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δ Scuti and related stars: Analysis of the R00 Catalogue

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Abstract. We present a comprehensive analysis of the properties of the pulsating δ Scuti and related variables based mainly on the content of the recently published catalogue by Rodríguez et al. (2000a, hereafter R00). In particular, the primary observational properties such as visual amplitude, period and visual magnitude and the contributions from the Hipparcos, OGLE and MACHO long-term monitoring projects are examined. The membership of these variables in open clusters and multiple systems is also analyzed, with special attention given to the δ Scuti pulsators situated in eclipsing binary systems. The location of the δ Scuti variables in the H–R diagram is discussed on the basis of HIPPARCOS parallaxes and $uvby\beta$ photometry. New borders of the classical instability are presented. In particular, the properties of the δ Scuti pulsators with nonsolar surface abundances (SX Phe, λ Boo, ρ Pup, δ Del and classical Am stars subgroups) are examined. The Hipparcos parallaxes show that the available photometric $uvby\beta$ absolute magnitude calibrations by Crawford can be applied correctly to δ Scuti variables rotating faster than $v \sin i \sim 100$ km s^{-1} with normal spectra. It is shown that systematic deviations exist for the photometrically determined absolute magnitudes, which correlate with $v \sin i$ and δm_1. The photometric calibrations are found to fit the λ Boo stars, but should not be used for the group of evolved metallic-line A stars. The related γ Dor variables and the pre-main-sequence δ Scuti variables are also discussed. Finally, the variables catalogued with periods longer than $0\overset{\mathrm{d}}{.}25$ are examined on a star-by-star basis in order to assign them to the proper δ Scuti, RR Lyrae or γ Dor class. A search for massive, long-period δ Scuti stars similar to the triple-mode variable AC And is also carried out.

Key words. stars: variables: δ Scuti – stars: oscillations – stars: fundamental parameters

1. Introduction

δ Scuti-type variables are pulsating stars of short periods ($<0\overset{\mathrm{d}}{.}3$) located in the lower part of the Cepheid instability strip, with luminosities ranging from the zero-age-main-sequence (ZAMS) to about 2 mag above the main sequence with spectral types ranging from about A2 to F2. A handbook with astrophysical reviews and discussions of these variables has now become available (Breger & Montgomery 2000).

Recently, an updated catalogue of δ Scuti stars has been published (Rodríguez et al. 2000a) covering observational information available up to January, 2000. This new catalogue contains 636 variable stars, of which more than 50% have only been discovered during the last six years. The majority of these new variables were found in the data of long-term monitoring projects such as the Hipparcos mission (ESA, 1997), OGLE (Udalski et al. 1994, 1995a,b, 1996, 1997) and MACHO (Alcock et al. 2000) projects. Nevertheless, even ignoring the contributions from these three main projects, a large number of new variables have been discovered since 1994 by individual groups. Hence, an immense amount of new information on δ Scuti variables has been made available during the last few years.

The main aim of this work is to present a comprehensive analysis on the present status of the δ Scuti and related stars based mainly on the content of the R00 catalogue. In Sect. 2, the observational properties of the stars in the catalogue are presented together with an analysis of the δ Scuti variables which are members of double or multiple systems and open clusters. In Sect. 3, we analyse the location of these variables in the Hertzsprung-Russell (H–R) diagram on the basis of $uvby\beta$ photometry and parallaxes. In Sect. 4, several interesting groups of peculiar and/or related variables are also studied.

2. Distributions

2.1. Amplitudes, periods and apparent magnitudes

The statistical distribution of the amplitudes, periods and apparent magnitudes of the known δ Scuti stars

Send offprint requests to: E. Rodríguez is examined in Figs. 1 to 3. Tables 1 and 2 compare the new average values with those presented in the earlier catalogue on δ Scuti stars (Rodríguez et al. 1994, hereafter R94). The histograms also show the distributions for the variables discovered by the Hipparcos mission (ESA, 1997) and OGLE (Udalski 1994, 1995a,b, 1996, 1997) and MACHO (Alcock et al. 2000) projects are also studied.

The distribution of the amplitudes of the known δ Scuti stars does not reflect the true distribution among the group: severe selection effects exist, especially among the variables discovered by the OGLE and MACHO projects, for which a limit of $0\overset{\mathrm{m}}{.}1$ are found (see Fig. 1). This is connected with extreme faintness of these stars (see Fig. 3) leading to lower measurement precision. The HIPPARCOS measurements present an intermediate case between the OGLE/MACHO and the classical telescope surveys with millimag precision.

Figure 1 shows that the amplitudes are strongly dependent on the origin of the discovery. The average amplitude of the variables discovered during high-accuracy variability surveys is only about $0\overset{\mathrm{m}}{.}01$ (see Fig. 3 of Breger 1979). On the other hand, nearly all the δ Scuti variables discovered during the OGLE and MACHO projects have amplitudes larger than $0\overset{\mathrm{m}}{.}1$. The variables discovered during the Hipparcos mission have amplitudes between those of the MACHO/OGLE projects and the "other" sources. Our interpretation that these differences are a reflection of the accuracy of the variability measurements is confirmed by the brightness distribution of the stars, which is shown in Fig. 3: the new δ Scuti variables discovered by Hipparcos satellite are much brighter than those discovered by OGLE and MACHO projects. The higher accuracy of the measurements of the brighter stars makes it possible to discover smaller amplitudes. Consequently, the new MACHO/OGLE variables severely distort the true statistics of the amplitude distribution among δ Scuti stars. In spite of the great number of δ Scuti-type pulsators with large amplitudes discovered by the OGLE and MACHO projects, the majority of the known δ Scuti variables display small amplitudes. In fact 51% of these variables have visual amplitudes smaller than $0\overset{\mathrm{m}}{.}05$. Additionally, the number of low amplitude variables increases nearly exponentially with decreasing amplitude. In particular, nearly 30% of them show amplitudes smaller than $0\overset{\mathrm{m}}{.}02$. This percentage is about 45% if we ignore the contributions from Hipparcos, OGLE and MACHO.

The increased data used for Fig. 1 solves a puzzle from a similar histogram of amplitudes (Fig. 2) in the R94 catalogue: the apparent amplitude gap between $0\overset{\mathrm{m}}{.}1$ to $0\overset{\mathrm{m}}{.}3$. In the R94 catalogue there were only 14 variables in this interval ($0\overset{\mathrm{m}}{.}1 < \Delta V \leq 0\overset{\mathrm{m}}{.}3$), that is, 5% of the full sample. However, in the R00 catalogue there are 94 variables (which means, 15% of the total sample). Hence, it seems that there is not a strict separation in two groups relative to the amplitude for the δ Scuti-type pulsators (low amplitude variables with $\Delta V < 0\overset{\mathrm{m}}{.}1$ and high amplitude variables with $\Delta V > 0\overset{\mathrm{m}}{.}3$). Note that the disappearance of the gap has been due to the contributions from OGLE and MACHO projects. In fact, in both cases the number of variables discovered, with visual amplitudes between $0\overset{\mathrm{m}}{.}1$ to $0\overset{\mathrm{m}}{.}3$ and larger than $0\overset{\mathrm{m}}{.}3$, is very similar (26 and 25 from OGLE; 41 and 42 from MACHO). Thus, it seems that the gap shown in the R94 catalogue was due to a selection effect.

The period histogram (Fig. 2) shows that the majority of the variables have short periods and that the number of variables decreases with increasing period. This result is expected since the longer period stars are more evolved because of the existence of a period-luminosity relation. Because of the relatively long life-time on the main sequence, the probability of finding an evolved star is smaller than the probability of detecting a main-sequence star. However, there exists another reason as well. The majority of short-period stars on the main sequence have very small amplitudes, which are more difficult to detect in stars with longer periods because of the very high quality photometric data required. This selection effect had a very strong influence in the $< \Delta V > -P$ diagram of R94 catalogue. However, our Table 1 (full sample) shows that this effect almost disappears for the variables with periods longer than $0\overset{\mathrm{d}}{.}05$. This is caused by the Hipparcos, OGLE and MACHO data, where the selection effect is not present. However, in the other data (not containing the three data sets) the selection effect still exists.

Figure 3 shows the distribution in visual amplitude. Presently there exists a large number of δ Scuti stars with visual apparent magnitudes greater than $16\overset{\mathrm{m}}{.}0$ mostly due to the OGLE and MACHO contributions. In particular, 59 δ Scuti variables fainter than $18\overset{\mathrm{m}}{.}0$ have been discovered during the last six years.

Table 2 shows that the selection effect *"that the amplitude is larger when the star is fainter"*, still remains. This effect was very pronounced in the older data used in the R94 catalog, where the stars fainter than $V = 10^{\mathrm{m}}$ had large amplitudes. The explanation lies in the difficulty in detecting small amplitudes in faint variables. For the new MACHO data, an amplitude jump to large amplitude is evident only around 16^{m}. The increased astronomical precision in the new data, which leads to the detection of small-amplitude variability in faint stars, is also evident in the line marked "Other" in Table 2. This decrease is due to the very low-amplitude δ Scuti variables recently discovered during surveys in open clusters using high quality CCD photometry (Balona & Laney 1995; Frandsen et al. 1996; Frandsen & Arentoft 1998a; Kim et al. 1999).

2.2. δ Scuti stars in double or multiple systems

Figure 4 shows the distribution in apparent magnitude of the δ Scuti variables known to be part of binary or multiple stellar systems. The R00 catalogue lists 86 such variables (62 with CCDM identification; Dommanget & Nys 1994). This represents only 14% of the total sample of known δ Scuti stars. Only five variables are fainter

Table 1. Average of the visual peak-to-peak amplitude (<ΔV>; in mag) versus period from different contributions and comparison with the R94 catalogue

	$\leq 0\overset{d}{.}05$	$0\overset{d}{.}05-0\overset{d}{.}10$	$0\overset{d}{.}10-0\overset{d}{.}15$	$0\overset{d}{.}15-0\overset{d}{.}20$	$0.^{d}20-0\overset{d}{.}25$	$0\overset{d}{.}25-0\overset{d}{.}30$
Hipparcos	–	0.098	0.066	0.062	0.074	0.065
OGLE	0.160	0.294	0.317	0.320	0.343	–
MACHO	–	0.317	0.303	0.226	–	–
Other	0.024	0.084	0.213	0.226	0.352	0.238
Full sample	0.025	0.151	0.202	0.186	0.278	0.214
R94	0.029	0.097	0.254	0.278	0.444	0.262

Table 2. Average visual peak-to-peak amplitude (<ΔV>; in mag) versus visual apparent magnitude from different contributions and comparison with the R94 catalogue

	2^m-4^m	4^m-6^m	6^m-8^m	8^m-10^m	10^m-12^m	12^m-14^m	14^m-16^m	16^m-18^m	18^m-20^m
Hipparcos	–	0.020	0.056	0.088	0.093	–	–	–	–
OGLE	–	–	–	–	–	–	–	0.264	0.322
MACHO	–	–	–	–	–	0.160	0.153	0.303	0.348
Other	0.043	0.030	0.044	0.096	0.238	0.191	0.373	0.514	0.570
Full sample	0.043	0.030	0.047	0.094	0.229	0.189	0.351	0.340	0.332
R94	0.043	0.032	0.052	0.120	0.281	0.436	0.544	0.594	

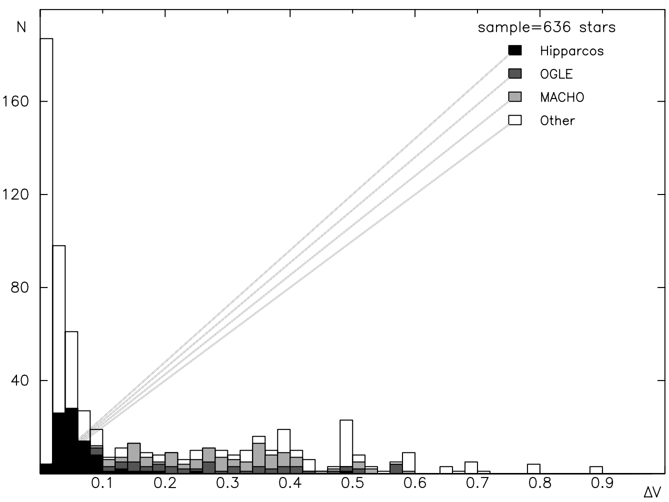

Fig. 1. Distribution of the variables in the catalogue (N) as a function of the visual amplitude (ΔV). The contributions from Hipparcos, OGLE and MACHO are also shown

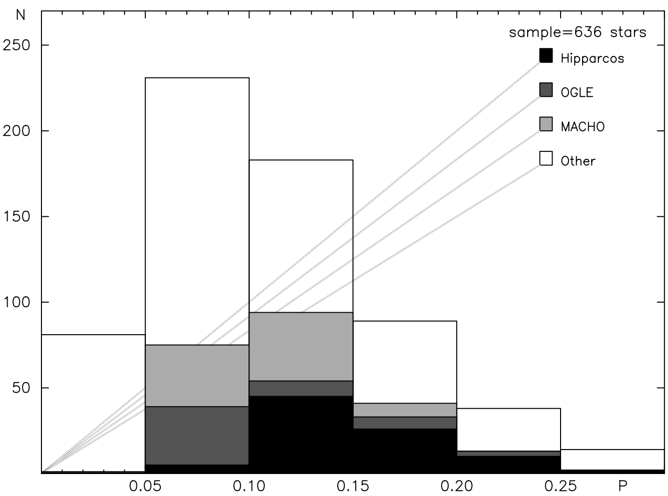

Fig. 2. Distribution of the variables in the catalogue (N) as a function of the period (P). The contributions from Hipparcos, OGLE and MACHO are also shown

than $V = 10\overset{m}{.}0$: three eclipsing binaries AB Cas ($V = 10\overset{m}{.}17$, $P_{\rm orb} = 1\overset{d}{.}37$, Rodríguez et al. 1998), Y Cam ($V = 10\overset{m}{.}54$, $P_{\rm orb} = 3\overset{d}{.}31$, Broglia & Conconi 1984) and V577 Oph ($V = 11\overset{m}{.}01$, $P_{\rm orb} = 6\overset{d}{.}08$, Diethelm 1993) and the two recently discovered spectroscopic binaries PL 43 ($V = 13\overset{m}{.}51$, $P_{\rm orb} = 317$ d) and 29499-057 ($V = 13\overset{m}{.}8$, $P_{\rm orb} \sim 2750$ d; this case is not completely confirmed yet) (Preston & Landolt 1999). Hence, multiplicity is catalogued for 22% of all the δ Scuti known up to $10\overset{m}{.}0$. This percentage is very low because more than 50% of the stars are expected to be members of multiple systems. It would probably be incorrect to intepret the statistics to imply that multiplicity inhibits pulsation since the observational bias against detecting multiplicity is very high. One reason for this bias immediately comes to mind: both pulsation and multiplicity lead to radial-velocity variability. Long and accurate observations are required to separate the two effects. These are generally not available.

Pulsating stars in eclipsing binaries are important for accurate determinations of fundamental stellar parameters and the study of tidal effects on the pulsations. However, so far very few such systems with a δ Scuti variable as one of its components have been discovered. Only 9 cases seem to be well established and they are listed in Table 3 and shown in Fig. 4. Two of these variables have

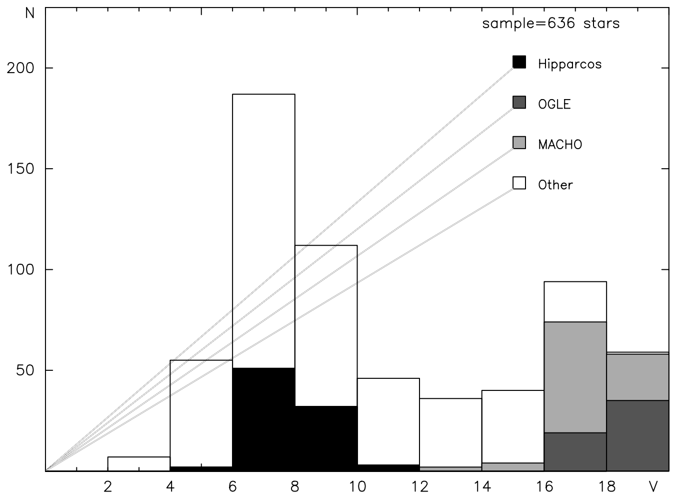

Fig. 3. Distribution of the variables in the catalogue (N) as a function of the visual magnitude (V). The contributions from Hipparcos, OGLE and MACHO are also shown

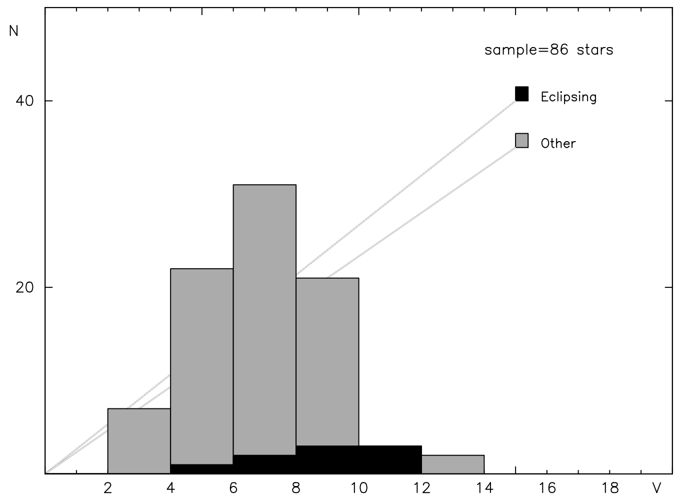

Fig. 4. Distributions of δ Scuti stars in double or multiple systems as a function of the visual magnitude (V). The contribution from eclipsing binary systems is also shown

been very recently discovered: AS Eri by Gamarova et al. (2000) and R CMa by Mkrtichian & Gamarova (2000). In all the cases listed in the table, the pulsation amplitude is small. This, in combination with the large variations produced by the binarity, makes it very difficult to detect δ Scuti-like variations in such systems. One excellent example is the bright Algol-type eclipsing binary system RZ Cas. This star was discovered to be variable by Muller in 1906. Later, Dugan (1916) obtained a complete light curve using a visual polarizing photometer and derived the orbital elements for the system. During the last two decades, unusual changes in the light curves have been detected, leading to a number of different interpretations, but the δ Scuti-type variability of the primary component of this system has only recently been discovered by Ohshima et al. (1998). This demonstrates how difficult it is to detect low amplitude δ Scuti-like variations in this type of binary systems: only measurements of very high quality lead to successful results. Besides the 9 stars listed in Table 3, two other δ Scuti variables (UX Mon and DL Uma) had been pointed out to belong to eclipsing binary systems being listed in the R94 catalogue. However, these two cases seems to be wrong. Olson & Etzel (1995) do not confirm the δ Scuti-like variations claimed by earlier authors for the primary component of the Algol-type system UX Mon. In the case of DL UMa, new photometry carried out by Rodríguez et al. (2000c) does not confirm the existence of eclipsing binarity with an orbital period of $0\overset{d}{.}42$ as given in Kholopov et al. (1987).

Table 3 lists, for each system, the spectral types of both components (ST_1, ST_2), visual magnitude V, period and amplitude of the pulsation ($P_{\rm pul}$, $\Delta V_{\rm pul}$), orbital period and depths of the primary and secondary minima ($P_{\rm orb}$, $\Delta V_{\rm prim}$, $\Delta V_{\rm sec}$) and type of binarity. In addition, the δ Scuti component and the number (N) of pulsation frequencies found are also listed. In all the cases, these 9 systems are Algol-type binaries from an observational point of view as described in the GCVS (Kholopov et al. 1985). However, from an evolutionary point of view, only the six first cases listed in Table 3 are Algol-type systems where the hotter component is an A-F type star, whereas the secondary component is much cooler and much less luminous. In these cases the δ Scuti variable is the primary component. On the other hand, AI Hya and RS Cha are early F-type and A-type double-lined eclipsing binaries, respectively, where the secondary components display δ Scuti-type variations. Finally, V577 Oph is probably an A-type double-lined eclipsing system. In this case, the δ Scuti component would be the primary. In all the cases only one or two reliable frequencies of pulsation have been determined, while more frequencies of pulsation can probably still be found. In two cases (RZ Cas and Y Cam), multiperiodicity and nonradial pulsation are confirmed (Ohshima et al. 1998; Rodríguez et al. 2000b; Broglia & Conconi 1984). On the other hand, monoperiodicity and radial pulsation have been found in AB Cas (Rodríguez et al. 1998).

Pulsation provides an additional method to detect multiplicity through a study of the light-time effects in a binary system. This method generally favors high-amplitude variables with only one or two pulsation periods (which tend to be radial). Several decades of measurements are usually required to study these (O–C) residuals in the times of maxima.

A good example of such a system is the star SZ Lyn. Moffett et al. (1988) found that the ephemeris of this star can be well described with two terms: 1) a secular increase of the period at a rate of 9 10^{-9} d/y and 2) an orbital period, as component of a binary system, of $P_{\rm orb} = 1118$ d with a semiamplitude of $0\overset{d}{.}006$. Furthermore, five other high-amplitude δ Scuti stars have been suggested as members of binary systems. They are listed in Table 4 together with their probable orbital periods.

Table 3. δ Scuti variables in eclipsing binary systems. N is the number of frequencies detected. Sources other than the R00 catalogue: 1) Rodríguez et al. 1998, 2) Rodríguez et al. 2000b, 3) Sarma & Abhyankar 1979, 4) Popper 1973, 5) Sarma et al. 1996, 6) Broglia & Marin 1974, 7) Broglia & Conconi 1984, 8) Jørgensen & Grønbech 1978, 9) Clausen & Nordström 1980, 10) Volkov 1990, 11) Diethelm 1993

Star	ST_1	ST_2	V (mag)	P_{pul} (d)	ΔV_{pul} (mag)	P_{orb} (d)	ΔV_{prim} (mag)	ΔV_{sec} (mag)	Type	δ Scuti component	N	Source
AB Cas	A3V	K1V	10.17	0.0583	0.05	1.3669	1.63	0.10	Algol	1	1	1
RZ Cas	A3V	K0IV	6.26	0.0156	0.02	1.1953	1.50	0.07	Algol	1	2	2
WX Eri	A5	K0V	9.39	0.1645	0.04	0.8233	0.55	0.15	Algol	1	2	3
AS Eri	A3V	K0IV	8.30	0.017	0.01	2.6641	0.70	0.10	Algol	1	1	4
R CMa	F0V	K1IV	5.70	0.047	0.01	1.1359	0.58	0.08	Algol	1	1	5
Y Cam	A9IV	K1IV	10.54	0.0665	0.04	3.3055	1.70	0.10	Algol	1	2	6, 7
AI Hya	F0	F2	9.90	0.1380	0.02	8.2897	0.56	0.50	F-type	2	1	8
RS Cha	A8IV	A8IV	6.05	0.08	0.01	1.6699	0.62	0.45	A-type	2	1	9
V577 Oph	A?	A?	11.01	0.0695	0.05	6.0791	0.65	0.55	A-type?	1	1	10, 11

For a number of other variables, the interpretation of the (O–C) residuals in terms of binarity is more controversial e.g., for CY Aqr. The (O–C) variations are very complex with interpretations in terms of period jumps (Rodríguez et al. 1995; Breger & Pamyatnykh 1998). However, Zhou & Fu (1998) propose that the period changes of this star are a consequence of a continuously increasing period combined with the light-time effect in a binary system with an orbital period of $P_{\rm orb} = 62$ years. Another controversial example VZ Cnc, where Arellano et al. (1994) indicate binarity as one possibility to explain the remaining residuals in their O–C analysis, while Fu & Jiang (1999b) point out that multiperiodicity with more than two frequencies might be the correct interpretation.

The question of binarity also plays an important role in the asteroseismological interpretation of small-amplitude, nonradially pulsating δ Scuti stars studied through large, multisite campaigns. The main frequencies of the star θ^2 Tau (Breger et al. 1989) with peak-to-peak amplitudes of 3 millimag or more show the (O–C) values between -2 and $+2$ mins predicted from the 141-day orbit. The companion is a less luminous star on the main sequence, also inside the instability strip. The frequency spectrum of θ^2 Tau also includes a number of very small-amplitude modes at values of approximately twice that of the main frequencies. From an asteroseismological point of view, it is important to determine whether these modes originate in the companion or are part of a second excited frequency range of excited modes in the primary star of θ^2 Tau.

2.3. δ Scuti stars in open clusters

δ Scuti-type pulsating stars in open clusters provide to the astronomer an important tool to test stellar structure and evolution theory because the same distance, age, initial chemical abundance and interstellar reddening can be assumed for all the stars in the same cluster. This provides strong constraints on the evolutionary status and the mode identification of the observed frequencies.

Table 4. δ Scuti stars in double or multiple systems from O–C analysis. Sources for $P_{\rm orb}$ are: 1) Fu & Jiang 1996, 2) Moffett et al. 1988, 3) Kiss & Szatmary 1995, 4) Liu et al. 1991, 5) Pocs & Szeidl 2000, 6) Fu & Jiang 1999a

Star	V (mag)	P_{pul} (d)	ΔV (mag)	P_{orb} (years)	Source
AD CMi	9.39	0.1230	0.30	30.0	1
SZ Lyn	9.44	0.1205	0.51	3.1	2
BE Lyn	8.82	0.0959	0.39	6.4	3
KZ Hya	9.96	0.0595	0.80	9.3	4
DY Her	10.46	0.1486	0.51	43.0	5
BS Aqr	9.40	0.1978	0.44	31.7	6

The classical studies of stars inside bright, nearby clusters using photomultiplier detectors have recently been extended to more clusters by utilizing CCD detectors. Especially for stellar clusters, CCD cameras have important advantages because of the large number of cluster stars which can be monitored simultaneously on the same frame, higher quantum efficiency and the ability to work under nonphotometric weather conditions. Some examples of such successful surveys are the open clusters NGC 7789 (Jahn et al. 1995), NGC 3496 (Balona & Laney 1995), NGC 6134 (Frandsen et al. 1996), NGC 7062, NGC 7245 and NGC 7654 (Viskum et al. 1997), NGC 1817 (Frandsen & Arentoft 1998a) or Melotte 71 (Kim et al. 1999).

A difficulty with statistics of stars in clusters concerns their membership. For the R00 list, the main source of information has been the open clusters catalogue of Mermilliod (1995), although other sources have also been consulted to determine whether or not a particular δ Scuti star is a cluster member. In Table 5, the clusters are listed together with their relevant parameters such as log(age), [Me/H] and E_{B-V}. In addition, the number (N) of δ Scuti variables found to be members of each cluster together with the mean values of the visual magnitude, period,

Table 5. δ Scuti variables in open clusters. N is the number of δ Scuti variables found in each cluster. Sources for log(age), [Me/H] and E_{B-V}: 1) Loktin & Matkin 1994, 2) Twarog et al. 1997, 3) Viskum et al. 1997, 4) Bruntt et al. 1999, 5) Kim et al. 1999, 6) Balona & Laney 1995, 7) Jahn et al. 1995, 8) Mermilliod 1995, 9) Cayrel de Strobel 1990

Cluster	log(age)	[Me/H]	E_{B-V} (mag)	N	$< V >$ (mag)	$< P >$ (d)	$< \Delta V >$ (mag)	$< v \sin i >$ (km s^{-1})	Source
α Persei	7.90	0.06	0.09	3	8.98	0.048	0.013	92	1, 9
Pleiades	7.92	0.03	0.04	5	8.12	0.036	0.013	69	1, 9
Hyades	8.80	0.18	0.01	8	4.81	0.084	0.016	114	1, 2
NGC 1817	8.87	−0.27	0.30	7	13.72	0.049	0.009	-	1, 2
NGC 2264	6.99	−0.15	0.06	2	10.03	0.150	0.040	-	1, 8
Melotte 71	9.0	−0.29	0.20	4	13.61	0.098	0.028	-	5, 8
NGC 2516	7.79	−0.07	0.10	1	10.70	0.060	0.020	-	1
Praesepe	8.84	0.14	0.02	14	7.83	0.070	0.018	139	1, 2
NGC 2682	9.72	0.00	0.07	2	11.60	0.056	0.025	73	1, 2
NGC 3496	8.6	-	0.52	3	13.81	0.178	0.023	-	6
Coma Ber	8.69	−0.03	0.01	2	6.92	0.048	0.013	115	1, 8
NGC 5999	8.60	-	0.45	1	17.71	0.150	0.240	-	8
NGC 6134	8.84	0.28	0.36	7	12.93	0.096	0.014	-	4
NGC 6882	9.16	−0.02	0.08	2	10.36	0.055	0.030	-	8
Melotte 227	8.57	-	0.04	1	8.01	0.055	0.010	-	8
NGC 7062	8.7	-	0.47	1	14.01	0.040	0.010	-	3
NGC 7245	8.5	-	0.40	2	14.80	0.098	0.015	-	3
NGC 7654	8.2	-	0.58	1	14.42	0.278	0.020	-	3
NGC 7789	9.3	−0.26	0.24	1	14.06	0.087	0.030	-	7

visual amplitude and $v \sin i$ are also listed. Altogether, Table 5 lists 67 δ Scuti stars distributed in 19 open clusters. The great majority of these variables lie on the main sequence together with the other cluster stars. Some variables have already evolved off the main sequence, i.e., the variables KW 204, KW 284 and KW 348 in Praesepe (Hernández 1998) and IFA 161 in NGC 6134 (Frandsen et al. 1996; Bruntt et al. 1999). The variables EX Cnc and EW Cnc in NGC 2682 (Gilliland & Brown 1992) and V10 in NGC 7789 (Jahn et al. 1995; Mochejska & Kaluzny 1999) are blue stragglers; the variables W 2 and W 20 in NGC 2264 probably are in a pre-main sequence status (Breger & Pamyatnykh 1998). For V16 in NGC 1817 (Frandsen & Arentoft 1998a) the location in the H–R diagram is uncertain, but the star may be a nonmember.

As it can be seen from Table 5, the δ Scuti variables in open clusters tend to show short periods and very low amplitudes. One exception from the low amplitudes exists: the variable V32 in NGC 5999 (Pietrzynski et al. 1998) shows $\Delta V = 0\overset{\mathrm{m}}{.}24$, but its membership is not fully confirmed. If the membership is confirmed, then the star promises to be a very interesting object of study. A few clusters contain δ Scuti variables with periods longer than $0\overset{\mathrm{d}}{.}1$ (NGC 2264, NGC 5999, NGC 3496, NGC 7654). Special attention is drawn from the variable V10 in NGC 7654 (Viskum et al. 1997; Choi et al. 1999). This variable seems to be a member of the cluster on the main sequence, but shows a very long period ($0\overset{\mathrm{d}}{.}278$), typical of an evolved star. If it is a pulsating star, then g-modes are present.

Values of the projected rotational velocities, $v \sin i$, are available for the δ Scuti variables in only 6 clusters (in which all the δ Scuti pulsators have available $v \sin i$ values). These rotational velocities are not unusual: inside the same cluster, the δ Scuti variables present a very wide range of $v \sin i$ values, e.g., in Pleiades, $v \sin i =$ 10 km s^{-1} for TR 390 and 175 for TR 410; in Hyades, the range of values is also very wide, from 30 to 205 km s^{-1} for 60 Tau and 69 Tau, respectively; in α Persei, the $v \sin i$ values are between 50 km s^{-1} for H 606 to 150 km s^{-1} for H 906; in Praesepe, the majority of the δ Scuti stars present values higher than 100 km s^{-1} (the greatest is 200 km s^{-1} for KW 207), but a very low value of $v \sin i = 30$ km s^{-1} corresponds to KW 284.

As it can also be seen from Table 5, the open clusters in which a larger number of δ Scuti variables have been found are Praesepe (14), Hyades (8), NGC 1817 (7) and NGC 6134 (7). The two first clusters are bright and were investigated during the decade of the seventies using single-channel photometers while the two latter clusters are much fainter and the corresponding surveys have been carried out recently (Frandsen et al. 1996; Frandsen & Arentoft 1998a) using CCD cameras. All the four clusters have similar ages, about log(age) $\sim$ 8.8–8.9. There does exist a detection bias in favor of a certain age range slightly below 1 Gyr: this corresponds to open clusters in

Table 6. Open clusters where surveys for δ Scuti variables have been unsuccessful. N is the number of stars observed in each cluster. Sources: 1) Pietrzynski 1996a, 2) Pietrzynski 1996b, 3) Balona & Laney 1995, 4) Martín et al. 2000, 5) Viskum et al. 1997, 6) Loktin & Matkin 1994

Cluster	N	Survey	Source (1)	log(age)	Source (2)
NGC 654	-	CCD	1	7.08	6
NGC 663	-	CCD	2	7.13	6
Melotte 105	∼20	CCD	3	8.4	3
IC 4665	∼6	*uvby*	4	7.58	6
IC 4756	∼11	*uvby*	4	8.78	6
NGC 6633	∼14	*uvby*	4	8.66	6
NGC 7092	∼10	*uvby*	4	8.61	6
NGC 7226	∼68	CCD	5	8.7	5

which the isochrone turns upwards near the hot border of the instability strip and almost follows the instability strip. Younger clusters only contain main-sequence stars inside the instability strip, which leads to a lower detection probability because of the very small amplitudes of the unevolved stars. Considerably older clusters, on the other hand, no longer contain stars inside the classical instability strip (except possibly for blue stragglers or post-main-sequence objects). Frandsen & Arentoft (1998b) give a list of open clusters suitable for CCD-camera variability surveys of δ Scuti variables.

Table 6 lists some open clusters in which variability surveys for δ Scuti variables have not been successful in discovering these variables. N refers to the number of cluster stars located inside the instability strip which have been monitored for variability. Column 3 indicates the type of photometry carried out: CCD or simultaneous *uvby* photometry with photomultiplier detectors. In fact, in NGC 7226, 68 potential δ Scuti pulsators have been monitored (Viskum et al. 1997; log(age) = 8.7), but none of them has been found to be variable. While the interpretation can be argued to be uncertain for individual stars (e.g., contamination of the sample by less reddened field stars outside the instability strip), the large number of nonvariable stars indicates that a presently unknown physical parameter causes the lack of pulsation in these stars. Follow-up studies of this interesting cluster seem warranted.

3. The position of δ Scuti stars in the Hertzsprung-Russell (H–R) diagram

In this section we will discuss the location of the δ Scuti variables listed in the R00 catalogue in the H–R diagram on the basis of their $uvby\beta$ Strömgren–Crawford photometry and parallaxes determined by the Hipparcos satellite. The two sources of absolute magnitudes allow us to compare the photometric and parallax methods and to examine possible systematic errors in the photometric calibrations used, especially for metallic-line stars. The dereddened $uvby\beta$ indices and photometric absolute magnitudes (M_v(ph)) were calculated in the same way as in Rodríguez et al. (1994), following the method described in Philip et al. (1976) and using the reference lines of Philip & Egret (1980). The typical uncertainty for the derived M_v(ph) is about $0\overset{\mathrm{m}}{.}3$. For stars with available Hipparcos parallaxes, we have also calculated absolute magnitudes ($M_v(\pi)$) by using $M_v(\pi) = V{+}5 + 5\log\pi$ (π in arcsec). Here, the error bars are determined from $\sigma_{M_v(\pi)} = 2.171 s_\pi$ where $s_\pi = \sigma_\pi/\pi$. Since the apparent magnitude (but not the Hipparcos parallax) is affected by interstellar reddening, we have applied a reddening correction determined from $uvby\beta$ photometry by using the standard relation $V_0 = V - 4.3E_{b-y}$ (Crawford & Mandwewala 1976). Additionally, when the components of a binary system are resolved in the bibliography (mainly the Hipparcos catalogue (ESA 1997)), corresponding corrections were applied.

We also have restricted the Hipparcos parallaxes to those stars with the Hipparcos parallax uncertainty ≤ 0.20 of the parallax value, $s_\pi \leq 0.20$. This criterion corresponds to $\sigma_{M_v(\pi)} \leq 0\overset{\mathrm{m}}{.}43$. Note this criterion also eliminates the uncertain parallax of AD CMi, which made the star appear to lie below the main sequence (Høg & Petersen 1997; Antonello & Mantegazza 1997; Petersen & Høg 1998).

There are three stars which we have omitted because of the very uncertain photometry and nature of variability: HD 60987, HD 193084 and 2362-16[1].

[1] HD 60987 ($P = 0\overset{\mathrm{d}}{.}1374$, $V = 7\overset{\mathrm{m}}{.}78$, $\Delta V = 0\overset{\mathrm{m}}{.}06$): this star seems to be too cool for a δ Scuti-type pulsator ($b-y = 0\overset{\mathrm{m}}{.}299$, $B-V = 0\overset{\mathrm{m}}{.}48$ and $\beta = 2\overset{\mathrm{m}}{.}640$). This leads to a null reddening with $(b-y)_0 = 0\overset{\mathrm{m}}{.}299$ and $M_v(\mathrm{ph}) = 3\overset{\mathrm{m}}{.}16$, far away from the red border of the δ Scuti instability region. Additionally, we find a $M_v(\pi)$ value of $2\overset{\mathrm{m}}{.}46(\pm 0.45)$ from its parallax. This star was discovered as variable by the Hipparcos satellite (ESA 1997) but no type of variability was assigned. According the the Hipparcos catalogue, it is a binary system with a separation between both (A and B) components of $0\farcs3$ and $\Delta H_{\mathrm{p}} = 1\overset{\mathrm{m}}{.}40$. Later, Kazarovets et al. (1999) proposed this star a DSCTC: and suggested that the pulsations come from the fainter (B) component. However, the Tycho colour indices $B_{\mathrm{T}} - V_{\mathrm{T}} = 0\overset{\mathrm{m}}{.}42$ and $0\overset{\mathrm{m}}{.}43$ for the A and B components, respectively, do not support this suggestion. We are probably dealing with a W UMa system with a period of $0\overset{\mathrm{d}}{.}275$, not with a δ Scuti pulsator.

HD 193084 ($P = 0\overset{\mathrm{d}}{.}056$, $V = 7\overset{\mathrm{m}}{.}61$, $\Delta V = 0\overset{\mathrm{m}}{.}02$): this star was discovered as a multiperiodic variable by Paunzen (1997) on three nights of good quality observations, however its spectral type (B8V from Houk 1982) places this star too hot to be a δ Scuti-type pulsator. The Johnson colour index $B-V = -0\overset{\mathrm{m}}{.}08$ (ESA 1997) and the Strömgren colours of $b-y = -0\overset{\mathrm{m}}{.}029$ and $\beta = 2\overset{\mathrm{m}}{.}764$ (Handler 1999b) agree very well with its spectral type, leading to the following values (dereddened as a B-type star) of $E_{b-y} = -0\overset{\mathrm{m}}{.}033$, $(b-y)_0 = -0\overset{\mathrm{m}}{.}062$ and $M_v(\mathrm{ph}) = 0\overset{\mathrm{m}}{.}44$. Moreover, from its parallax, we obtain $M_v(\pi) = 0\overset{\mathrm{m}}{.}16(\pm 0.60)$. Hence, this star seems to be too hot for a δ Scuti pulsator, but to cool for a β Cep variable. On the other hand, this star is not catalogued as binary system in

Before the position of all the δ Scuti stars in the catalogue can be correctly placed in the H–R diagram, several subgroups need to be investigated in more detail.

3.1. λ Boo, ρ Pup, δ Del and classical Am variables

These four classes of stars are spectroscopically defined subclasses with surface abundance anomalies. Although the stars ρ Pup, δ Del are also pulsators, the groups named after these stars should not be regarded as pulsation subclasses of δ Scuti stars. The abundance anomalies in these stars affect the pulsation properties, e.g., the classical Am stars are constant in light or show only small pulsation amplitudes (e.g., HD 1097, Kurtz 1989).

These four groups are only a small selection from the bewildering zoo of stars with unusual surface abundances in this temperature region (e.g., see Kurtz 2000) and represent the groups with δ Scuti pulsation.

λ Boo stars are metal-poor Pop. I objects with spectral types from late-B to mid-F. Details on the abundances of the different elements can be found in Heiter (2000). These stars cover the whole main-sequence range between the zero-age and the terminal-age main sequence. Both the λ Boo and SX Phe stars (see below) show metal-poor spectra and positive δm_1 indices in the $uvby\beta$ system. This can make it difficult to classify field stars correctly if detailed spectroscopic or space velocity information are not available. The status of BS Tuc (HD 6870) is now clear: it is not an SX Phe variable, but a strong λ Boo star (hF0A1V, Paunzen 2000).

The classical Am stars, which are on the main sequence, have their evolved counterparts: the evolved Am, ρ Pup and δ Del stars. Gray & Garrison (1989) make a valiant attempt to provide a refined classification scheme for these stars (e.g., they propose to abolish the δ Del designation in favor of spectroscopically more meaningful subgroups). A possible reason for the present confusion may be our present lack of physical understanding of these phenomena. Consequently, here we combine all these groups together (albeit in an oversimplified manner) as classical and evolved Am stars.

Both the λ Boo stars and the SX Phe variables show metal-poor spectra and positive δm_1 indices in the $uvby$ system. This can make it difficult to classify field stars correctly if detailed spectroscopic or space velocity information is not available. The status of BS Tuc (HD 6870) is now clear: it is not an SX Phe variable, but a strong λ Boo star (hF0A1V, Paunzen 2000).

Table 7 lists the λ Boo stars in the R00 catalogue. Only the star 29 Cyg have CCDM number, but it is not resolved by the Hipparcos catalogue (ESA 1997). Hence, no corrections due to binarity is made for any λ Boo star. Inspection of the table shows the good agreement between the photometric and Hipparcos absolute magnitudes for λ Boo stars. The position in the H–R diagram of the pulsating λ Boo stars from the catalogue is shown in Fig. 5.

We now turn to the more difficult question of the classical and evolved (ρ Pup and δ Del) metallic-line A stars, which are listed in Table 8. Five of these stars have CCDM numbers (CP Oct, ρ Pup, V527 Car, XZ Men and V1004 Ori), but corrections are available for only V527 Car ($0\overset{\mathrm{m}}{.}09$) and XZ Men ($0\overset{\mathrm{m}}{.}74$). The Hipparcos parallaxes for both stars were too uncertain to be used (see Table 8), so that no corrections due to binarity were applied to the listed $M_v(\pi)$ values.

Since metallic-line A stars were chosen, it is not surprising that the δm_1 index usually has a negative value. However, the value of $+0\overset{\mathrm{m}}{.}040$ for V527 Car, at first sight, appears incompatible with the classification of A3m/A7/A9. However, the δm_1 index is an unreliable indicator of metallicity for evolved stars and should only be used with caution. Furthermore, the group of evolved Am stars in the table contains some stars with abnormal element abundances, which include both overabundances as well as underabundances of different elements (e.g., the star δ Del itself).

Table 8 clearly shows that for the group of classical and evolved metallic-line A stars, the photometrically calculated absolute magnitudes are seriously and systematically in error. In all cases, the photometry underestimates the luminosity (i.e., the Balmer jump is too small) with the error ranging from $0\overset{\mathrm{m}}{.}4$ to $3\overset{\mathrm{m}}{.}0$. A median value of $0\overset{\mathrm{m}}{.}75$ is found for the stars in Table 8. Further evidence of this problem (and a confirmation of the correctness of the Hipparcos absolute magnitudes) is provided by the length of the pulsation periods: the period of $0\overset{\mathrm{d}}{.}12$ for CC Oct is compatible only with the Hipparcos parallax.

We conclude that the photometric absolute magnitude calibrations of the $uvby\beta$ system are not applicable to the group of classical and evolved metallic-line A stars. These will not be used to determine the location of these stars in the H–R diagram. The middle panel of Fig. 5 shows the position of the pulsating evolved metallic-line A stars in the H–R diagram. Note that the interesting classical Am star HD 1097 could not be plotted because of insufficient accuracy of the Hipparcos parallax.

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the bibliography. One possibility, as pointed out by Paunzen (1997), is that HD 193084 is an unrecognized spectroscopic binary with a pulsating A-type component.

2362-16 ($P = 0\overset{\mathrm{d}}{.}060$, $V = 10\overset{\mathrm{m}}{.}56$, $\Delta V = 0\overset{\mathrm{m}}{.}02$): was discovered as variable by Balona & Laney (1996). It is the object number 16 in their study of the young open cluster NGC 2362. This star does not belong to the AF group because its $b-y = 0\overset{\mathrm{m}}{.}060$ and $\beta = 2\overset{\mathrm{m}}{.}787$ values are not consistent with each other. Moreover, the corresponding absolute magnitude $M_v(\mathrm{ph}) = 3\overset{\mathrm{m}}{.}24$ is too low. If this star belongs to the B-group, the derived values of $(b-y)_0 = -0.051$ and $M_v(\mathrm{ph}) = 0\overset{\mathrm{m}}{.}55$ locate this variable in a similar position as HD 193084 which is too hot to be a δ Scuti-type pulsator. The third possibility is to assume this star as a member of the photometric A-intermediate group, for which different photometric calibrations apply. In this case the derived values are $(b-y)_0 = 0\overset{\mathrm{m}}{.}047$ and $M_v(\mathrm{ph}) = 1\overset{\mathrm{m}}{.}24$ and the star lies only slightly outside the blue edge of the instability strip. Consequently, the variable is not a member of NGC 2362 as it was pointed out by Balona & Laney (1996).

Table 7. λ Boo variables

Variable	HD	P (d)	V (mag)	ΔV (mag)	E_{b-y} (mag)	$(b-y)_0$ (mag)	δm_1 (mag)	M_v(ph) (mag)	π (mas)	s_π	$M_v(\pi)$ (mag)
BS Tuc	6870	0.065	7.49	0.02	0.000	0.170	0.060	1.97	10.30(±0.61)	0.06	2.55(±0.13)
BD Phe	11413	0.0373	5.94	0.03	0.003	0.102	0.060	1.45	13.37(±0.64)	0.05	1.56(±0.10)
EX Eri	30422	0.021	6.18	0.01	0.000	0.101	0.022	2.26	17.40(±0.68)	0.04	2.38(±0.08)
	64491	0.049	6.23	0.007	0.000	0.195	0.049	2.69	16.55(±0.92)	0.06	2.32(±0.12)
HZ Vel	75654	0.087	6.38	0.01	0.000	0.161	0.046	1.80	12.82(±0.58)	0.05	1.92(±0.10)
AK Ant	83041	0.066	8.80	0.005	0.010	0.220	0.066	1.59	4.48(±1.07)	0.24	
	84948B	0.078	8.14	0.01	0.000	0.196	0.036	1.27	4.97(±1.14)	0.23	
	102541	0.050	7.94	0.02	0.021	0.142	0.055	2.47	8.03(±1.00)	0.12	2.37(±0.27)
	105058	0.040	8.89	0.002					5.32(±1.04)	0.20	2.52(±0.42)
II Vir	105759	0.0423	6.52	0.05	0.000	0.142	0.053	1.62	9.05(±0.92)	0.10	1.30(±0.22)
	109738	0.033	8.28	0.02	0.011	0.154	0.062	1.78			
MO Hya	111786	0.0322	6.14	0.02	0.003	0.159	0.062	2.20	16.62(±0.72)	0.04	2.23(±0.09)
	120500	0.049	6.60	0.009	0.009	0.059	0.033	1.18	6.97(±0.90)	0.13	0.78(±0.28)
λ Boo	125162	0.023	4.18	0.002	0.007	0.044	0.020	1.75	33.58(±0.61)	0.02	1.78(±0.04)
HR Lib	142703	0.060	6.11	0.01	0.000	0.182	0.065	2.30	18.89(±0.78)	0.04	2.49(±0.09)
IN Lup	142994	0.127	7.18	0.05	0.003	0.196	0.056	0.93			
V346 Pav	168740	0.036	6.13	0.01	0.001	0.135	0.064	1.88	14.03(±0.69)	0.05	1.87(±0.11)
V704 CrA	168947	0.058	8.12	0.02	0.028	0.144	0.064	1.42			
V1431 Aql	183324	0.021	5.79	0.004	0.004	0.047	0.037	1.73	16.95(±0.87)	0.05	1.92(±0.11)
	191850	0.074	9.62	0.03							
29 Cyg	192640	0.0267	4.93	0.02	0.000	0.099	0.049	1.80	24.37(±0.55)	0.02	1.86(±0.05)
	210111	0.036	6.37	0.02	0.000	0.136	0.046	1.73	12.70(±0.89)	0.07	1.89(±0.15)
V340 And	221756	0.044	5.55	0.005	0.004	0.052	0.040	1.13	13.97(±0.63)	0.05	1.26(±0.10)

3.2. Field SX Phe variables

The SX Phe variables are the δ Scuti stars of Pop. II and old disk population. Since such old stars at ~8500 K should have already evolved away and no longer exist in this part of the Hertzsprung–Russell diagram, they are also unusual from an evolutionary point of view. They probably are in a post-giant branch stage of evolution and may be merged binary stars. This would also explain the position of these stars on or near the main sequence. Verification of the existence of SX Phe stars as a group with an evolutionary history different from that of the normal Pop. I δ Scuti star comes from the discoveries of SX Phe stars in globular clusters such as ω Cen, M 3 and M 55. The recent paper by Rodríguez & López-González (2000) discusses these SX Phe stars in globular clusters in detail so that the much smaller sample of SX Phe field stars does not reveal much additional astrophysical information.

Table 9 lists the known field SX Phe stars. The absolute magnitudes were calculated from the calibrations of $uvby\beta$ photometry as well as Hipparcos parallaxes. The table also shows that only one SX Phe field star (SX Phe itself) has an accurate Hipparcos parallax with $s_\pi < 0.2$. For SX Phe, the photometric and Hipparcos absolute magnitudes differ by $0\overset{\mathrm{m}}{.}8$: this may be caused by systematic errors in applying the Pop. I calibrations to this extremely metal-poor star. Such an uncertainty in the photometric absolute magnitudes, though of smaller size, may also apply to the other stars in the table.

The first 7 stars in Table 9 were already classified as field SX Phe variables in the R94 catalogue. The other 6 stars (V879 Her, V2314 Oph, BQ Ind, PL 43, BQ Psc and 29499-057) are new and were discovered by Wetterer et al. (1996), Martín & Rodríguez (1995), Hipparcos catalogue (ESA, 1997), Preston & Landolt (1998), Bernstein et al. (1995) and Preston & Landolt (1999), respectively. The position of the field SX Phe stars is also shown in Fig. 5, which reveals the preference of these stars for the cooler half of the instability strip, similar to that shown in globular clusters (Rodríguez & López-González 2000).

3.3. Comparison of Hipparcos with photometric absolute magnitudes

In Fig. 6, we compare the results obtained for M_v(ph) and $M_v(\pi)$ for the δ Scuti variables listed in the R00 catalogue with both $uvby\beta$ photometry and parallax available. Stars with less accurate Hipparcos parallaxes of $s_\pi > 0.20$ were omitted.

Table 8. Classical and evolved Am variables

Variable	HD	P (d)	V (mag)	ΔV (mag)	E_{b-y} (mag)	$(b-y)_0$ (mag)	δm_1 (mag)	M_v(ph) (mag)	π (mas)	s_π	$M_v(\pi)$ (mag)
CP Oct	21190	0.1498	7.61	0.05	0.003	0.229	−0.042	1.42	4.16(±0.63)	0.15	0.70(±0.33)
UY Col	40765	0.1696	9.58	0.14	0.052	0.219	−0.076	2.90			
ρ Pup	67523	0.1409	2.83	0.09	0.040	0.220	−0.049	2.02	51.99(±0.66)	0.01	1.24(±0.03)
V527 Car	95321	0.2137	9.00	0.06	0.005	0.120	0.040	0.39	1.01(±1.38)	1.37	
V388 Pav	199434	0.1583	8.75	0.05	0.035	0.247	−0.054	2.15	3.65(±1.09)	0.30	
UZ Ret	26892	0.1228	9.22	0.05	0.026	0.225	−0.061	2.37	2.48(±0.73)	0.29	
XZ Men	31908	0.1083	7.85	0.03	0.050	0.162	−0.021	1.63	2.14(±1.55)	0.72	
V356 Aur	37819	0.1893	8.07	0.08	0.108	0.266	−0.095	2.02			
V1004 Ori	40372	0.061	5.89	0.02	0.000	0.122	−0.007	1.32	9.24(±0.97)	0.10	0.72(±0.23)
V383 Car	52788	0.12	8.39	0.04	0.035	0.207	−0.029	1.47	3.46(±0.62)	0.18	0.94(±0.39)
BO Cir	129494	0.1412	9.73	0.01	0.100	0.219	−0.068	2.69			
CC Oct	188136	0.1249	8.01	0.06	0.007	0.265	−0.182	4.62	5.29(±0.87)	0.16	1.60(±0.36)
ρ Pav	195961	0.1141	4.86	0.03	0.021	0.232	−0.091	2.52	16.73(±0.64)	0.04	0.89(±0.08)
δ Del	197461	0.1568	4.43	0.07	0.004	0.187	0.018	1.31	16.03(±0.68)	0.04	0.43(±0.09)
EW Aqr	201707	0.0966	6.47	0.04	0.009	0.168	0.000	1.17	7.43(±0.93)	0.13	0.78(±0.27)
AU Scl	1097	0.0564	9.09	0.01	0.000	0.239	−0.148	4.20	4.90(±1.41)	0.29	

Table 9. Field SX Phe variables

Variable	HD	P (d)	V (mag)	ΔV (mag)	E_{b-y} (mag)	$(b-y)_0$ (mag)	δm_1 (mag)	M_v(ph) (mag)	π (mas)	s_π	$M_v(\pi)$ (mag)
BL Cam		0.0391	13.10	0.33	0.211	0.149	0.098	2.00			
KZ Hya	94033	0.0595	9.96	0.80	0.039	0.180	0.082	2.29			
SU Crt	100363	0.055	8.65	0.01	0.013	0.185	0.033	2.42	3.94(±1.27)	0.32	
XX Cyg		0.1349	11.87	0.80	0.065	0.156	0.056	1.31	1.48(±2.00)	1.35	
CY Aqr		0.0610	10.93	0.71	0.036	0.164	0.053	1.83	0.71(±2.28)	3.21	
DY Peg	218549	0.0729	10.36	0.54	0.055	0.155	0.048	1.78	0.36(±2.02)	5.61	
SX Phe	223065	0.0550	7.28	0.41	0.000	0.151	0.063	2.07	12.91(±0.78)	0.06	2.83(±0.12)
V879 Her		0.0569	15.65	0.65							
V2314 Oph	161223	0.144	7.43	0.05	0.093	0.147	0.059	0.97			
BQ Ind	198830	0.0820	9.87	0.25					−0.10(±1.54)		
PL 43		0.0374	13.51	0.10							
BQ Psc		0.0608	18.35	0.57							
29499-057		0.0417	13.8	0.04							

The agreement between the Hippacos and photometric absolute magnitudes is not satisfactory: the Hipparcos parallaxes indicate, on the average, higher luminosities of $\sim 0\overset{m}{.}4$. Figure 7 shows that the deviations originate in stars with low rotational velocities and/or high metallicities (low δm_1 indices). (Note that metallic-line stars are usually slow rotators so that it is not easy to separate the two effects. Since the Hipparcos parallaxes should not be effected by these stellar properties, the photometric luminosity calibrations must be in error for these stars.

The deviations of the photometric absolute magnitudes found by us for δ Scuti stars have been noticed before in late A/early F stars. Guthrie (1987) already proposed a correction based on δm_1. However, Domingo & Figueras (1999) have shown that the Guthrie correction is not appropriate since it leads to systematic errors for the normal A stars for which the classical Crawford calibrations (as used by us) are quite satisfactory. In their comparison of the Hipparcos and photometric absolute magnitudes, Domingo & Figueras (1999) also noticed the rotational velocity and δm_1 correlations in the differences of the Hipparcos and photometric absolute magnitudes. Considerable work is still required to improve the photometric absolute magnitude calibrations and include the effects of rotational velocity, metallicity and to provide a more accurately determined ZAMS relation.

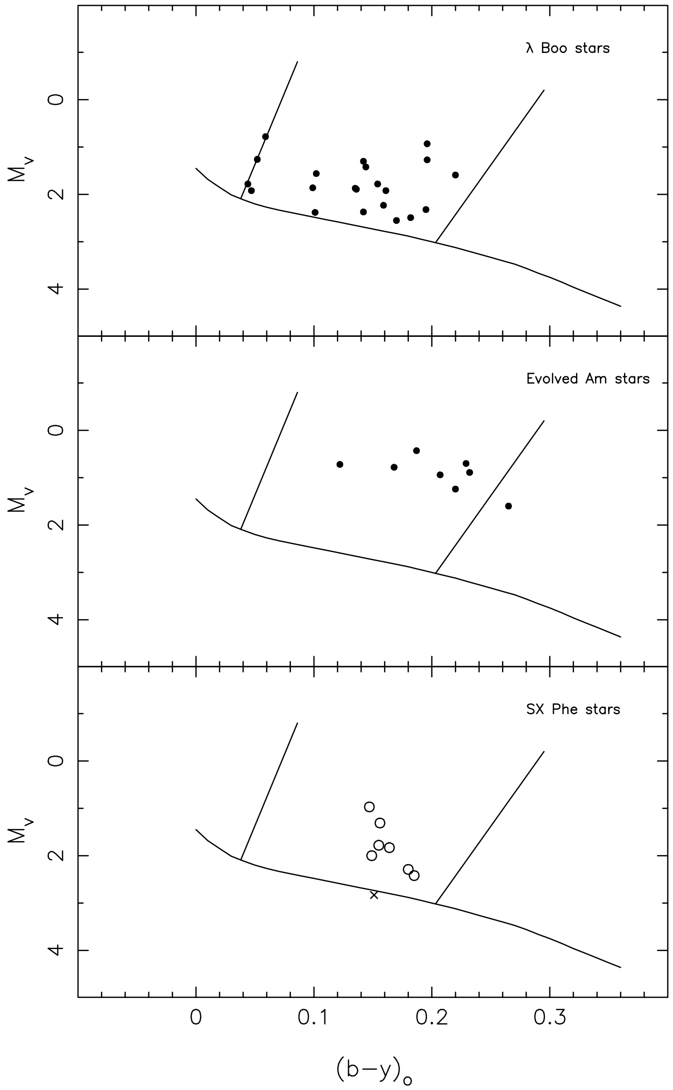

Fig. 5. Position of δ Scuti subgroups in the H–R diagram. The drawn borders of the instability strip are determined in a later section. For the stars with a λ Boo spectral classification, absolute magnitudes were mostly calculated from the available accurate Hipparcos parallaxes. For the evolved Am (ρ Pup and δ Del) stars only Hipparcos parallaxes were used (see text). For field SX Phe stars most absolute magnitudes were photometrically determined (open circles), while for SX Phe itself an accurate Hipparcos parallax is used (cross)

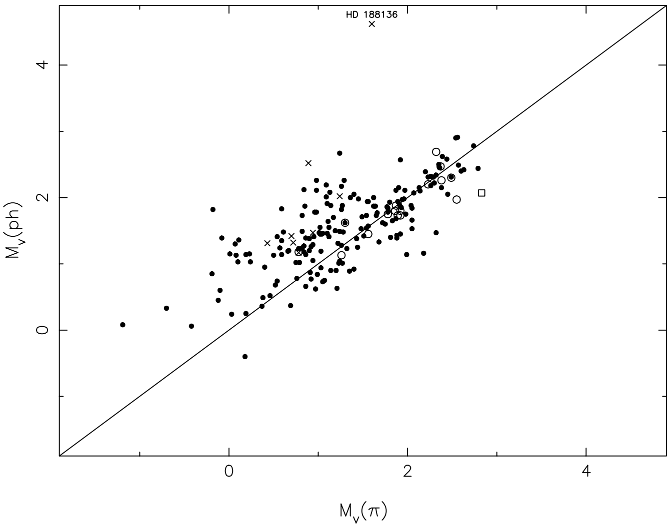

Fig. 6. Comparison between absolute magnitudes of δ Scuti stars derived from photometric indices, M_v(ph), and those from Hipparcos satellite parallaxes, $M_v(\pi)$. Less accurate Hipparcos parallaxes with $s_\pi > 0.20$ were omitted. Some subgroups are marked with special symbols: λ Boo stars (open circles), evolved Am stars (crosses), field SX Phe stars (open squares)

The situation may be summarized as follows: for δ Scuti stars with normal metals and rotational velocities of 100 km s^{-1} the photometric calibrations are in agreement with the Hipparcos parallaxes. For the other stars, systematic corrections need to be applied to the photometrically derived values of M_v, but the size of these corrections still needs to be determined.

3.4. The composite H–R diagram

In the previous section, we have compared the results of Hipparcos parallaxes with the absolute magnitudes determined from *uvbyβ* photometry. We have isolated one subgroup for which the calibrations of the *uvbyβ* system are not applicable, viz., the group of evolved and classical metallic-line A stars. For these stars, the photometric calibrations are not used in this section. We can now examine the location of the δ Scuti stars in the H–R diagram, using both these methods. The following procedure was adopted:

(i) the colors were determined from the *uvbyβ* photometry. All the stars were dereddened following the method for AF stars described in Philip et al. (1976). A few hot stars can also be dereddened as A-intermediate stars, but the results are very similar;

(ii) for those stars with accurate Hipparcos parallaxes (uncertainties $< 0\overset{\mathrm{m}}{.}20$), only the Hipparcos absolute magnitudes were used, after correcting the apparent magnitude, V, of the reddened stars for interstellar extinction (determined in (i));

(iii) for those stars with Hipparcos parallaxes with uncertainties in the absolute magnitudes between $0\overset{\mathrm{m}}{.}20$ and $0\overset{\mathrm{m}}{.}43$ (our previous limit), an average absolute magnitude was calculated with weighting according to the square of the standard deviation, which was assumed to $0\overset{\mathrm{m}}{.}3$ for the photometric absolute magnitudes;

(iv) for those stars with no (or very uncertain) Hipparcos parallaxes, only the absolute magnitude calibrations of the *uvbyβ* system were used.

Note that our approach omits a few stars with poor absolute magnitude determinations. An example is the evolved metallic-line star, V527 Car, for which both the Hipparcos and photometric absolute magnitudes are extremely unreliable.

Figure 8 shows the location of the δ Scuti variables in the H–R diagram. Stars situated outside the instability

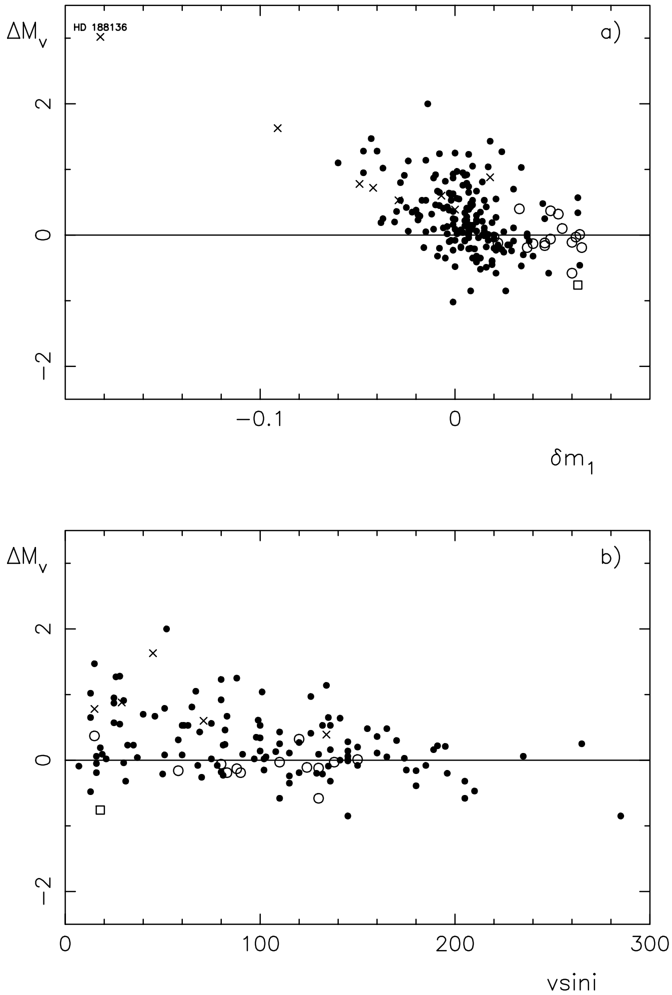

Fig. 7. The dependence of $\Delta M_v = M_v(\mathrm{ph}) - M_v(\pi)$ on: **a)** the metallicity index δm_1 and **b)** the measured rotational velocity, v sin i. The symbols and selection of stars are the same as in Fig. 6

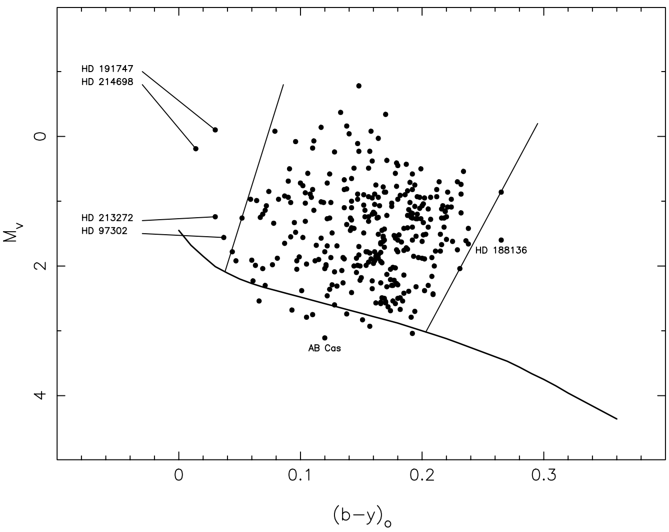

Fig. 8. Location of 318 δ Scuti variables in the H–R diagram. The borders of the instability strip were drawn to include all stars after considering the observational uncertainty of $\sim 0\overset{\mathrm{m}}{.}01$ in the color of each star. Stars situated outside the instability strip borders have been marked with their names and the reasons for their unusual positions are discussed in the text

strip borders have been marked with their names and are discussed below:

(i) AB Cas: this star appears to lie a magnitude below the ZAMS, but the location is unreliable. The star is an Algol-type binary system where the primary component is a δ Scuti variable. A temperature of $T_{\mathrm{e}} = 8000$ K and $M_{\mathrm{bol}} = 2\overset{\mathrm{m}}{.}2$ was derived by Rodríguez et al. (1998) for the δ Scuti component, placing the star inside the δ Scuti region;

(ii) The four hottest stars δ Scuti stars (HD 191747, HD 214698, HD 213272 and HD 97302) were already discussed by Rodríguez et al. (1994). In all these four cases, very small variations have been claimed to be present ($\Delta V < 0\overset{\mathrm{m}}{.}01$, from peak to peak). However, new observations of HD 191747 (Rolland et al. 2000) and HD 213272 (Handler 1995) have not confirmed the variability. More high-quality observations are needed to check whether or not these stars are indeed δ Scuti stars;

(iii) The evolved Am variable, HD 188136 (=CC Oct) shows the most extreme overabundances of all the stars in our sample. Consequently, it is to be expected that the photometric indices are unusual and that the observed color is too red for the stellar temperature.

4. Longer-period δ Scuti and γ Dor variables

In this section we will discuss the current status of some interesting groups of peculiar and/or related δ Scuti variables in order to clarify their situation, connection with the δ Scuti-type pulsators and inclusion in the R00 catalogue.

4.1. γ Dor-type variables

During the last few years, a number of long period variables are being discovered on or beyond the cool border of the instability strip intersects with the main sequence. They are called γ Dor variables and their periods are too long as compared with the corresponding ones for δ Scuti variables. These stars are typically early F-type stars of luminosity class V or IV, displaying low visual amplitudes of a few hundredths of a magnitude and periods ranging from $0\overset{\mathrm{d}}{.}3$ to $2\overset{\mathrm{d}}{.}$. If one considers the mean densities of these stars, the corresponding pulsation modes must be nonradial gravity modes of high order. Moreover, the radial velocity curves are nearly in phase with the corresponding light curves, quite different to that occurring in δ Scuti variables (Garrido 2000). Some γ Dor stars coexist with the δ Scuti variables inside the instability strip, but the majority are located outside the cool border. Since Krisciunas (1993) proposed these variables as a new group of pulsating variables, a great effort has been made to confirm the pulsational nature of these variables and to add new members to the sample. The pulsational nature seems to be well established from observed multiperiodicity and interactions between frequencies in some well studied objects. However, the precise mechanism producing the pulsations is still subject of study.

The relatively long periods and very low amplitudes make the observational detection very difficult. The majority of the γ Dor stars have been discovered by accident. Some were used as comparison stars for differential photometry of previously known δ Scuti variables, e.g., HD 108100 (Breger et al. 1997). The connection between γ Dor and δ Scuti variables has been the subject of several investigations, e.g., Breger & Beichbuchner (1996). Multisite coordinated campaigns of observation have also been carried out for some of these objects, e.g. γ Dor (Balona et al. 1994, 1996), 9 Aur (Zerbi et al. 1997a), HD 108100 (Breger et al. 1997), HR 2740 (Poretti et al. 1997), HD 164615 (Zerbi et al. 1997b), HR 8799 (Zerbi et al. 1999), HD 62454 and HD 68192 (Kaye et al. 1999b). Systematic observations in open clusters have also been recently carried out, e.g., NGC 2516 (Zerbi et al. 1998), Hyades (Krisciunas et al. 1995; Martín et al. 2000), M 34 (Krisciunas & Crowe 1997; Krisciunas & Patten 1999), Pleiades (Martín & Rodríguez 2000), NGC 2301 (Kim et al. 2000).

Lists of bona fide members and candidates are available in the literature (Krisciunas & Handler 1995; Handler & Krisciunas 1997). We caution that some of the variables are still uncertain. The last revised list of γ Dor-type variables (Kaye et al. 1999a) contains only 13 objects, and one of them (HD 152569) was later reclassified as a δ Scuti variable (Kaye et al. 2000). This star was, therefore, included into the R00 catalogue. One very interesting object is HR 8799 which seems to link three astrophysically interesting classes of stars: γ Dor, λ Boo and Vega-like stars (Gray & Kaye 1999). Six new γ Dor variables, discovered from systematic observations in open clusters, have been added to this list (Martín et al. 2000). Five of them are members of open clusters. Altogether, more than 100 candidates have been proposed as likely γ Dor variables. Most of these were studied through the Hipparcos mission (Aerts et al. 1998; Handler 1999a). Further studies of these interesting candidates are necessary in order to confirm their γ Dor-type nature.

Studies of these variables in open clusters can give us some insight about the constraints of the incidence of γ Dor pulsation. Age was proposed by Krisciunas et al. (1995) as an important parameter in the sense that pulsation would only be excited in young open clusters. Handler (1999a) found that the γ Dor stars to be slightly deficient in metal abundances. In an unpublished study, one of the authors (ER) finds a correlation between the Strömgren δm_1 colour index and temperature, in the sense that δm_1 tends to be positive (that is, deficient in metallicity) for the hotter stars and δm_1 is decreasing as the temperature decreases. For the coolest stars this leads to δm_1 equal to zero ([Me/H] = 0.12, Nissen 1988). Hence, the metal abundance, rather than age, seems to be a good parameter to characterize these stars. This also explains why the surveys have been unsuccessful in the Hyades cluster ([Me/H] = 0.18, Table 5). This conclusion is also in good agreement with the results obtained by Martín et al. (2000) from systematic surveys in several open clusters. Thus, the clue to find new γ Dor variables seems to be to observe open clusters with [Me/H] $\lesssim 0.10$ and a lot of main-sequence stars in the region of interest. If we are dealing with field stars, a good rule would be to observe in this region AF stars (that is, $2\overset{\text{m}}{.}70 \lesssim \beta \lesssim 2\overset{\text{m}}{.}76$ and $\delta c_1 \lesssim 0\overset{\text{m}}{.}1$) being slightly deficient in metal abundances (that is, $0\overset{\text{m}}{.}00 \lesssim \delta m_1 \lesssim 0\overset{\text{m}}{.}04$).

4.2. Pre-main sequence δ Scuti variables

During the pre-main-sequence (PMS) contraction stage, many stars cross the classical instability strip and δ Scuti-type pulsation can take place. Recently, Marconi & Palla (1998) have calculated the location of the instability strip for PMS stars in the H–R diagram for the first three radial modes. These authors show that, if the mass is larger than 1.5 $M_{\odot}$, the star crosses this region of pulsational instability as a PMS object. However, the typical time spent by a star within the boundaries of the instability strip as PMS star is very small as compared with that spent as a MS star. Hence, the probability of finding one star in this phase of evolution is very small. However, a few PMS δ Scuti-type pulsators have been already identified (see Table 10) and a number of new PMS candidate pulsators have also been proposed (Marconi & Palla 1998; Pigulski et al. 2000a).

On the other hand, the interior structure in a PMS star is not the same as that of a classical δ Scuti variable evolving from the MS. Consequently, the discovery of pulsations in PMS stars is extremely important because it provides constraints on the internal structure of young stars being a good method to test evolutionary models (Marconi & Palla 1998). Moreover, as shown by Breger & Pamyatnykh (1998), the theoretically predicted evolutionary period changes are a factor of 10 to 100 larger than those for δ Scuti variables in MS and with different sign (the period must be decreasing in PMS). Thus, the evolutionary changes might not be hidden among other effects. Hence, the study of period changes among the PMS δ Scuti-type variables appears to be very promising in contrast to MS and post-MS stars (Breger & Pamyatnykh 1998).

Table 10 lists the PMS δ Scuti variables known up to date in the same order they were discovered. The first four variables are already listed in the R00 catalogue, but the four latter ones have been discovered very recently (Marconi et al. 2000; Pigulski et al. 2000b) and they were not included. Additionally, Table 10 lists the visual magnitude, visual amplitude, main period and number of pulsation frequencies detected for each variable.

The first evidence for the existence of PMS δ Scuti stars came from the discovery of δ Scuti-type pulsations in two members, V588 Mon and V589 Mon, of the young open cluster NGC 2264 (Breger 1972) with main periods

Table 10. Pre-main sequence δ Scuti variables. N is the number of frequencies detected. Sources (other than the R00 catalogue): 1) Breger 1972, 2) Kim 1996, 3) Kurtz & Marang 1995, 4) Donati et al. 1997, 5) Kurtz & Müller 1999, 6) Marconi et al. 2000, 7) Pigulski et al. 2000b

Star	HD	V (mag)	ΔV (mag)	P (d)	N	Source
V588 Mon	261331	9.73	0.04	0.1400	3	1, 2
V589 Mon	261446	10.32	0.04	0.1594	4	1, 2
V856 Sco	144668	7.00	0.02	0.2078	1	3
	104237	6.58	0.02	0.030	2	4, 5
	35929	8.2	0.02	0.196	1	6
V351 Ori	38238	8.9	0.04	0.058	1	6
BL50		~12.5	~0.02	0.072	2	7
HP57		~12.5	~0.02	0.079	2	7

of about 3.5 hours. New observations were carried out by Kim (1996), who detected 3 and 4 frequencies, respectively. The existence of this subgroup was confirmed by the discovery of δ Scuti-like variations in the well-known pre-main-sequence Herbig Ae star HR 5999 = V856 Sco by Kurtz & Marang (1995). In this case, only one frequency was detected corresponding to a period of 4.99 hours. However, the existence of additional secondary frequencies can not be ruled out. The pulsation properties of this star suggest, using the models of Marconi & Palla (1998), that the mass of this star is about 4 $M_{\odot}$ with second overtone pulsation. A new member of this kind of objects is the Herbig Ae star HD 104237. The δ Scuti-like variations were discovered by Donati et al. (1997) and confirmed by Kurtz & Müller (1999). These authors found two very short and close periods of $P_1 = 0\overset{\mathrm{d}}{.}030$ and $P_2 = 0\overset{\mathrm{d}}{.}027$. This indicates nonradial pulsation. PMS δ Scuti-type pulsations have also been detected in the two Herbig Ae stars HD 35929 and V351 Ori (Marconi et al. 2000) with quite different pulsation periods of $0\overset{\mathrm{d}}{.}196$ and $0\overset{\mathrm{d}}{.}058$, respectively. These periods suggest masses of about 3.6 $M_{\odot}$ for HD 35929 and 2 $M_{\odot}$ for V351 Ori (Marconi et al. 2000). In these two cases, only a few measurements were collected and multiperiodicity can not be ruled out. Finally, two new PMS δ Scuti variables have been found in the young open cluster NGC 6823 (BL50 and HP57) by Pigulski et al. (2000b). Over thirty nights of CCD photometry revealed that both variables are double-mode pulsators.

4.3. Variables with periods between $0\overset{\mathrm{d}}{.}25$ to $0\overset{\mathrm{d}}{.}3$

Only a few variables with periods ranging from $0\overset{\mathrm{d}}{.}25$ to $0\overset{\mathrm{d}}{.}3$, are listed in the R00 catalogue. The true number may be larger, since a selection effect probably exists for pulsators with such periods because of the period overlap with other types of pulsators. Pulsating variables with periods ranging within this interval are very interesting because in this region the evolved Population I δ Scuti stars and the Population II RRc-type variables can coexist. Since δ Scuti stars include all stars evolving from the main sequence to the giant region (while inside the instability strip), even δ Scuti stars with periods longer than $0\overset{\mathrm{d}}{.}3$ are expected.

However, due to the rapid evolution of massive stars evolving towards the giant region, the probability of finding a massive δ Scuti variable in this region of the H–R diagram is small. Consequently, when a new pulsating variable is discovered with periods longer than $0\overset{\mathrm{d}}{.}25$, it is usually assumed that the star is a RR Lyrae-type star situated on the horizontal branch. Only when other parameters are known such as metallicity, galactic location or spatial motions, is it possible to distinguish between the two groups.

It is also possible to confuse a δ Scuti star with a relatively long period with the γ Dor gravity-mode pulsators, especially among the cool stars between spectral types F0 and F5. Since γ Dor stars are on or near the main sequence and the long-period δ Scuti stars are evolved, knowledge of the luminosity allows us to distinguish between the two classes.

In this section, we will analyze star by star the variables catalogued in the R00 list with periods longer than $0\overset{\mathrm{d}}{.}25$, in order to assign the appropriate type (and, by inference, the evolutionary status). Some of these variables have been included by earlier authors in lists of δ Scuti variables and by other authors in lists of RR Lyr variables. On the other hand, we are sure that some of these longer-period variables were missed and not included in the R00 catalogue. A larger number of long-period δ Scuti stars would allow us to improve the period-luminosity relations (e.g., Petersen & Høg 1998 and references therein) by extending the calibrating sample to include longer periods.

Table 11 lists, in order of increasing periods, the 14 variables listed in the R00 catalogue with periods between $0\overset{\mathrm{d}}{.}25$ and $0\overset{\mathrm{d}}{.}30$ together with their relevant observed parameters. In this table, N is the number of detected frequencies: this number is important since RR Lyrae stars are pulsating with only one or two radial modes. The variable with the longest period is SS Psc ($P = 0\overset{\mathrm{d}}{.}2878$). Table 12 lists the derived parameters, where the notation and limits are similar to those used in earlier tables. The metallicity values, [Me/H], have been calculated using the Nissen's (1988) calibration for $\beta < 2\overset{\mathrm{m}}{.}72$ or Smalley's (1993) calibration for $\beta > 2\overset{\mathrm{m}}{.}72$. None of these stars is known to contain peculiar abundances. Only one star, DE Oct, is a known binary, which was not resolved by the Hipparcos satellite (ESA 1997). Consequently, the computed luminosities and colors should be accurate. There exists good agreement between the luminosities derived photometrically and those derived from parallaxes. Note that the photometric absolute magnitudes (M_v(ph)) have not been determined for stars too luminous ($\delta c_1 > 0\overset{\mathrm{m}}{.}28$). In the last column of Table 12, we list the most probable identification of each star.

The variable 7654-501 is a member of the open cluster NGC 7654 being located near to the blue edge of the instability strip. It was discovered by Viskum et al. (1997) and confirmed by Choi et al. (1998, 1999). Hence, it probably is a δ Scuti variable. There is very little information available on the variables II-52 and 4996-V5. II-52 was discovered by Yao et al. (1994) in the direction of the globular cluster M 3, but its low amplitude and light curve suggest this star to be a field δ Scuti variable. In the case of 4996-V5, the amplitude is large and was discovered in the field of the young open cluster IC 4996 by Pietrzynski (1996c). If this object is a member of the cluster, then it would be a high amplitude δ Scuti variable. However, these two latter cases need to be confirmed.

The low amplitudes displayed by HN CMa, V388 Cep and S Eri suggest that we are not dealing with RR Lyrae-type variables. This is also supported by the large values of their rotational velocities. All three variables are located in the upper part of the δ Scuti region. HN CMa = HR 2724 was discovered as a multiperiodic variable by Baade & Stahl (1982). This was confirmed by Breger et al. (1991) who found long term amplitude variations and four frequencies consistent with excited p-modes. This is similar to V388 Cep = HR 8851, discovered to be a multiperiodic δ Scuti variable by Hao & Huang (1993). Later, Hao et al. (1995) identified 5 frequencies suggesting that 4 of them can be interpreted with the same ℓ-number ($\ell = 2$) and different m-values ($m = -2, -1, +1, +2$). There is very little information available about S Eri = HR1611. This variable was discovered by Millis (1967) and later re-observed photometrically by Coates et al. (1981). Coates et al. suggest that S Eri is a luminous δ Scuti variable with a main period of $0\overset{\mathrm{d}}{.}273$. The properties of this star are similar to those of HN CMa and V388 Cep.

AD Ari and DE Oct were discovered by the Hipparcos mission (ESA 1997). AD Ari is classified as δ Scuti variable in both the Hipparcos catalogue and the list of Kazarovets et al. (1999). In the case of DE Oct, the Hipparcos catalogue does not give an specific type of variability while Kazarovets et al. (1999) list this star as RRc:. However, this star was included in the R00 catalogue on basis of its visual amplitude and location in the H–R diagram. In both cases, they are Population I main sequence stars near the cool edge of the instability strip. This means that nonradial g-modes pulsations of high order are indicated by their periods. Thus, we are probably dealing with two γ Dor variables with the shortest periods known to date.

V1719 Cyg is a high-amplitude δ Scuti-type pulsating variable. This star has been widely studied in the literature since its discovery by González-Bedolla & Peña (1979), e.g., Gupta & Padalia (1980, 1982), Padalia & Gupta (1982), Poretti (1984), Joner & Johnson (1985). Johnson & Joner (1986) made an exhaustive study using $uvby\beta$ photometry concluding that this star is a high amplitude multiperiodic δ Scuti variable with a high metal abundances ([Me/H] ~ 0.5). The star also exhibited an unusual light curve of the m_1-index. The reverse shape of the m_1 light curve was later explained by the high metallicity of this star together with its position in the H–R diagram (Rodríguez et al. 1991). In fact, a metallicity of about [Me/H] $= 0.45$ can be inferred from the observed m_1-index curve. This is also in good agreement with the metal abundances derived from spectroscopy by Fernley & Barnes (1997). On the other hand, Poretti & Antonello (1988) found two frequencies $f_1 = 3.7412$ c/d ($P_1 = 0\overset{\mathrm{d}}{.}2673$) and $f_2 = 4.6775$ c/d and the interactions $f_1 + f_2$ and $f_2 - f_1$. These authors suggested that f_1 and f_2 correspond to the first and second overtone of radial pulsation, respecticely. In addition, these authors also found that the light curves of V1719 Cyg are atypical in the sense that descending branch is shorter than the ascending one. This is similar to two other δ Scuti variables: AN Lyn ($P = 0\overset{\mathrm{d}}{.}0983$) and V798 Cyg ($P = 0\overset{\mathrm{d}}{.}1948$) (Rodríguez et al. 1997). Finally, a value of $v \sin i = 31$ km s^{-1} has been determined by Solano & Fernley (1997) whereas the RR Lyrae variables have no detectable rotation (Peterson et al. (1996) estimated an upper limit of $v \sin i < 10$ km s^{-1} for the RR Lyr stars).

The luminosities and solar metallicity values of DE Lac and SS Psc suggest that these stars are evolved Population I δ Scuti rather than γ Dor or RR Lyrae variables. For DE Lac, the conclusion is supported by the measured rotational velocity of $v \sin i = 32$ km s^{-1} (Solano & Fernley 1997). In addition, approximately solar abundances were also derived from spectroscopy by Fernley & Barnes (1997) for these two objects. Moreover, in the case of SS Psc, simultaneous $uvby\beta$ observations were also collected by Rodríguez et al. (1993) leading to [Me/H] $= 0.02$, in very good agreement with the value of [Me/H] $= 0.03$ listed in Table 12 (photometry from McNamara & Redcorn 1977). Furthermore, [Me/H] $= 0.02$ is in very good agreement with the behaviour of the m_1-index curve observed in SS Psc (Rodríguez et al. 1993).

The low metallicity values and too high luminosities ($\delta c_1 \gg$) of DH Peg and UY Cam exclude a δ Scuti and a γ Dor origin and suggests the membership in the RR Lyrae group. (In principle, it could be argued that these stars are long-period SX Phe stars which also are metal-poor. But such long-period SX Phe stars, which are typically found in globular clusters, would be situated on the horizontal branch, i.e., they would be RR Lyrae stars.) Low metal abundances have also been spectroscopically determined by Solano et al. (1997) ([Me/H] $= -1.35$ for DH Peg) and Fernley & Barnes (1997) ([Me/H] $= -1.51$ for UY Cam). In the case of DH Peg, the RR Lyrae interpretation is also supported by the bump displayed just before the maximum of the light curve (Lub 1977), which is common among RRc-type variables.

YZ Cap is also metal-poor ([Me/H] $= -1.29$, Kemper 1982), typical of RR Lyr-type stars. Cacciari et al. (1989) find this star showing typical properties of these variables. In addition, this star also presents a bump just before the light maximum (Lub 1977). Consequently, we assign it to the RR Lyrae class.

Table 11. Observed properties of variables with periods $P > 0^{\rm d}.25$

Star	P (d)	V (mag)	ΔV (mag)	ST	$v \sin i$ ($\rm km\,s^{-1}$)	$b-y$ (mag)	m_1 (mag)	c_1 (mag)	β (mag)	π (mas)	N
HN CMa	0.2501	6.59	0.01	A5IV-V	155	0.117	0.152	1.088	2.784	3.97(±0.65)	4
4996-V5	0.251	15.0	0.36								1
DE Lac	0.2537	10.28	0.32	F6	32	0.317	0.154	0.779	2.703	−0.20(±1.84)	1
II-52	0.2551	16.77	0.05								1
DH Peg	0.2555	9.56	0.50	A5-F0		0.246	0.075	1.116	2.772	0.15(±1.42)	1
UY Cam	0.2670	11.44	0.34	A3-6III		0.149	0.110	1.140	2.754	−1.64(±2.08)	1
V1719 Cyg	0.2673	8.01	0.31	F2III	31	0.249	0.174	0.833	2.710	4.28(±0.71)	2
AD Ari	0.2699	7.43	0.06	F0		0.191	0.171	0.727	2.747	11.80(±0.88)	1
V388 Cep	0.2717	5.56	0.04	A7V	145	0.171	0.165	0.962	2.734	9.15(±0.57)	5
S Eri	0.273	4.78	0.03	F0V	195	0.165	0.170	1.007	2.750	11.21(±0.74)	1
YZ Cap	0.2735	11.38	0.49	A6						2.97(±2.52)	1
DE Oct	0.2778	9.15	0.07	A9IV		0.223	0.166	0.746	2.759	4.39(±1.03)	1
7654-501	0.278	14.42	0.02								1
SS Psc	0.2878	10.99	0.39	A9	≤18	0.189	0.172	0.960	2.735	3.81(±2.05)	1

Table 12. Derived properties of variables with periods $P > 0^{\rm d}.25$

Star	s_π	$M_v(\pi)$ (mag)	E_{b-y} (mag)	$(b-y)_0$ (mag)	m_0 (mag)	c_0 (mag)	δc_1 (mag)	δm_1 (mag)	M_v(ph) (mag)	[Me/H]	Type
HN CMa	0.16	−0.42(±0.36)	0.000	0.117	0.152	1.088	0.340	0.045		−0.39	δ Scuti
4996-V5											δ Scuti?
DE Lac			0.085	0.232	0.181	0.762	0.223	−0.008	1.18	0.23	δ Scuti?
II-52											δ Scuti?
DH Peg	9.47		0.108	0.138	0.110	1.094	0.370	0.083		−0.80	RR Lyrae
UY Cam			0.001	0.148	0.110	1.140	0.452	0.076		−0.72	RR Lyrae
V1719 Cyg	0.17	1.05(±0.36)	0.028	0.221	0.183	0.827	0.269	−0.009	0.73	0.25	δ Scuti
AD Ari	0.07	2.79(±0.16)	0.000	0.191	0.171	0.727	0.052	0.013	2.44	−0.06	γ Dor?
V388 Cep	0.06	0.37(±0.14)	0.000	0.171	0.165	0.962	0.326	0.015		−0.08	δ Scuti
S Eri	0.07	0.03(±0.14)	0.001	0.164	0.170	1.007	0.326	0.014		−0.07	δ Scuti
YZ Cap	0.85										RR Lyrae
DE Oct	0.23	2.2(±0.5)	0.043	0.180	0.180	0.737	0.039	0.008	2.50	0.00	γ Dor?
7654-501											δ Scuti
SS Psc	0.53		0.010	0.179	0.175	0.958	0.319	0.005		0.03	δ Scuti?

Table 13. AC And-type variables. The sources are: 1) Fitch & Szeidl 1976, 2) ESA 1997, 3) Preston 1959, 4) Antipin 1997, 5) Diethelm 1997, 6) Handler et al. 1998, 7) Handler 1999b

Star	b (°)	V (mag)	ΔV (mag)	ST	[Me/H]	P_1(mode) (d)	P_2(mode) (d)	P_3(mode) (d)	Period ratios 1H/F	2H/1H	Source
AC And	−11	11.07	0.4	F4	−0.07	0.7112(F)	0.5251(1H)	0.4211(2H)	0.738	0.592	1, 2, 3
GSC04018-01807	+1	11.4	0.5	-	-	0.5126(1H)	0.6689(F)	0.4110(2H)	0.766	0.614	4
V829 Aql	−11	10.28	0.3	F5	+0.17	0.2209(1H)	0.2924(F)	0.1767(2H)	0.756	0.604	5, 6, 7

4.4. AC And-type variables

Stars with masses of 3 or more solar masses also cross the classical instability strip as they evolve from the main sequence towards the giant branch. The location inside the instability strip also excites pulsation, but with periods in excess of the usual $0^{\rm d}.25$ or $0^{\rm d}.30$ limit. These stars with periods of pulsation typical of RR Lyrae stars will nevertheless show the properties of δ Scuti stars because of the identical stage of evolution. In particular, the rotational velocity, $v \sin i$, can, in principle, be as high as 200 km s^{-1}, while RR Lyrae stars show $v \sin i \leq 10$ km s^{-1} (Peterson et al. 1996). This, together with period ratios, allows us to recognize long-period δ Scuti stars. Due to the rapid evolution across the so-called Hertzsprung Gap, the probability of detecting such stars at a given time is very small.

The most prominent example is the star AC And, which shows three simultaneously excited pulsation periods, viz., $P_1 = 0\overset{\mathrm{d}}{.}7112$, $P_2 = 0\overset{\mathrm{d}}{.}5251$ and $P_3 = 0\overset{\mathrm{d}}{.}4211$, together with a large number of harmonics and combinations between the three main frequencies (Fitch & Szeidl 1976). The period ratios are different from those of RR Lyrae stars. Fitch & Szeidl (1976) concluded that this object is not an RR Lyr star but an evolved δ Scuti variable with a mass of about 3 $M_\odot$ pulsating in the three first radial modes (fundamental, first and second overtone, respectively). The same conclusion was found by Kovacs & Buchler (1994) who calculated a large number of radial pulsation models to fit the periods and period ratios observed in AC And. This is also supported by the Population I metallicity found for this star (Preston 1959, found $\Delta S = -1$ which is equivalent to [Me/H] = 0.07 using the calibration of Fernley & Barnes 1997) and its very low galactic latitude ($b = -11°$). The properties of AC And and two other members of the group are listed in Table 13, where the observed periods, P_1, P_2 and P_3, are listed in order decreasing amplitude and F, 1H, 2H refer to the mode identification of radial fundamental, first and second overtone, respectively. Fernie (1994) showed that the interpretation of AC And as a normal post-main-sequence star with 3 $M_\odot$ predicts the correct period length based on his period-luminosity relation (Fernie 1992). This suggests that this star is intermediate between δ Scuti and classical Cepheids variables, bridging the gap between these two classes of pulsators.

Another new three-mode variable similar to AC And is GSC04018-01807 (hereafter GSC), discovered by Antipin (1997). For GSC, the fundamental radial mode has a period of $0\overset{\mathrm{d}}{.}6689$. V829 Aql, on the other hand, is similar to these two variables, but has much shorter periods (Diethelm 1997). This star was discussed by Handler et al. (1998) as a radial triple-mode 2.1 $M_\odot$ pulsator with $P_2 = 0\overset{\mathrm{d}}{.}2924$ as the fundamental radial mode. The identified evolutionary status is supported by the Strömgren indices. Handler (1999b) finds $b - y = 0\overset{\mathrm{m}}{.}390$, $m_1 = 0\overset{\mathrm{m}}{.}135$, $c_1 = 0\overset{\mathrm{m}}{.}748$ and $\beta = 2\overset{\mathrm{m}}{.}675$. These colour indices place this star as an evolved δ Scuti variable near the cool egde with $M_v = 0\overset{\mathrm{m}}{.}86$ and $(b - y)_0 = 0\overset{\mathrm{m}}{.}265$. Moreover, the metallicity inferred by δm_1 and Nissen's (1988) calibration ([Me/H] = 0.17) is typical of normal Population I stars. In addition, the Q value derived for the pulsation constant is of $0\overset{\mathrm{d}}{.}028$ in very good agreement with $P_1 = 0\overset{\mathrm{d}}{.}2209$ as the first overtone. Thus, the two variables AC And and GSC seem to be similar to V829 Aql, but with much longer periods.

Two other possible examples of variables belonging to this part of the H–R diagram are FW Lup ($P = 0\overset{\mathrm{d}}{.}4842$, $V = 9\overset{\mathrm{m}}{.}05$, $\Delta V = 0\overset{\mathrm{m}}{.}4$, ESA 1997) and ST Pic ($P = 0\overset{\mathrm{d}}{.}4857$, $V = 9\overset{\mathrm{m}}{.}48$, $\Delta V = 0\overset{\mathrm{m}}{.}5$, ESA 1997). Only single periods were observed for these stars so that the radial period ratios cannot be used to assign the evolutionary status of these stars. However, Eggen (1994) suggests on the basis of a period-luminosity relation that these two stars resemble first-overtone δ Scuti stars rather than RR Lyrae variables. In both cases, the metal abundances seems to be normal of Pop. I: Eggen (1994) deduced [Me/H] = -0.2 and -0.3, respectively. Other metallicities determinations are available for FW Lup, in very good agreement with the one derived by Eggen (1994): [Me/H] = -0.20 by Solano et al. (1997) (from spectroscopic observations) or [Me/H] = 0.04 by Jurcsik & Kovack (1996) (from their [Me/H] versus light curves relations).

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