some 35 (candidate) γ Doradus stars spectroscopically in the past few years.

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