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The discovery of new γ Doradus stars from the HIPPARCOS mission

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Abstract. We present a classification of 39 new variable stars with spectral type between A2 and F8 discovered by Hipparcos with the aim to find new γ Doradus stars. We have used a multivariate classification scheme and report the discovery of 14 new γ Doradus variables among this unbiased sample. Our results point out the biased nature towards hot temperatures of earlier, ground-based surveys of these variables. The coolest star among our sample has an effective temperature only slightly hotter than 6 000 K.

For most of the 14 new γ Doradus stars, we are able to detect more than one period in the Hipparcos light curve. The multiperiodicity points towards the presence of high-order g-modes. In view of the lack of a pulsation mechanism for these objects, we determine their position in the HR diagram with respect to the δ Scuti stars.

Key words: stars: variables: other – stars: oscillations – stars: statistics – methods: statistical

1. Introduction

It is by now fairly well accepted by the astronomical community that the γ Doradus stars (hereafter called γ Dor stars, for a review see Krisciunas 1998) consist of a new group of pulsating stars. Since the multiperiodic variations detected in them have periods roughly a factor 20 longer than the period of the radial fundamental mode for such stars, high-order g-modes are believed to be the cause of the variability. There is yet no pulsation mechanism that can explain the onset and the maintenance of the pulsations in these stars. One of the main difficulties in studying pulsations in this type of stars is the fact that convection plays an important role (see e.g. Gautschy & Löffler 1996). Therefore, instability analyses based on the usual κ mechanism performed so far for other types of variables cannot be easily generalised to take this convection into account in a physically justified way.

Handler & Krisciunas (1997) give an updated list of 11 *bona fide* members of the group, besides 17 stars that have been referenced in connection with the γ Dor phenomenon. Among the *bona fide* members, one star is of spectral type A5V, one is an A8V star and all others have spectral type F 0–2 V. The rotational velocities range from 18 up to 185 km/s, while the pulsational periods range from 0.51 d up to 2.90 d.

It is clear that too few members of the group are sufficiently known to derive general physical parameters of the γ Dor stars, let alone to define the boundaries of a "γ Dor strip". This is one of the reasons why the γ Dor stars have gained a lot of interest recently. More importantly, they are studied quite intensively since they seem to exhibit g-mode pulsations and have temperatures only slightly hotter than the Sun. The search for this type of pulsation in the Sun has been going on for many years and its firm discovery in stars similar to the Sun would be extremely important for seismological reasons.

Another important aspect of the γ Dor stars is that line-profile variability with time scales of the order of days has been found in some of them (see e.g. Aerts & Krisciunas 1996, Zerbi et al. 1997). The same variability was recently proposed as an alternative to the presence of planets for the observed radial-velocity changes of some solar-type stars such as 51 Peg (Gray 1997). Whether or not Gray's suggestion was correct has been a matter of important and intense debate in the recent past. At present, it is believed that g-mode pulsations do not occur in the latter stars so that the planet hypothesis is the only remaining one that can explain the radial-velocity variations (Willems et al. 1997, Hatzes et al. 1998, Terquem 1998, Brown et al. 1998a,b, Gray 1998). Nevertheless, the search for Sun-like stars that show line-profile variations with periods of days remains a relevant and active field in the context of the search for extrasolar planets.

In this paper, we take the first steps towards the discovery of cool line-profile variables by searching for γ Dor stars in an unbiased sample of new variable A2–F8 stars discovered by means of the Hipparcos mission. In Sect. 2 we present the selection of new variables that are relevant for our study. Sect. 3 describes our classification of the new variables, as well as the position of the new γ Dor stars in the HR diagram. In Sect. 4 we present the results of the period analyses of the Hipparcos data. We finally discuss our findings in Sect. 5.

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2. Selection of the candidates

The stars considered here were selected from the Hipparcos catalogue of periodic variable stars (van Leeuwen et al. 1997, Grenon et al. 1997). This catalogue is the result of a general analysis of the Hipparcos photometric time series (Eyer 1998, van Leeuwen 1997). It contains a total of 2712 periodic stars, with 970 newly discovered variable stars.

In order to get a sample which might contain γ Dor stars, we made a wide selection of stars by considering spectral types from A2 to F9. The γ Dor candidates that are missed by this selection must be few in number because 96% of the stars from the catalogue have a spectral classification. In a next step, we retained only the stars which are classified as new variables, the stars to which a variability type was assigned that differs from the one available in the literature, and stars without a variable type assignment. From this list, we then removed stars which have an easily recognizable non-γ Dor light curve (i.e. eclipsing binaries of EA and EB types, which stands for respectively eclipsing binaries of the Algol and β Lyrae types) and stars with a period longer than 5 days. The presumed eclipsing binaries of EW (eclipsing binaries of W UMa type) or E types (eclipsing binaries without any further specification) were kept as candidates with half of the periods assigned to them in the catalogue of periodic variables.

After this selection procedure, we end up with a list of 243 periodic variables that we use for the discovery of new γ Dor stars. Among these 243 variables, three stars are common to the list of γ Dor stars given by Handler & Krisciunas (1997): HD 27290 (γ Dor itself), HD 164615 (V 2118 Oph), and HD 218396 (V 342 Peg). It is interesting to note that the periods given in the literature and those obtained from the Hipparcos mission are similar for these three *bona fide* γ Dor stars. We find 0.757 d and 0.733 d, 0.811 d, and 0.518 d as main periods for respectively γ Dor, V 2118 Oph, and V 342 Peg, while the corresponding periods listed by Handler & Krisciunas (1997) are 0.733 and 0.757 d, 0.815 d, and 0.510 d. Since the number of data points and the total time span is about the same for all the Hipparcos targets in our study (see also Table 1), we conclude from this that the Hipparcos data are suitable to derive the correct periods and that the periodograms are not dominated by aliasing problems due to the time sampling or the orbital period of the satellite.

The three known γ Dor stars are removed from the list and are, together with the eight other *bona fide* members, used as definition stars for the class of γ Dor variables (see the following section). We next removed all the δ Scuti stars common to our selected list and the catalogue published by Rodriguez et al. (1994). Finally, the variable stars in our list that are also a member of the catalogue of chemically peculiar stars (hereafter called CP stars) recently published by Catalano & Renson (1997) were also removed. In this way, we end up with 208 candidate γ Dor stars in our list.

3. Classification

The classification scheme that we use in this paper is basically the same as the one described by Waelkens et al. (1998), i.e. we use multivariate discriminant analysis which we implemented by means of the statistical software package SAS (1990). We recall that such a multivariate classification scheme uses the knowledge of stellar parameters in the n-dimensional space, instead of considering e.g. bivariate plots. A first decision to make is which parameters we want to consider for the classification. The Hipparcos catalogue gives us the spectral type and the main period present in the light curves of all the candidates. However, the spectral types are often inaccurate. Moreover, it is better to base the classification on more than two (uncertain) parameters. We therefore consider only those candidates for which we have Geneva data at our disposal. The reason to do this is that the Geneva colour B2-V1 is an accurate indicator of the effective temperature of stars in the considered spectral region. Besides this colour index, we also considered the Geneva Y and Z indices, the latter being a good indicator of the chemical composition of the star. The inclusion of Z as a parameter for the classification allows us to distinguish the variable CP stars from the other variables with a normal chemical composition. For 39 of the stars in our list, we have Geneva data at our disposal. Our classification of these 39 stars is thus based on stellar parameters in a 4-dimensional space.

In order to perform the discriminant analysis, we need to consider prototypes of the classes of variables in which we want to partition the 39 new variables in our list. As three calibration classes, we use the known *bona fide* γ Dor stars listed by Handler and Krisciunas (1997) for which Geneva data are available (6 stars), the known δ Scuti stars from the list of Rodriguez et al. (1994) that have been measured in the Geneva system (107 stars), and the variable CP stars taken from the catalogue of Catalano & Renson (1997) which are in the Geneva data base (23 stars).

It is beyond the scope of our paper to give the detailed results of the multivariate classification here. These full details are available upon request from the authors. Instead, we focus on the main result with respect to the discovery of new γ Dor stars, but let us first mention that the stars HD 11956, HD 58634, HD 113537, HD 135383, and HD 191301 are classified by us as new δ Scuti stars.

Fourteen stars are identified as new γ Dor variables by our classification. These stars and some of their physical parameters are listed in Table 1. The spectral types and the rotational velocities were taken from the Simbad data base when available. We encounter rotational velocities between 0 and 130 km/s. The $B-V$ colours were taken from the Hipparcos catalogue. They were obtained from ground-based observations or derived from Tycho data ($B_T - V_T$). The absolute magnitudes Mv were obtained through the parallax and the Johnson V magnitude, both from the Hipparcos catalogue, by means of the expression $M_V = 5\log(\pi/1000)+5+V$ (π expressed in mas). Finally, we derived the effective temperature and gravity from the Geneva

Table 1. Stellar parameters of the 14 new γ Dor candidates. N is the number of Hipparcos data points and ΔT gives the total time span expressed in days. P_1 and P_2 stand for respectively the main period and the one found after prewhitening with P_1. The fraction of the variance explained by a sine fit to the original data with P_1, to the prewhitened data with P_2, and to the original data with a biperiodic model based on P_1 and P_2 are denoted by respectively f.v.1, f.v.2, and f.v.3. The derivation of the other parameters is given in the text.

HD nr	HIP nr	SpT	$v \sin i$	$T_{\rm eff}$	$\log g$	$B-V$	M_V	N	ΔT (d)	P_1 (d)	f.v.1	P_2 (d)	f.v.2	f.v.3
11443	8796	F6IV	103	6270	3.69	0.49	1.95	89	1124	0.8681	33%	0.9494	18%	46%
14940	11192	F0IV/V	-	7120	4.41	0.31	2.71	92	1167	0.5004	33%	0.9800	29%	52%
25998	19335	F7V	18	6260	4.38	0.52	3.87	130	1123	3.0469	36%	1.7159	16%	47%
40745	28434	F2IV	33	6790	3.98	0.36	2.32	183	1198	0.8752	19%	0.8920	8%	26%
107192	59767	F2V	-	7010	4.46	0.35	2.93	127	1178	0.7237	49%	4.9554	20%	59%
111709	62774	A3:m	-	6750	3.32	0.36	-0.89	173	1171	1.1857	45%	0.3351	8%	50%
112429	63076	A5n	130	7190	4.40	0.30	2.93	116	1182	0.4245	52%	0.4458	32%	68%
147787	80645	F4IV	0	6960	4.58	0.38	2.25	127	1124	1.4556	57%	2.9464	29%	70%
149989	81650	A9V	-	7070	4.43	0.32	2.86	135	1123	0.4266	38%	0.4793	28%	55%
167858	89601	F2V	13	7180	4.45	0.31	2.64	90	1098	1.3070	64%	0.9165	37%	79%
187028	97590	F0V	-	7090	4.47	0.28	3.10	163	1078	0.6953	49%	1.2719	20%	59%
214291	111718	F7V	-	6080	3.92	0.54	1.54	109	932	0.8713	80%	6.6050	21%	84%
216910	113402	F2IV	-	6930	4.27	0.34	2.39	271	1179	0.6935	23%	0.6136	29%	45%
218225	114127	F3IV	-	6790	4.02	0.38	2.97	103	1057	0.8668	54%	0.4641	19%	63%

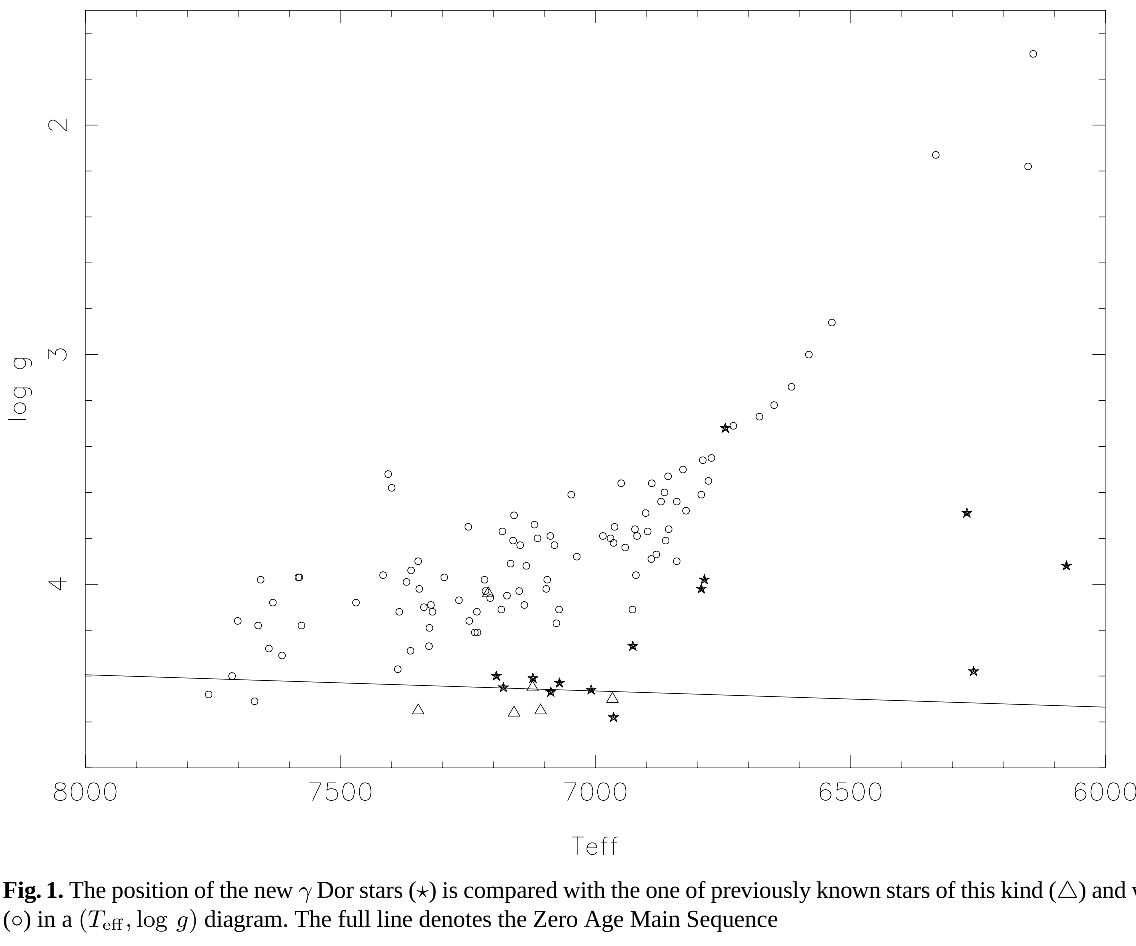

Fig. 1. The position of the new γ Dor stars ($\star$) is compared with the one of previously known stars of this kind ($\triangle$) and with known δ Scuti stars ($\circ$) in a $(T_{\rm eff}, \log\ g)$ diagram. The full line denotes the Zero Age Main Sequence

reddening free parameters B2-V1 and d by means of the code recently published by Künzli et al. (1997).

It is of great interest to consider the position of the γ Dor variables with respect to the δ Scuti stars and in general in the HR diagram. In Fig. 1, we show a $(T_{\rm eff}, \log\ g)$ diagram in which we plot the δ Scuti and the γ Dor definition stars, together with the 14 newly found γ Dor stars. It can be seen from this figure that the new candidate γ Dor stars are situated on or very near the main sequence, to the cooler part of the δ Scuti domain. A remarkable result is that the new γ Dor stars extend over a wider range of temperatures compared to the stars listed by Handler & Krisciunas (1997), i.e. we find an extension towards cooler

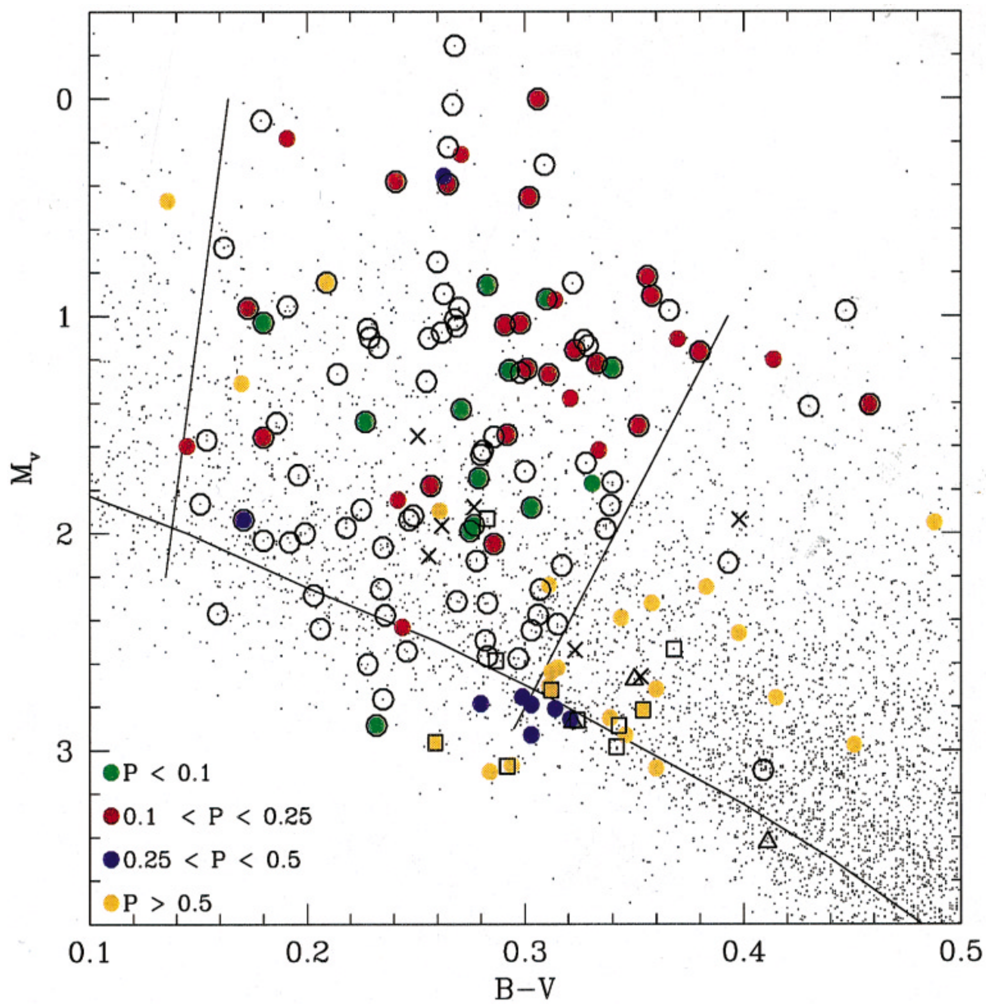

Fig. 2. The position of the new γ Dor stars is compared with other variables in the HR diagram. The open symbols and the crosses are data from the literature: open circles for δ Scuti stars, open squares and triangles for *bona fide* and suspected γ Dor stars, crosses for roAp stars. The filled circles denote the periodic variables with periods derived from the Hipparcos data for different period intervals (different colours). The full lines denote the border of the δ Scuti instability strip. The tiny dots are stars observed by Hipparcos with an accurate determination of M_V

temperatures than considered so far for these stars. The reason probably is that earlier ground-based surveys looked particularly for stars very near the δ Scuti instability strip. The coolest among the new γ Dor stars has an effective temperature of only 6080 K. As already mentioned, the confirmation of g-mode pulsations in stars with temperatures fairly close to the one of the Sun is extremely important from a seismological point of view. It is therefore evident that these cool γ Dor stars deserve close attention in the near future.

The position of all new candidate γ Dor stars with respect to other variables in that part of the HR diagram can be seen in Fig. 2. This diagram contains more than the 14 identified γ Dor stars, i.e. we also show the new variables with periods in the range of γ Dor variability of which we have no Geneva data at our disposal. It can first of all be seen in Fig. 2 that most of the variables found from the Hipparcos photometry are situated in the δ Scuti instability strip and have the expected periods for such stars. Secondly, we find that the positions of most of the new variables with periods longer than a quarter of a day are consistent with the position of the *bona fide* and the suspected γ Dor stars known so far in the literature. Our diagram presented in Fig. 2 shows that regular variability extends towards the cooler part of the classical δ Scuti instability strip.

4. Frequency analysis

The total time base and the number of data points per star are listed in Table 1 for the γ Dor candidates. The average values of these numbers are 1124 days and 136 respectively. The times of the sampling were generally taken in such a way that they should allow an accurate determination of the frequencies. This is confirmed by period analyses of the known γ Dor stars and also of known Slowly Pulsating B Stars (see Aerts et al. , in preparation), which all have the same frequency range as the new candidate γ Dor stars studied here. The period range of the main period found for the 14 stars is $P \in [0.42, 3.05]$ d, well compatible with Handler & Krisciunas' period range for the *bona fide* members. The fits to the data usually are satisfactory (see fractions given in Table 1 and top panels shown in Figs. 3 & 4), especially since the stars are expected to be multiperiodic.

We have performed a frequency analysis on the Hipparcos photometry after having checked for, and prewhitened with, the main period listed in the catalogue for the 14 γ Dor stars. We have used a Scargle periodogram (Scargle 1982) and the θ statistics of a PDM analysis (Stellingwerf 1978) to identify the main period and a possible secondary period. The results for the 14 stars are given in Table 1, while we show the phase

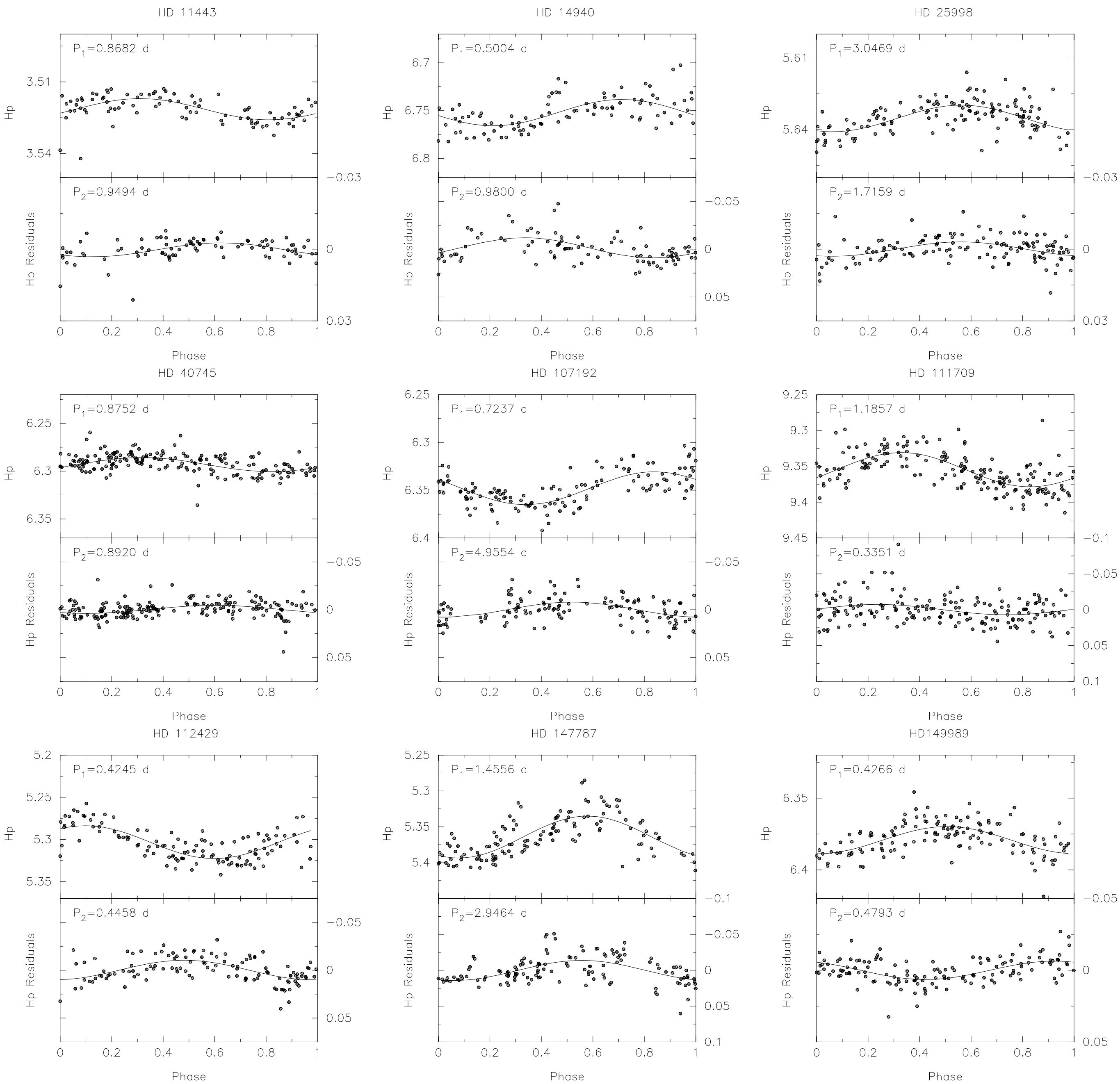

Fig. 3. Phase diagrams of the Hipparcos data of the first 9 new γ Dor stars listed in Table 1. The diagrams were constructed for the periods given in Table 1. Top panels: for the main periods P_1, lower panels: for the periods P_2 obtained after prewhitening with P_1

plots for the first and second period for all 14 stars in Figs. 3 & 4. All the main periods that we derived are compatible with those suggested in the Hipparcos catalogue. As can be seen from these plots, the peak-to-peak amplitudes range from a few hundredths up to a tenth of a magnitude.

In order to have an idea about the significance of the frequency peaks, we show the Scargle periodograms of the star with the largest (HD 167858) and smallest (HD 11443) amplitude in Fig. 5. The top panels give the results for the main frequency and the lower panels show the periodogram after prewhitening with this main frequency. The periodograms for all other stars give peaks with a significance between the ones of these two chosen examples.

We emphasize that the detection of secondary periods in the range of a few days, in combination with a main period that is much shorter (see e.g. HD 214291), can be due to the sampling of the data. This phenomenon was also encountered by Cuypers et al. (in preparation) in their study of the variability of B-type stars by means of Hipparcos photometry. Also, we sometimes detect frequencies that are close to multiples of the

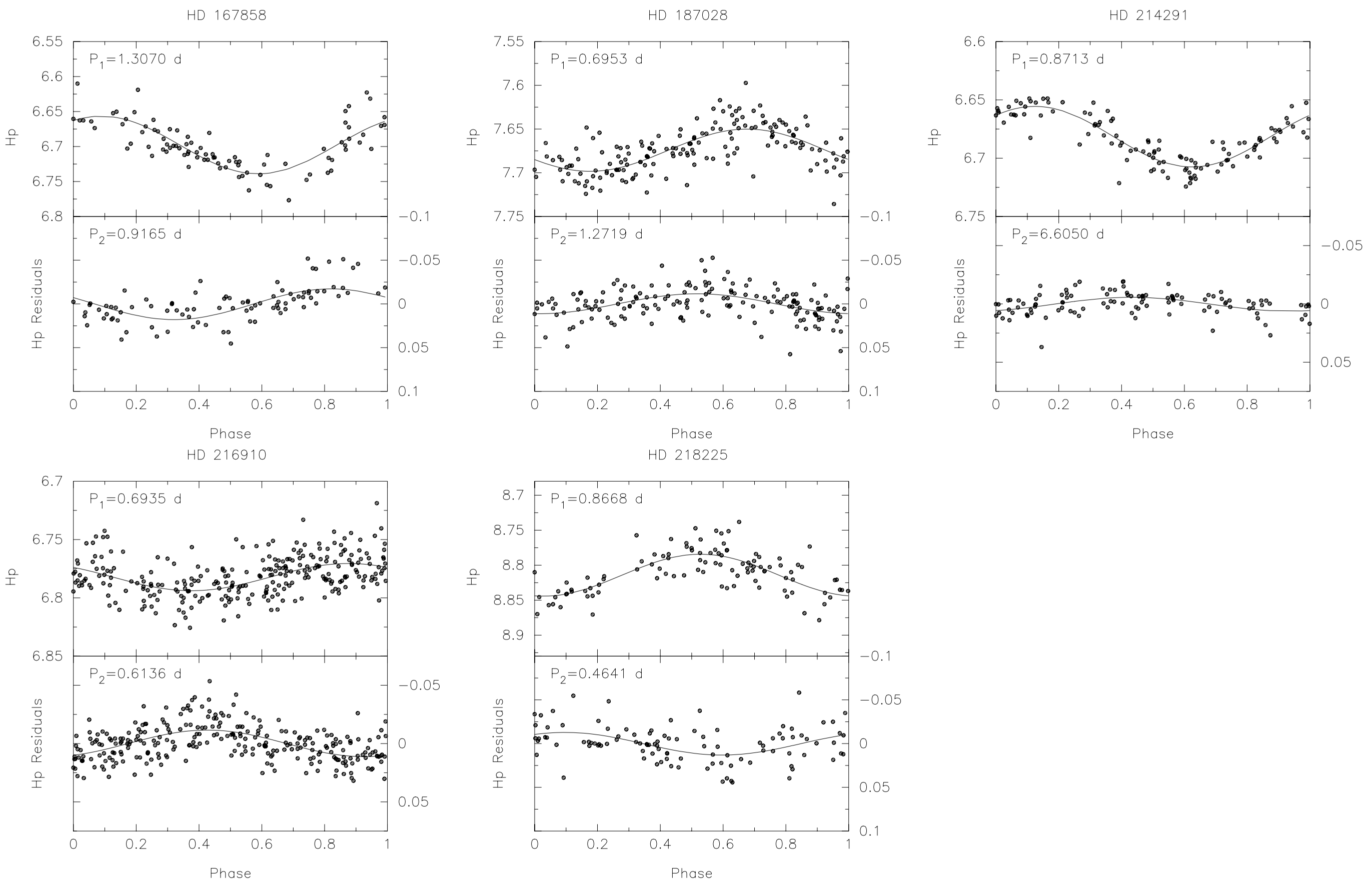

Fig. 4. Phase diagrams of the Hipparcos data of the 5 last new γ Dor stars listed in Table 1. The diagrams were constructed for the periods given in Table 1. Top panels: for the main periods P_1, lower panels: for the periods P_2 obtained after prewhitening with P_1

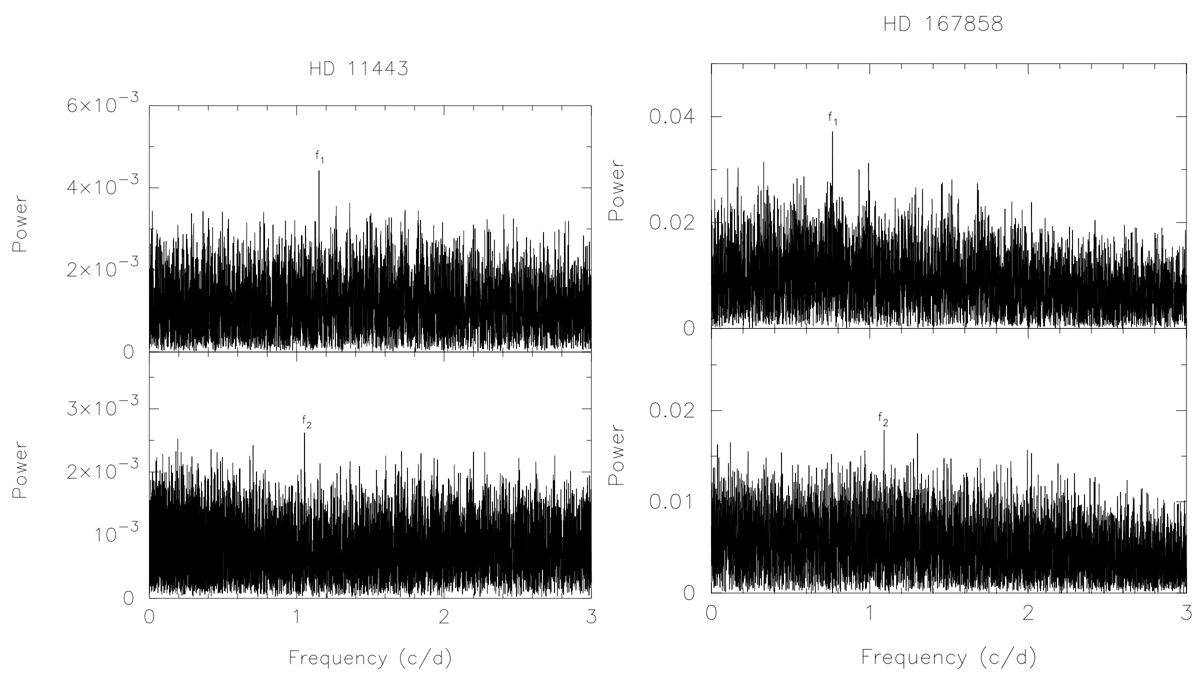

Fig. 5. Scargle periodograms for the Hipparcos photometry (upper panel) and the residuals (lower panel) of the γ Dor candidate with the smallest (left) and largest (right) amplitude

main frequency after prewhitening (e.g. HD 147787). Especially for these cases, our results should of course be confirmed by ground-based follow-up data. We nevertheless are confident that the secondary frequencies are real for most stars, as is the case for γ Dor itself.

We did not attempt to find more than two frequencies, since this is beyond the scope of our paper and also because the Hipparcos data are in general not suited to find very complicated variability patterns. The latter should be obtained from well-planned, preferably multi-site, ground-based campaigns. In any case, all the periods that we encountered so far are at least an order of magnitude larger than the fundamental mode for such stars and thus point towards g-mode pulsations.

5. Discussion

We report the discovery of 14 new candidate γ Dor variables. They were found by means of Hipparcos and Geneva photometry. The periods and the amplitudes found in the Hipparcos data are typical for γ Dor stars. Nevertheless, our identification has to be checked by means of ground-based photometric and spectroscopic follow-up data to definitely exclude other reasons for the variability (e.g. ellipsoidal variations). Such data will then also point towards the presence/absence of important properties such as line-profile variations, which have recently been claimed in Sun-like stars around which Jupiter-like planets are suspected.

The effective temperatures derived from the Geneva multicolour photometry point out that the γ Dor stars extend to cooler temperatures than thought up to now. This can have important consequences with respect to the detection of g-mode pulsations in stars as cool as the Sun. Moreover, extended efforts have been performed to look for solar-like p-mode pulsations in other stars, but have not been very successful up to now (e.g. Bedding & Kjeldsen 1998). Our discovery of cool γ Dor stars is particularly relevant to extend these surveys. In this respect, it should be stressed that we primarily focused on the limited group of new variables for which both Hipparcos and Geneva data are available, mainly because the latter allow an accurate determination of the effective temperature. It is very likely, however, that our list of candidate γ Dor stars of which no Geneva data are at our disposal contains more objects of this type. Also, a search for new variable stars with spectral type G similar to our approach might reveal stars exhibiting (solar-type) pulsations.

We briefly also mention that we have started a search for new γ Dor stars by means of ground-based Geneva photometry in the course of 1996 which is still ongoing. This has resulted so far in the discovery of three new and some five suspected γ Dor stars. We will report on these stars in a forthcoming paper once the gathering of the photometric data has been completed.

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