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Multi-site, multi-technique survey of γ Doradus candidates

I. Spectroscopic results for 59 stars⋆

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Abstract. We present the first results of a 2-year high-resolution spectroscopy campaign of 59 candidate γ Doradus stars which were mainly discovered from the HIPPARCOS astrometric mission. More than 60% of the stars present line profile variations which can be interpreted as due to pulsation related to γ Doradus stars. For all stars we also derived the projected rotation velocity (up to more than 200 km s^{-1}). The amplitude ratios $2K/\Delta m$ for the main HIPPARCOS frequency are in the range 35–96 km s^{-1} mag^{-1}. About 50% of the candidates are possible members of binary systems, with 20 stars being confirmed γ Doradus. At least 6 stars present composite spectra, and in all but one case (for which only one spectrum could be obtained), the narrow component shows line profile variations, pointing towards an uncomfortable situation if this narrow component originates from a shell surrounding the star. This paper is the first of a series concerning mode identification using both photometric and spectroscopic methods for the confirmed γ Doradus stars of the present sample.

Key words. line: profiles – stars: variables: general – stars: oscillations – stars: binaries: spectroscopic

1. Introduction

In the coming decade, thanks to dedicated satellites (COROT, EDDINGTON), the detailed knowledge of the internal structure of stars should be achieved through the technique of asteroseismology. The goal of this, relatively new, research domain is to derive the internal processes in stars with an unprecedented precision through a detailed study of their oscillations.

This paper deals with a class of non-radial pulsators along the main sequence, namely the γ Doradus stars (see e.g. Kaye et al. 1999a, for the main observational characteristics of this class of variables). These stars are multiperiodic high-order gravity-mode oscillators with spectral types around F0. The origin of the mode destabilization is not clearly known yet, and driving mechanisms have been proposed by Guzik et al. (2000), Wu (2002) and Löffler (2002).

Much effort is currently made to find new members of this group, to constrain their pulsation characteristics and their position in the HR Diagram, especially the γ Doradus star's red border in relation with the solar-like star's blue border. Indeed, they show quite a large variety in their observational behaviour, and the number of confirmed members is still low. This observational campaign should contribute to the necessary comparison between the observational HR diagram and the theoretical one recently defined by Warner et al. (2003). Because of their relatively low amplitude (few tens of mmag in photometry, of the order of 1 km s^{-1} in radial velocity), and due to the long time scales of the variation (between 0.3 and 3 d), the detection of such variables is still difficult. Up to now the best tool has been the HIPPARCOS satellite. The HIPPARCOS sampling does not suffer from the aliasing problems of a single Earth site which is of particular annoyance for γ Dor studies. However, there are two major drawbacks: the precision of photometric individual measurements degrades quite rapidly for fainter stars and the non-continuous sampling makes the detection/interpretation of multiperiodic phenomena difficult.

Several studies selected γ Dor candidates from HIPPARCOS: Eyer (1998) proposed a list of such candidates extracted from the periodic variable stars in the

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⋆ Partially based on observations obtained at the Observatoire de Haute-Provence.

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HIPPARCOS variability annex which have well defined absolute magnitude and colour. Aerts et al. (1998) used stars from the same catalogue which have furthermore Geneva photometry. It permitted to use a multivariate discriminant analysis which proved to be very efficient for detecting new slowly pulsating B stars (Waelkens et al. 1998), which are also main-sequence gravity-mode oscillators. Handler (1999) broadened the search for γ Dor stars to the unsolved variable stars of the HIPPARCOS variability annex and relaxed selection criteria, focusing more on the nature of the power spectra. These studies proposed about 60 bona fide and prime candidates stars. One star in our sample, HD 173977, which was in Handler's list (1999), has been discarded since it is now classified as a δ Scuti variable (Chapellier et al. 2004).

However, the spectroscopic studies of most of the candidates having well-known photometric properties are much less detailed. In 2001, we undertook a spectroscopic campaign whose objective was twofold:

- to derive basic spectroscopic parameters (rotation velocity, line profile variations, duplicity, etc.) for better identification of the pulsation modes. This is particularly important for stars with similar rotation and pulsation frequencies (Dintrans & Rieutord 2000);
- to prepare the COROT and EDDINGTON space missions by including at least one γ Doradus star in the core program (Mathias et al. 2003a,b).

This paper presents the first descriptive part of the campaign concerning 59 γ Doradus candidates. Only the very homogeneous OHP spectroscopy is discussed. The observations are described in Sect. 2. In Sect. 3, results are given for individual stars, depending on the detection of line profile variations, in Sect. 3. Sections 4 and 5 present the pulsation and stellar environments for some candidates. Concluding remarks are given in Sect. 6.

2. The data

The spectroscopic data were obtained at the Observatoire de Haute-Provence, using the AURELIE spectrograph attached to the 1.52 m telescope. The spectral domain covers the range 4470–4540Å with a resolution power $\lambda/\Delta\lambda$ = 55 000, which is enough to detect the expected low degree Line Profile Variations (LPV). We focused our study on the two unblended lines of Fe II and Ti II at respectively 4501.273 and 4508.288 Å. Spectra were reduced using the standard packages of IRAF. The exposure time was adapted to ensure a S/N ratio above 150, but limited to 1 h to avoid phase smearing.

The selected targets and the main characteristics of the observations are presented in Tables 1 and 2. Table 1 summarizes the observational results on the stars showing LPV, which represents 2/3 of the sample. We report below on some special cases. Table 2 lists the stars for which nothing has been detected, which does not mean that LPV are not present (LPV below our detection threshold, or insufficient data); in some cases spectra are just useful to detect accurate $v \sin i$ values. The projected rotation velocities $v \sin i$ are computed as the mean value of the first zero of the Fourier transform corresponding to the two considered unblended lines. The uncertainties are typically of 5 km s^{-1} for rapid rotators and of the order of 1 km s^{-1} for the slow ones. The radial velocities were obtained with two methods: a simple Gaussian fit and first line moment. Both methods have their limitations: for the first one, it is accurate only when LPV are small, while the second one presents larger errors due to the uncertainty on the location of the integration domain, and a stronger effect of the noise. Generally, only the first moment was computed when the line profiles were too broad i.e., when the projected rotation velocity value was above 50 km s^{-1}.

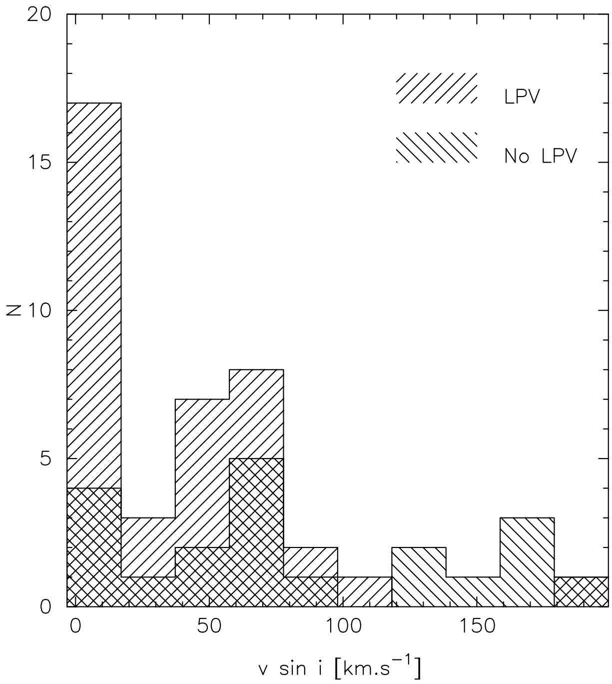

Fig. 1. Histogram showing the number of stars N showing LPV as a function of the projected rotation velocity. It can be noticed that LPV are easier to detect for stars having low $v \sin i$ values.

3. Results on stars with marked or suspected LPV

Most of the 59 stars of our sample were chosen in the updated web list[1] initiated by Handler & Krisciunas (1997), or in few other works, such as the potential candidates in the COROT fields. Therefore, most candidates present light variations, and the objective was thus to see if LPV were present. Depending on a few factors, the major ones being the too low S/N level, the large projected rotation velocity, or too few spectra, sometimes we could hardly detect LPV. Even if LPV are easier to detect when $v \sin i$ is small, they were also detected in some rapid rotators. As shown in Fig. 1, setting a limit of 80 km s^{-1}, we find 35 stars with LPV against 12 stars without LPV below the detection threshold, and 4 stars with LPV against 8 stars without LPV above this limit. Even for those targets that do show LPV, it is not always clear if the variations are caused by g-modes or not. This is due to unexpected line profile behaviour (such as a change of the residual flux in the line core) or to the lack of clear periodicity in the observed LPV. However, we can

[1] http://www.astro.univie.ac.at/~dsn/gerald/gdorlist.html

Table 1. γ Doradus stars candidates observed at OHP showing LPV. The first 2 columns give the HD or HIP star number (if this latter exists). Asterisked stars are both good γ Doradus candidates and possible members of binary systems (see Sect. 5). Next columns respectively provide the number of spectra, the observation window, the mean exposure time, the mean S/N value, the number of photometric frequencies previously detected, the LPV signature, remarks about the binarity, the $v \sin i$ value and some references†.

HD	HIP	N	Range [d]	Exp. [sec]	S/N	Phot.	LPV	Binarity	$v \sin i$ [km s^{-1}]	Ref
							Bona fide γ Dor stars			
277	623	24	527	3500	215	3	strong		31	H99 HF01 FW03
12901	9807	5	268	2000	240	3	evident		66	H99 EA00 AC03
62454	37863	12	353	2800	240	5	in the primary	SB2	10.5 and 5	KH99
68192*	40462	3	4	2800	220	2	weak	RV var.	95	HE99 KH99
86371*	48830	4	348	1900	220	2	weak ?	SB2, ell. ?	11 and 6	H99 KE02
105458*	59203	25	421	3600	200	6	evident	binary?	39	H99 HF01
108100*	60571	5	322	2700	190	3	in the slow rot.	binary	65 and 13	BH97 HF02
164615	88272	13	379	2300	180	4	evident		65	ZR97 E98
167858*	89601	11	366	2200	210	2	evident but small	SB	9.0	E98 AE98 H99 FW03
218396	114189	162	505	1100	250	4	evident		38	E98 ZR99
221866*	116434	32	506	3300	220	2	in the sec.	SB2	13 and 10	H99 FW03
224638	118293	23	410	3300	200	5	evident		17	PK02
224945	159	2	346	1800	190	5			54	PK02
							Prime candidates			
2842*	2510	2	346	3600	210	3	in the blue wing	maybe	77	H99 KE02 FW03
7169*	5674	4	137	3200	210	2	in both stars	visual	90 and 8	H99 FW03
9365*	7280	6	269	4000	200	2	weak	RV var.	69	H99 FW03 LJ89
23874*	17826	4	5	3600	200	2	in the slow rot.	visual	90 and 9	H99 FW03
48271	32263	19	423	3400	240	6	evident		21	E98 H99 MB03
63436*	38138	7	347	3000	190	2	in the blue wing	binary ?	66	H99 MB03
70645*	41488	10	423	3600	230	2	evident	SB1	11	H99 MB03
80731*	46099	11	422	3400	210	5	evident	SB1	13	H99 MB03
86358*	48895	3	2	1800	220	2	in the slow rot.	binary	37 and 25	H99 KE02 FW03
100215*	56275	11	422	3000	240	2	evident	SB1	13	H99 KE02 FW03
113867*	63951	7	572	1800	210	2	weak	SB2 ?	8.5 and 110	H99 FW03
171244*	90919	4	316	3000	200	2	very weak in the wings	binary?	50	H99 FW03
175337	92837	7	315	3300	230	2	evident	unlikely	38	H99 KE02 FW03
195068	100859	36	564	1300	240	2	evident		46	E98 H99 FW03
211699	110163	21	399	3700	210	2	evident		12	H99
							Other candidates and COROT targets			
44195	30154	4	345	3000	220	cst	weak ?		50	PG02
44333	30217	2	3	1400	160		in the slow rot.?	binary	160 and 15	PG02 RG02
49434	32617	92	422	850	230		in the blue wing		82	BC02
112429	63076	40	566	900	220	2	in the wings		101	E98 AE98 FW03
171834	91237	13	11	940	200	cst	very weak		65	GP02
171836	91272	3	75	3600	200	cst	observed		62	GP02
172506	91580	2	9	3100	180	var?	observed	binary ?	39	GP02
174353	–	2	8	3600	200		varying res. flux		11	H02

† AC03: Aerts et al. (2004) – AE98: Aerts et al. (1998) – BC02: Bruntt et al. (2002) – BH97: Breger et al. (1997) – E98: Eyer (1998) – EA00: Eyer & Aerts (2000) – FW03: Fekel et al. (2003) – GP02: Garrido et al. (2002) – H99: Handler (1999) – H02: Handler (2002) – HE99: Henry (1999) – HF01: Henry et al. (2001) – HF02: Henry & Fekel (2002) – KE02: Koen & Eyer (2002) – KH99: Kaye et al. (1999b) – LJ89: Liu et al. (1989) – MB03: Martín et al. (2003) – PG02: Poretti et al. (2002) – PK02: Poretti et al. (2002) – RG02: Royer et al. (2002) – ZR97: Zerbi et al. (1997) – ZR99: Zerbi et al. (1999).

be confident that when more than one period is found in photometry, and when LPV are present, the star can be considered as a real γ Doradus star. This is the case for about 40% of the stars in our sample.

The detection of LPV has been done using visual inspection of the profiles of the two considered unblended lines. The way the profile is distorted was generally the same for both ions. Also, we computed the standard deviation of

Table 2. γ Doradus star candidates observed at OHP not showing LPV. The first 2 columns give the HD or HIP star number (if this latter exists). Next columns respectively provide the number of spectra, the observation window, the mean exposure time, the mean S/N value, the status of their γ Dor variability (BF: Bona fide; PC: prime candidate; COROT: possible COROT target chosen as a γ Doradus candidate from its spectral type), the number of photometric frequencies previously detected, general remarks, the $v \sin i$ value and some references†.

HD	HIP	N	Range [d]	Exp. [sec]	S/N	status	N	Remarks	$v \sin i$ [km s^{-1}]	Ref
40745	28434	2	5	1500	210	PC	2		37	E98 AE98
41448	28778	2	5	2800	160	PC	2		93	E98 H99
43338	29758	5	346	2900	230	COROT	cst		170	PG03
44716	–	2	9	3600	220	COROT	geom.?	binary?	10	PG03
45138	–	2	52	3600	140	COROT	cst		60	PG03
45196	30611	2	48	3600	200	COROT	var	δ Sct?	190	PG03
46304	31167	23	7	1100	150	COROT	undetectable	binary ?	190	PG02 RG02
56359	35248	1	0	2100	170	COROT	var		210	PG03
65526	39017	1	0	3600	190	BF	4		59	H99 MB03
69715*	40791	2	4	2700	210	PC	4	binary?	145	H99 MB03
152569	82693	2	368	1800	190	BF		δ Sct	175	KH00
152896*	82779	2	318	2400	230	PC	2	SB2		H99 FW03
155154*	83317	3	348	1200	220	BF	4	binary?	175	H99 HF01
160295	86374	1	0	1800	180	PC	2	binary	60 and 9	H99 FW03
164259	88175	23	43	600	170	COROT			72	LL01
165645	88565	3	317	2700	170	BF			128	K98
172423	–	2	9	3600	190	COROT			14	H02
173073	91838	3	75	3600	190	COROT	cst		62	GP02
174704	–	2	10	3600	220	COROT			9.0	H02
175431	–	2	8	3700	190	COROT			62	H02
178596	94068	2	77	1500	200	COROT			68	H02
184064*	–	2	4	3600	230	COROT		SB ?	9.3	H02
206043	106897	3	312	620	200	BF	3		120	E98 HF01 FW03

† AE98: Aerts et al. (1998) – E98: Eyer (1998) – FW03: Fekel et al. (2003) – GP02: Garrido et al. (2002) – H99: Handler (1999) – H02: Handler (2002) – HF01: Henry et al. (2001) – HF02: Henry & Fekel (2002) – K98: Kaye (1998) – KH00: Kaye et al. (2000) – LL01: Lastennet et al. (2001) – MB03: Martín et al. (2003) – PG02: Poretti et al. (2002) – PG03: Poretti et al. (2003) – RG02: Royer et al. (2002).

individual spectra with respect to the average one. If present, LPV should manifest as an increase of this deviation along the line. Moreover, for g-modes, the ratio of tangential over radial velocity is large, so line wings should be more perturbed than they are for p-modes. This particular form is called hereafter a typical g-mode behaviour. Figure 2 provides an example of the application of these tools to the spectra of HD 277. We also note that when LPV are not particularly prominent, the presence of an undetected companion can be responsible for the modifications of the line wings (HD 2842, HD 49434, HD 63436, HD 112429 and HD 171244. For the first 3 stars in particular, only the blue wing is perturbed).

In the following, we discuss in detail some special cases, i.e., spectroscopic binaries with two spectra (HD 62454, HD 86371, HD 221866), with one spectrum only (HD 70645, HD 80731, HD 100215), and unclear cases of spectroscopic peculiarities (HD 108100, HD 113867, HD 211699).

3.1. HD 62454

This is a γ Doradus star first proposed by Henry (1999). Kaye et al. (1999a) discovered that it is a double-lined spectroscopic binary with a 11.6 d orbital period. To increase the accuracy of the orbital parameters, we computed a new ephemeris by including their velocities in addition to ours. The deduced orbital elements are given in Table 3, and the binary motion in Fig. 3. Kaye et al. (1999b) were able to detect up to 5 frequencies in their photometric data, implying that this star is a confirmed γ Doradus star. After removing the orbital motion and spectra containing the component lines, the primary indeed presents LPV. More observations will be necessary to observe the pulsation radial velocities. The projected rotation velocity is 10.5 km s^{-1}, a value comparable to the 11.5 km s^{-1} determined

Table 3. Parameters of the binary orbit for the SB2 star HD 62454. Our data together with those of Kaye et al. (1999) lead to a final rms of the residuals of 1.81 km s^{-1}.

P	=	11.61550 ± 0.00015 d
T_0	=	2450996.55 ± 0.04 d
e	=	0.205 ± 0.005
γ	=	7.5 ± 0.2 km s^{-1}
K_1	=	49.4 ± 0.4 km s^{-1}
ω_1	=	$261.0 \pm 1.3°$
K_2	=	66.0 ± 0.4 km s^{-1}
ω_2	=	$81.0 \pm 1.3°$
$a_1 \sin i$	=	$(7.73 \pm 0.07) \times 10^6$ km
$M_1 . \sin^3 i$	=	$0.994 \pm 0.013 M_\odot$
$a_2 \sin i$	=	$(10.31 \pm 0.08) \times 10^6$ km
$M_2 . \sin^3 i$	=	$0.745 \pm 0.011 M_\odot$

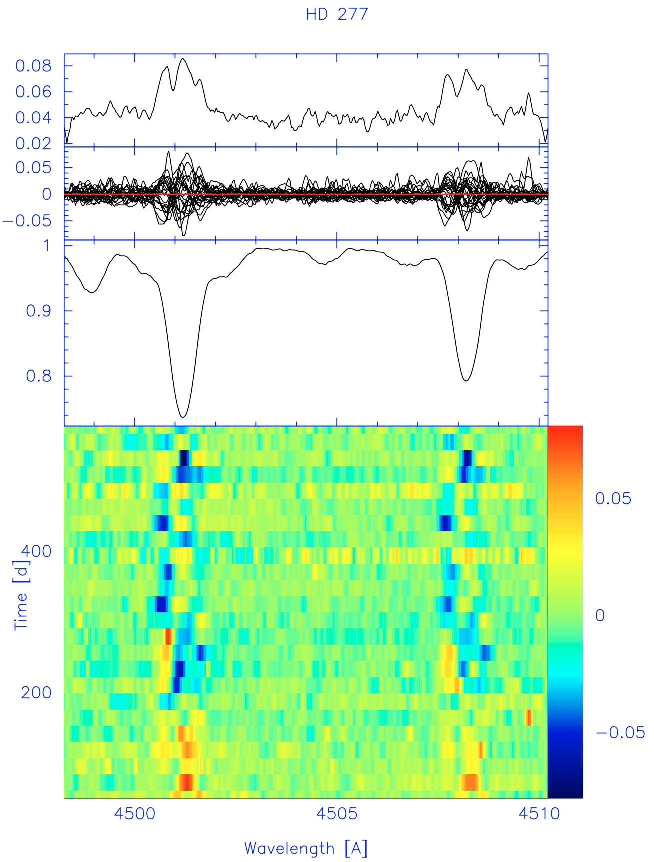

Fig. 2. *Lower part*: bi-dimensional plot of the temporal evolution (on an arbitrary scale) of the residual spectra for the star HD 277. *Upper part*: from bottom to top are successively represented the mean spectrum, the individual residual spectra and the dispersion σ around the mean residual (see text).

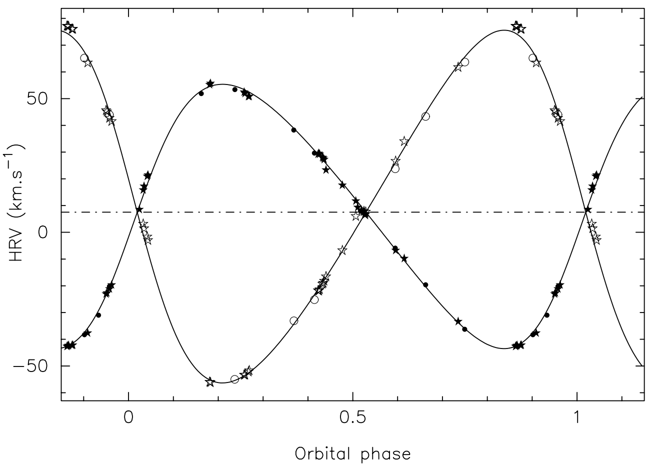

Fig. 3. Fit of the orbit of HD 62454. Empty symbols represent the companion velocities. The values of Kaye et al. (1999) are represented as stars. The dot-dash line represents the heliocentric velocity of the system.

by Kaye et al. (1999b), while we confirm the 5 km s^{-1} value of the v sin i of the companion.

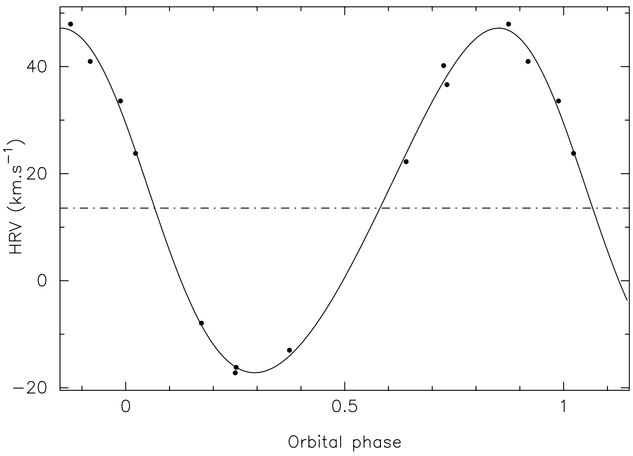

Fig. 4. Fit of the orbit of HD 70645. The dot-dash line represents the heliocentric velocity of the system.

Table 4. Parameters of the binary orbit for the star HD 70645. The final rms of the residuals is 2.32 km s^{-1}. Note that we have only used here the velocities computed from a Gaussian fit.

P	=	8.4450 ± 0.0025 d
T_0	=	2452270.82 ± 0.52 d
e	=	0.100 ± 0.033
γ	=	13.6 ± 0.8 km s^{-1}
K	=	32.2 ± 1.0 km s^{-1}
ω	=	$63. \pm 22.°$
$a \sin i$	=	$(3.72 \pm 0.13) \times 10^6$ km
$M. \sin^3 i$	=	$0.029 \pm 0.003\ M_\odot$

3.2. HD 70645

Handler (1999) classified this star as a prime γ Doradus candidate, with 2 frequencies. Martín et al. (2003) also detected 2 frequencies in both HIPPARCOS and Strömgren photometry data. We discovered that this star is a single-lined spectroscopic binary, whose orbital elements are provided in Table 4 and the orbit in Fig. 4. After removing the orbital motion, we derived a projected rotation velocity of 11 km s^{-1}. More spectroscopic observations are necessary to derive the pulsation radial velocities. LPV are easily detected, and this star should be definitively classified as a bona fide γ Doradus star.

3.3. HD 80731

This is also a prime γ Doradus candidate detected by Handler (1999) with 2 frequencies. Martín et al. (2003) were able to detect up to 5 frequencies in HIPPARCOS and Strömgren photometry data. We found that this star actually belongs to a binary system, and the orbital parameters we derived are given in Table 5. The corresponding motion is represented in Fig. 5.

Once the orbital motion is removed, we are able to derive $v \sin i = 13$ km s^{-1}. LPV are also present, which manifest mainly as a change in the intensity level of about 10%, a value well above the 1% uncertainty of the continuum level. This is also visible on the variations of the *EW* which changes in the same time by a factor of 2. This behaviour is close to that

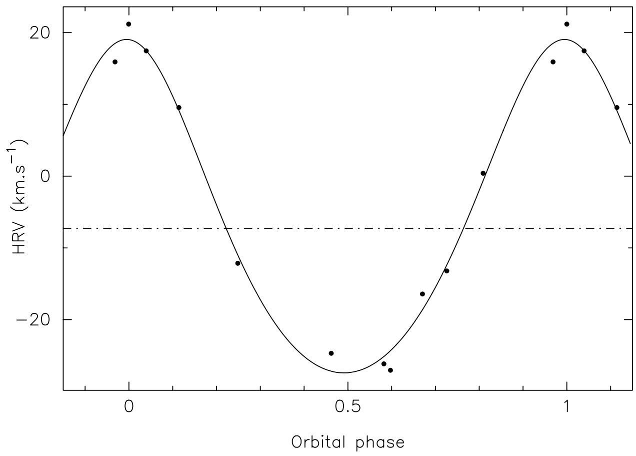

Fig. 5. Fit of the orbit of HD 80731. The dot-dash line represents the heliocentric velocity of the system.

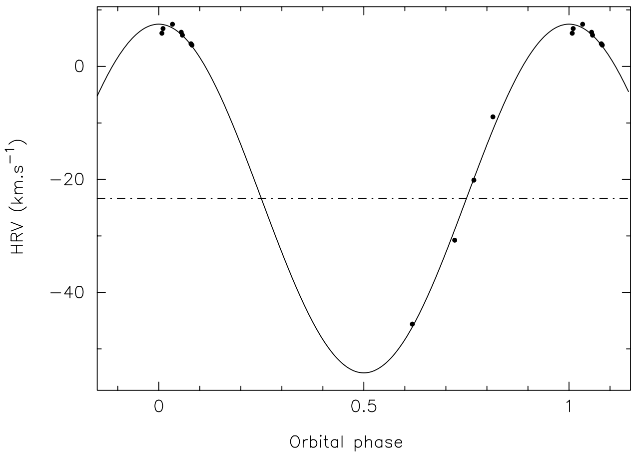

Fig. 6. Fit of the orbit of HD 100215 with a fixed null eccentricity (see text). The dot-dash line represents the heliocentric velocity of the system.

Table 5. Parameters of the binary orbit for the star HD 80731. The final rms of the residuals is 2.61 km s^{-1}. Note that we have only used here the velocities computed from a Gaussian fit.

P	=	13.572 ± 0.011 d
T_0	=	2 452 283.30 ± 1.43 d
e	=	0.133 ± 0.047
γ	=	−7.3 ± 1.1 km s^{-1}
K	=	23.2 ± 1.2 km s^{-1}
ω	=	2. ± 35.°
$a \sin i$	=	(4.30 ± 0.25) × 10^6 km
$M. \sin^3 i$	=	0.017 ± 0.003 $M_\odot$

Table 6. Parameters of the binary orbit for the star HD 100215. Because we have too scarce data, the eccentricity has been arbitrarily set to zero. Consequently, the longitude of the periastron is not given. The final rms of the residuals is 1.35 km s^{-1}. Note that we have only used here the velocities computed from a Gaussian fit.

P	=	42.628 ± 0.053 d
T_0	=	2 452 419.41 ± 0.29 d
γ	=	−23.4 ± 1.0 km s^{-1}
K	=	30.9 ± 1.5 km s^{-1}
$a \sin i$	=	(18.09 ± 0.92) × 10^6 km
$M. \sin^3 i$	=	0.130 ± 0.019 $M_\odot$

pointed out in HD 211699 (see below). We note that this change is not correlated to the binary motion. More spectroscopic observations are necessary to clearly derive the velocities associated with the pulsation.

3.4. HD 86371

This star is considered as a prime candidate by Handler (1999) who derived 2 frequencies from the HIPPARCOS data. However, Koen & Eyer (2002) derived, still from HIPPARCOS, a frequency typical of δ Scuti variations (11.68919 d^{-1}). Using Johnson's photometry, Handler & Shobbrook (2002) confirm the γ Doradus character from the amplitude ratio of the B and V filter. Our 4 spectra show that this star is actually a double-lined spectroscopic binary with two very similar components, hence very close spectral types, having projected rotation velocities of 6 and 11 km s^{-1} respectively. Therefore, the value of 18 km s^{-1} proposed by Royer et al. (2002) is certainly due to an unfortunate observing epoch, when the two spectra were heavily blended, with radial velocities close to the γ-value of the system. The maximum separation in our data is about 30 km s^{-1}, the minimum value of the 2K-amplitude of the binary motion. It is impossible to derive an orbital period, but based on the evolution of 2 consecutive spectra, we estimate a value of around 6 days i.e., close to twice the shorter frequency derived by Handler (1999). Therefore, this star can be ellipsoidal, but more observations are needed to derive the orbital ephemeris. LPV seem to be present as a change in the residual flux of one profile with respect to the other. The interpretation of such a change needs to be confirmed from new observations.

3.5. HD 100215

Handler (1999) classified this star as a prime γ Doradus candidate, with 2 frequencies, the first confirmed by Koen & Eyer (2002). Fekel et al. (2003) indicate that the star is a member of a binary system on the basis of the different values of the radial velocities provided in the literature. On one of their two spectra, they were able to partially resolve two lines. Although our data confirm the binarity, we were unable to detect a second line system in any of our 11 spectra, spread over 422 d. Unfortunately, our data are not well sampled to derive a definitive ephemeris. To converge, we arbitrarily fixed the eccentricity to a null value. The deduced orbital elements are given in Table 6 and the orbital motion is represented in Fig. 6. Our value of the projected rotation velocity, 13 km s^{-1}, has to be compared with the 25 km s^{-1} derived by Fekel et al. (2003). Since this star presents strong LPV, with an obvious γ Doradus character, it is probable that there has been a confusion in Fekel et al.'s interpretation, as the travelling bumps at a given phase

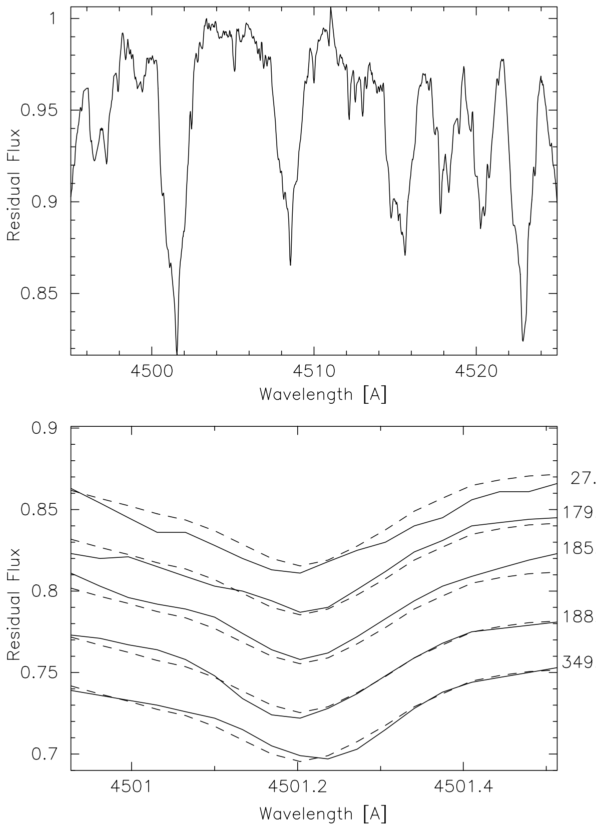

Fig. 7. *Upper panel*: a region of the composite spectrum of HD 108100 showing both broad and narrow components. *Lower panel*: zoom on the narrow component showing LPV as a function of the observation date written on the right side of the graph. The dashed line represents the average spectrum.

produce a profile similar to a double line. Therefore, this star is clearly confirmed as a new γ Doradus star in a SB1 system.

3.6. HD 108100

Breger et al. (1997) derived 2 frequencies from a multi-site photometric campaign, confirmed by Henry & Fekel (2002) who derived a third frequency in their Johnson's data. The spectrum is composite (Fig. 7), and we derived projected rotation velocities of 13 km s^{-1} and 65 km s^{-1} for each component, compared to respectively 5 km s^{-1} and 55 km s^{-1} derived by Henry & Fekel (2002). The Gaussian velocity fit associated with the narrow component is quite stable in our 5 spectra spread over 300 d, varying between −6.5 and −4 km s^{-1}, but we have not enough data to choose between the shell model of Henry & Fekel (2002) and the double-lined spectroscopic binary hypothesis of Nordström et al. (1997). LPV are easily detected in the narrow component, while nothing can be said concerning the broad one.

3.7. HD 113867

It is a prime γ Doradus candidate in Handler's list (1999), with 2 frequencies derived from the HIPPARCOS data, the first independently confirmed by Koen (2001). Radial velocities are in the range [+0.5; +3.2] km s^{-1}. An additional component may exist, appearing as a broad contribution around each narrow line. Fekel et al. (2003) observed such a composite spectrum, and explained it as a shell or a double-lined spectroscopic binary. They observed a slight change in the velocity, but within their error bars, and rather favoured the shell hypothesis. However, we note that compared to the preceding ones, our last spectrum, obtained 400 d after, is clearly the result of a Doppler shift such as that induced by a binary motion (displacement of the whole narrow profile). Moreover, the radial velocity measured by Fekel et al. (2003), +8.8 km s^{-1}, is significantly out of our range. Despite being unable to rule out the shell hypothesis, the star is certainly a spectroscopic binary with a rather long period. The $v \sin i$ value associated with the dominant component is 8.5 km s^{-1}, similar to the 10 km s^{-1} measured by Fekel et al. (2003). LPV associated with the narrow component are represented mainly by weak relative flux variations (also present in equivalent width variations).

3.8. HD 211699

Handler (1999) classified this star as a prime γ Doradus candidate, with 2 frequencies in the HIPPARCOS data. The projected rotation velocity is relatively low, 11.6 km s^{-1}. LPV are very well marked, and manifest as strong variations of the residual flux of the profiles. Indeed, our observations represent 2 groups of data separated by about 1 year, and the residual flux is 0.75 for the first group, while it is around 0.55 for the second one, with a maximum variation range of 30%. Since the FWHM of the two considered line profiles are more or less constant, it means that the EW have strongly varied on a 1 year time scale, increasing from 119 to 203 mÅ . The radial velocity range is [+5; +10] km s^{-1}. Those associated with the group of large EW have a wider range than the ones corresponding to low EW values. Therefore, the status of this star is still puzzling since usually pulsation induces moderate temperature changes (less than 100 K) probably too small to modify significantly the level populations. A possible explanation is stellar activity, but this latter has been poorly reported for γ Doradus star candidates (see e.g. Kaye & Strassmeier 1998). Therefore this star deserves further long term observations to define the origin of the noted variations.

3.9. HD 221866

This star is cited as a prime candidate by Handler (1999) who derived 2 frequencies in the HIPPARCOS data, one being common with the 3 frequencies detected by Henry & Fekel (2002) in their Johnson photometric data. Kaye et al. (2003) showed that the star is a double-lined spectroscopic binary with a primary and a secondary star of spectral type A8m V and F3 V respectively. Our ephemeris based on our own data (Table 7) confirms the results of Kaye et al. (2003), and the velocity curves are represented in Fig. 8. The projected rotation velocities we derive are slightly lower than the ones measured by Kaye et al. (2003), 13.2 and 9.9 km s^{-1} for the primary and the secondary, respectively. The primary seems to present marginal LPV but

Table 7. Parameters of the binary orbit for the SB2 star HD 221866. The final rms of the residuals is 2.28 km s^{-1}.

P	=	135.19 ± 0.52 d
T_0	=	2 450 412.41 ± 0.29 d
e	=	0.683 ± 0.013
γ	=	−13.7 ± 0.3 km s^{-1}
K_1	=	38.1 ± 1.0 km s^{-1}
ω_1	=	206.1 ± 2.3°
K_2	=	43.1 ± 1.1 km s^{-1}
ω_2	=	26.1 ± 2.3°
$a_1 \sin i$	=	(51.78 ± 2.45) × 10^6 km
$M_1 . \sin^3 i$	=	1.556 ± 0.090 $M_\odot$
$a_2 \sin i$	=	(58.52 ± 2.70) × 10^6 km
$M_2 . \sin^3 i$	=	1.376 ± 0.080 $M_\odot$

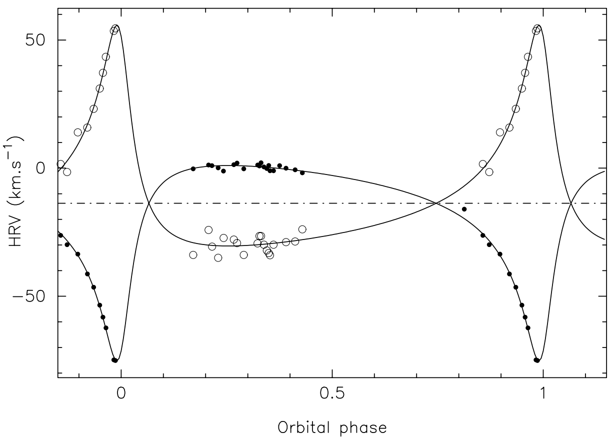

Fig. 8. Fit of the orbit of HD 221866. Empty symbols represent the companion velocities. The dot-dash line represents the heliocentric velocity of the system.

the secondary shows strong LPV, and is therefore a γ Doradus star, contrary to what is suggested by Fekel et al. (2003). Therefore, the link between Am and γ Doradus stars suggested by Fekel et al. (2003) is not yet proved.

4. Pulsation

Most of the stars in that sample were observed because they present photometric variations with compatible γ Doradus frequencies. We reanalyzed the HIPPARCOS data of our 59 stars to derive the amplitudes associated with the main frequency. Then, we imposed the main HIPPARCOS frequency on the radial velocity data. The results concerning the 9 stars for which this procedure converged are given in Table 8. For completeness, Table 9 gives the results for the stars observed either by HIPPARCOS or by spectroscopy. It appears that the velocity amplitude associated with the sine-fit is of the order of 50% of the total observed range. This, together with the fact that the fraction of the variance is sometimes very low, can be due to several reasons. First, as these stars are usually multiperiodic, a single frequency alone cannot account for the total variation. Second, the dominant frequency is not the same in spectroscopy and in photometry, because spectroscopy is sensitive to higher ℓ degrees than photometry. Third, if it is the same dominant mode with the two data sets, the amplitude could have changed between the HIPPARCOS epoch and our spectra. Such a change has been observed in many γ Doradus stars, see e.g. Poretti et al. (2002). However, Aerts et al. (2004) have shown, using very stable and homogeneous data, that such a change was not present in HD 48501 and only the amplitude associated with the third frequency was found variable in their other γ Doradus star HD 12901. Hence, the fit of photometric and spectroscopic data cannot converge or can be unsatisfactory owing to the physical reasons described above.

Table 8 provides the $2K/\Delta m$ amplitude ratios for 9 stars. If we exclude cases for which the fraction of the spectroscopic variance explained by the photometric frequency is below 30%, the amplitude ratio ranges between 35 and 96 km s^{-1} mag^{-1}. Actually, there are three cases: four stars (HD 277, HD 175337, HD 195068 and HD 211699) have a mean value of about 40 km s^{-1} mag^{-1}, 2 stars (HD 105458 and HD 112429) have a mean value of 95 km s^{-1} mag^{-1}, and one star (HD 9365) has an intermediate value around 65 km s^{-1} mag^{-1}. Of course, the HIPPARCOS photometric band is large, and Aerts et al. (2004) have shown that these values were very sensitive to the considered filter. Nevertheless, any future theoretical description of the pulsation in the surface layers needs to be compatible with our observational values of these $2K/\Delta m$ amplitude ratios.

5. Composite spectra: binarity and shell hypothesis

Among our 59 stars, there are 27 members or potential members of a binary system, and 21 out of these possible 27 couples are good γ Doradus candidates (stars asterisked in Tables 1 and 2). However, stars part of binary systems represent less than 50% of the candidates of our sample.

We confirm the composite spectra noted by Fekel et al. (2003) and Henry & Fekel (2002) for 5 stars (HD 7169, HD 23974, HD 108100, HD 113867 and HD 160295), and we discovered an additional one (HD 44333). All the observed photometric variations occur on a γ Doradus-like timescale with an amplitude of about 20 mmag. HD 44333 is the only star in our sample for which no photometric variations have been searched for so far. Composite spectra can be interpreted as a central star in rapid rotation surrounded by a circumstellar shell (see Fekel et al. 2003). This could be considered as an extension of the Be phenomenon towards A–F stars. Indeed, the known cases are very similar, because they concern fast rotators, above 160 km s^{-1}, and for the hotter A stars Balmer emission is seen (Jaschek et al. 1988).

It was suggested that not all the lines could present narrow components, but only the ones originating from a metastable level (Slettebak 1982). For our 6 stars, all lines seem to be affected, therefore the shell should reflect exactly the physical conditions of the embbeded stellar atmosphere. For Be stars, the formation of an envelope around lower luminosity stars remains a problem. For Be stars the large rotation velocity, non radial pulsations, activity producing large outbursts and of course radiation pressure are invoked, and all these phenomena

Table 8. List of stars for which the main HIPPARCOS frequency could be deduced (3rd column, in d^{-1}) and fitted to our spectroscopic data, with its corresponding amplitude (4rd column, in mmag). Then the next columns respectively provide the corresponding radial velocity amplitude [$km\,s^{-1}$] computed from a sine-fit with the f-frequency (together with the associated fraction of the variance this frequency accounts for), and then the total velocity range [$km\,s^{-1}$] measured. Finally, last column provides the $2K/\Delta m$ amplitudes ratio values [$km\,s^{-1}\,mag^{-1}$].

HD	HIP	f	a	K	Range	$2K/\Delta m$
277	623	1.0809	23	1.13 (44%)	[−9; −5]	49
9365	7280	1.5981	33	2.16 (86%)	[−2; +4]	65
48271	32263	0.52436	24	0.71 (10%)	[−20; −15]	30
105458	59203	1.3207	15	1.44 (51%)	[−14; −8]	96
112429	63076	2.3556	20	1.84 (37%)	[−15; 0]	92
113867	63951	0.93166	18	0.60 (23%)	[0; +3]	33
175337	92837	1.2712	16	0.56 (70%)	[−1; +1]	35
195068	100859	1.2505	37	1.69 (48%)	[−29; −20]	46
211699	110163	0.9328	42	1.52 (50%)	[+5; +10]	36

can also take place in A and F stars. However, we note that at least two stars, HD 108100 and HD 160295, have a $v \sin i$ of only 60 $km\,s^{-1}$, hence much lower than the values derived for the stars in the survey of Jaschek et al. (1988). Another possibility is that the shell is a remnant of the star formation. Indeed, one of the possibilities is that these stars are quite young, and some of them might be related to young objects such as λ Bootis stars, as supposed by Gray & Kaye (1999) for HD 218396. But HD 218396 presents no shell features on our spectra. In addition, the position of the confirmed γ Doradus stars on the HR Diagram suggests that they can exist over a significant fraction of the main sequence lifetime in the relevant temperature range. The relative velocity between broad and narrow components shows that half the stars presents an expanding shell, while the other half presents a contracting one, as found by Fekel et al. (2003). The case of HD 160295 is puzzling, since at least 2 narrow components seem to be present. This implies, if the shell hypothesis is valid, that 2 shells are present, a situation encountered in e.g. RV Tauri stars where it seems that multiple shell components are ejected through shock waves. Finally, all but one (HD 160295, for which we have only one spectrum) of our 6 stars that present composite spectra show LPV for the narrow component (Fig. 7). If shell variability has already been noticed (Jaschek et al. 1988), it concerns only its appearance/disappearance, on a timescale of decades. Here again, vibrations of the shell require explanation, since pulsation modes in outer layers are mostly detected in very luminous stars as "strange modes". For these stars close to the Main Sequence, with normal luminosities, a different mechanism has to be invoked.

Composite spectra can also be explained by the presence of two stars of similar spectral type but with different rotation velocities. The speckle technique has been able to resolve some stars into visual binaries: HD 7169 (a close couple, 14 a.u. away; Mason et al. (2001), and we note that the slow rotator component has a very stable radial velocity: s.d. 0.24 $km\,s^{-1}$), HD 23874 (in an eccentric orbit, Seymour et al. 2002), HD 44333 (Germain et al. 1999, but its γ Dor nature is uncertain).

Actually, for our 6 star sample, 2 are visual binaries, and 2 others are suspected binaries. Our radial velocity measurements more or less confirm those of Fekel et al. (2003) except for HD 113867 where we have a shift of about 5 $km\,s^{-1}$ for both components, which cannot be interpreted as due to binary motion (but it could be an explanation if both stars orbit a third one). The star HD 160295 could also be member of a triple system, or the narrow line star must have a significantly cooler spectral type to produce all the observed lines. The relative stability of the radial velocities would imply either a very long orbital period or systems seen almost pole-on.

Hence, both the above interpretations have problems and appear rather as ad-hoc explanations. In our point of view, the main problem is that only the narrow component shows LPV. If LPV seen in the narrow components are really related to the γ Doradus frequencies, circumstellar envelope mechanisms are difficult to understand. For this reason, the binary hypothesis, with at least one component being a pulsating star, seems more attractive.

6. Conclusion

We have presented spectroscopic observations of 59 candidate γ Doradus stars detected mainly from the HIPPARCOS space mission. The main goal was to confirm these stars as real members of the group through the presence of line profile variations typical of g-mode pulsations. The γ Doradus stars that are confirmed by the present work, in addition to the "bona fide" candidates given in Table 1 are HD 48271, HD 70645, HD 80731, HD 100215, HD 113867, HD 175337, HD 195068. We were unable to detect LPV in less than 40% of the candidates, but most stars being (spectroscopically) faint, the signal to noise ratios were not always sufficient to detect very weak variations. Moreover, for most stars we have a very limited number of spectra, so LPV cannot be ruled out for these candidates.

In only a very few cases were we able to impose the main HIPPARCOS frequency on the radial velocity curves deduced from the LPV. The deduced $2K$ amplitudes are generally low

Table 9. Same as Table 8, but for stars for which the combined fit of photometric and spectroscopic data is not possible. Light amplitude [mmag] and/or radial velocity ranges [km s^{-1}] are given.

HD	HIP	f	a	Range
HIPPARCOS data fit and velocity variation				
2842	2510	1.6100	22	[+8; +17]
7169	5674	1.8225	16	−19.4 and −9
23874	17826	2.2565	21	[−21; −17]
171244	90919	0.9964	14	[−15; −13]
40745	28434	1.2133	7	
41448	28778	2.3815	18	
65526	39017	1.5529	27	
69715	40791	2.3646	13	
70645	41488	1.2618	17	
80731	46099	0.8964	29	
86358	48895	1.2899	18	
86371	48830	0.4066	35	
100215	56275	1.3216	23	
152896	82779	1.3395	26	
155154	83317	2.897	8	
160295	86374	1.3238	35	
167858	89601	0.76512	41	
206043	106897	2.4324	16	
Only velocity variations				
12901	9807			[+18; +22]
44195	30154			[+9; +13]
49434	32617			[−10; −17]
63436	38138			[−15; −7]
68192	40462			[+15; +19]
108100	60571			[−6.5; +4]
164615	88272			[−38; −33]
171834	91237			[−29; −25]
171836	91272			−31.14 ± 0.04
172506	91580			[−40; −38]
174353				[+9; +10]
218396	114189			[−15; −8]
224638	118293			[−4.2; −1.4]
224945	159			[+5; +6.5]

(between 0.6 and 4.2 km s^{-1}), pointing towards two mean amplitude ratio of about 35 and 96 km s^{-1} mag^{-1}. The pulsation behaviour for the most interesting stars (observations are ongoing) will be described in subsequent papers.

Fekel et al. (2003) suggest a percentage of γ Doradus members of multiple systems as high as 74%. Our larger sample, containing however a larger proportion of stars which are not confirmed γ Doradus stars, shows that this percentage seems to be smaller, i.e. 50%. This value is still larger than the one measured for such stars (30%) in a previous radial velocity study (Nordström et al. 1997). Similar to that occuring in a number of δ Scuti-type pulsators (Lampens & Boffin 2000), we also found several γ Doradus variables in binary systems with eccentric orbits.

Our sample contains 6 stars that show composite spectra. This behaviour can be due either to binarity or to the presence of a shell surrounding the star. Our data easily show that the narrow component presents LPV in 5 out of the 6 candidates. If a shell is really present, one has to find the mechanism that induces LPV in this shell. A first step would be to detect the period, if existing, of the variations of this narrow component.

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