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CCD photometric search for peculiar stars in open clusters

III. NGC 2439, NGC 3960, NGC 6134, NGC 6192 and NGC 6451*

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Abstract. In total, more than 550 objects within the fields of five open clusters were investigated in order to find classical chemically peculiar stars. One bona-fide CP candidate was detected in each of the open clusters NGC 3960, NGC 6192 and NGC 6451. All three objects seem to be members of the corresponding cluster, taking the results from our photometry as well as from the literature. For NGC 6192 and NGC 6451 we found widely different interstellar reddening values and therefore distances and ages in the literature. From an analysis of published Johnson $UBVRI$ photometry, we were able to rule out a rather old age for NGC 6451. This is also supported by the finding of one peculiar object in this cluster with spectral type of about A2. Five variable objects within the field of NGC 6134 were detected. The variability exceeds 10 times (or typically 0.03 mag) the standard deviation of the weighted individual measurements. But since our observations were obtained mostly within one hour (typical integration times of five minutes per filter) on several nights within 45 days, no light curves could be derived. For this cluster, some Am candidates were reported for which we were not able to detect a significant positive Δa-value.

Key words. stars: chemically peculiar – stars: early-type – techniques: photometric – open clusters and associations: general

1. Introduction

Five open clusters of our Milky Way were investigated in order to find chemically peculiar (CP) objects using CCD Δa-photometry. Two previous papers (Bayer et al. 2000; Paunzen & Maitzen 2001) have already shown the high efficiency of this system.

The target clusters (NGC 2439, NGC 3960, NGC 6134, NGC 6192 and NGC 6451) have distances from 1400 to 4200 pc from the Sun and have ages from 0.02 to 0.8 Gyr. Two clusters (NGC 2439 and NGC 3960) are only poorly investigated whereas the other three objects are well studied, a fact that makes a calibration and comparison of our photometry possible.

For all clusters, Johnson UBV photometry is available from the literature. In addition, Strömgren $uvby\beta$ measurements were published for NGC 6134. This cluster was also investigated for δ Scuti type pulsators by Kjeldsen & Frandsen (1989).

We discuss the widely different reddening and thus distances and ages found for NGC 6192 and NGC 6451 in the literature.

In total, we report the detection of one bona-fide CP star in each of the open clusters NGC 3960, NGC 6192 and NGC 6451.

2. Observations, reduction and results

Observations of the five open clusters were performed with the Bochum 61 cm (ESO-La Silla) as well as the Helen-Sawyer-Hogg 61 cm telescope (UTSO-Las Campanas Observatory) in 1995. The instrumentation and filters used are described in Bayer et al. (2000). The observing log is listed in Table 1. In total, 119 frames for all five clusters in three filters were observed and used for the further analysis.

The basic reductions (bias-subtraction, dark-correction, flat-fielding) were carried out within standard IRAF routines. For all frames we have applied a point-spread-function-fitting within the IRAF task DAOPHOT (Stetson 1987). Photometry of each frame was performed separately and the measurements were then averaged and weighted by their individual photometric error.

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* Based on observations at ESO-La Silla and UTSO-Las Campanas.

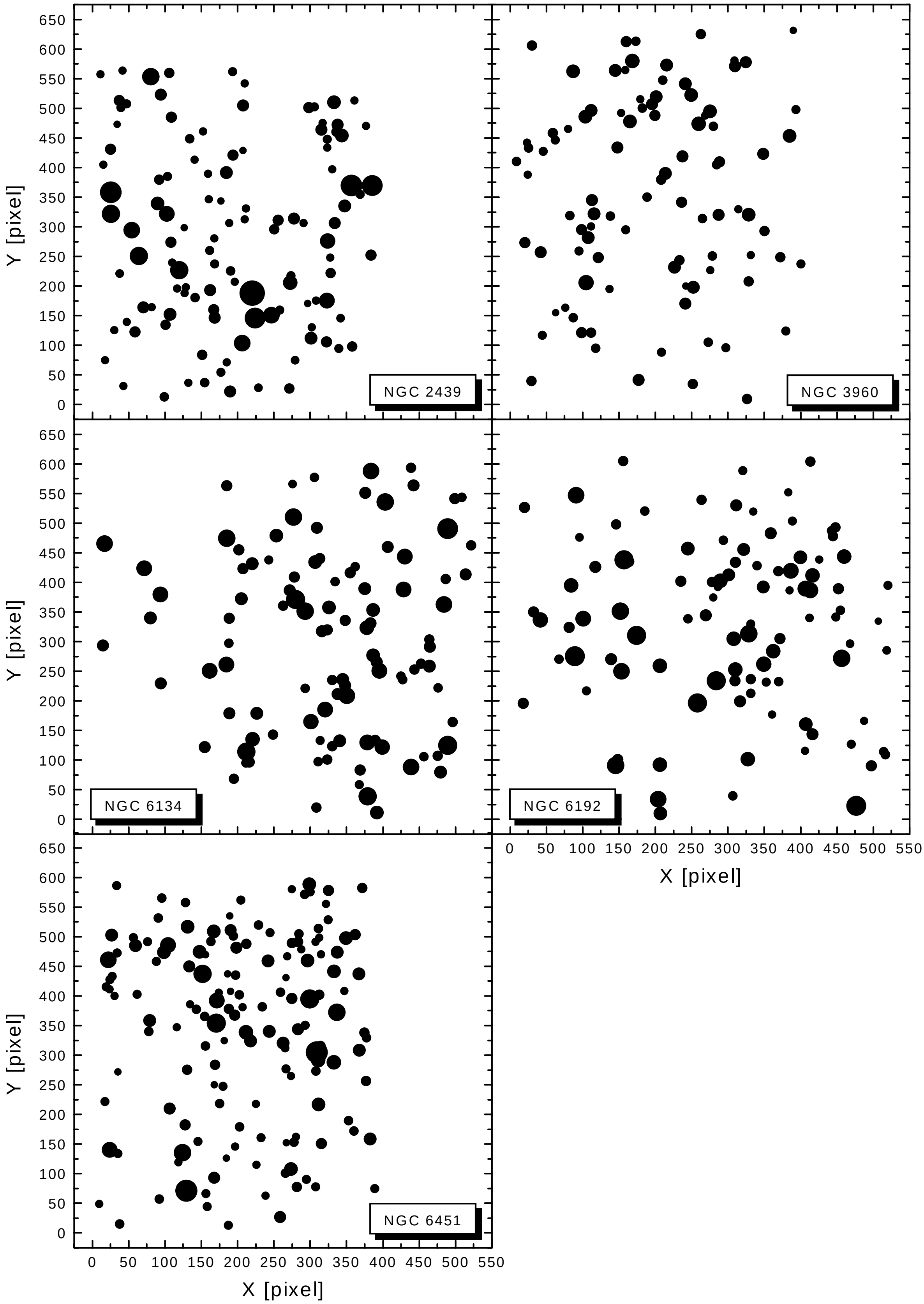

Fig. 1. Finding charts for the program clusters. North is to the right and west is upwards; 1 pixel = 0.5″. The sizes (by area) of the open circles are inversely proportional to the V-magnitudes taken from Tables 4 to 8 in the sense that larger open circles denote brighter objects.

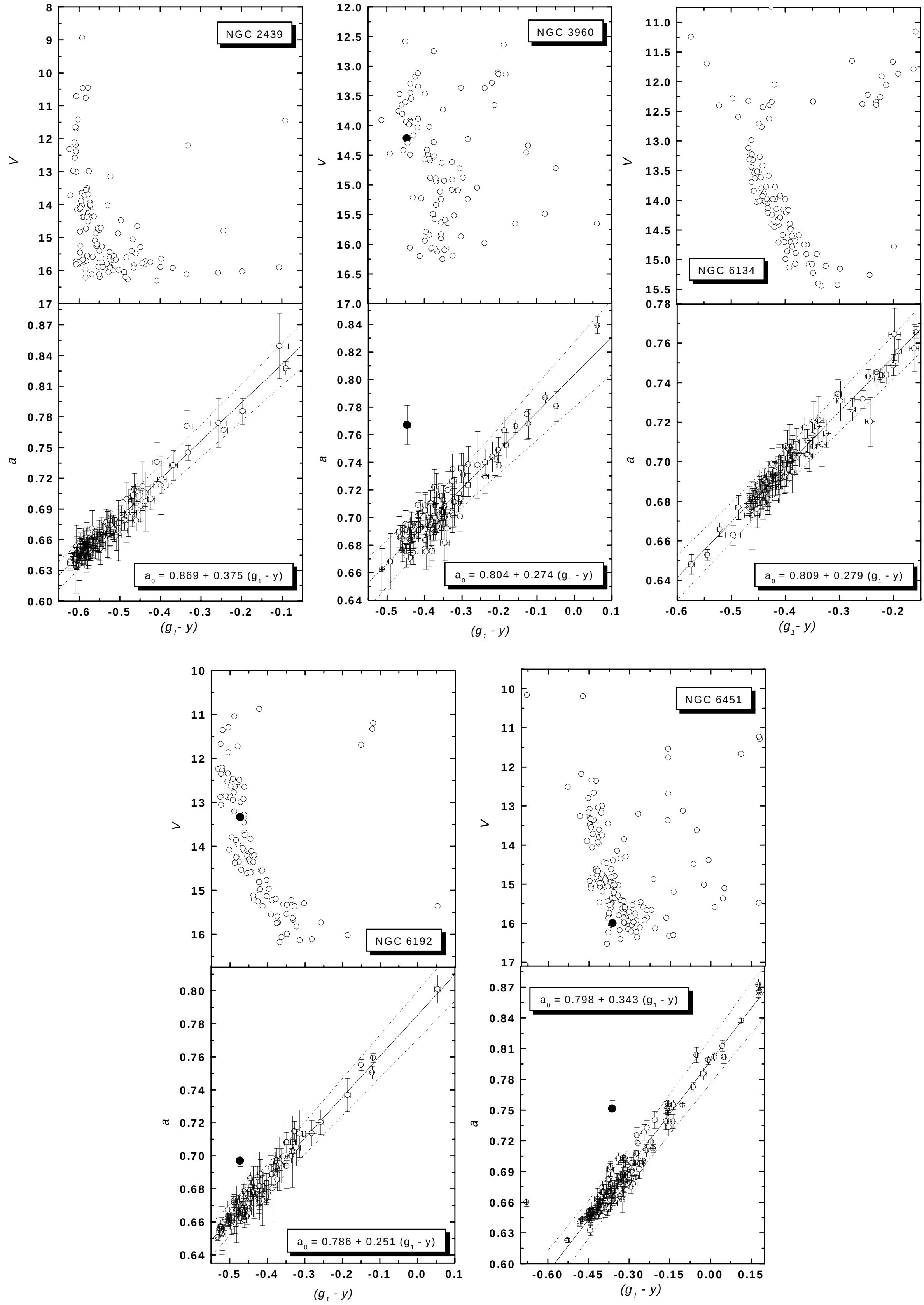

Fig. 2. V versus $(g_1 - y)$ and a versus $(g_1 - y)$ for our program clusters. Filled circles indicate apparent peculiar stars whereas open circles are non−peculiar objects. The solid line is the normality line whereas the dotted lines are the confidence intervals corresponding to 99.9%. The error bars for each individual objects are the mean errors. The measurement errors of V are much smaller than the symbols and have been omitted.

Table 1. Observing log.

Cluster	Site	Nights	$\#_{g1}$	$\#_{g2}$	$\#_{y}$
NGC 2439	ESO	4	10	6	4
NGC 3960	ESO	3	7	5	5
NGC 6134	ESO	5	7	12	8
	UTSO	1	2	2	1
NGC 6192	ESO	5	11	13	11
	UTSO	1	1	1	1
NGC 6451	ESO	2	4	4	4

The normality lines were independently derived for (g_1-y), $(B-V)$ and $(b-y)$, respectively. As in the other papers of this series, we did not transform the (g_1-y) values into standard $(B-V)$ or $(b-y)$ ones. Only for the bona-fide CP star in NGC 6451, a transformation as described in Paunzen & Maitzen (2001) was applied to have an estimate of its spectral type.

The way of calculating the normality line, deriving the errors and calibration of our y measurements, are the same as in Paunzen & Maitzen (2001).

Table 2 lists our observed open clusters and their characteristics from the literature (as listed in the corresponding sections). Furthermore, the number of observed stars, the number of individual frames (Table 1), the regression coefficients for all transformations and normality lines are listed. In addition, the described peculiar objects with their Δa-values and $(B-V)_0$ values as well as the 3σ detection limit are given.

The finding charts of our open clusters are shown in Fig. 1. The size of the symbols (by area) is inversely proportional to the apparent visual magnitudes of the objects in the sense that larger symbols denote brighter objects.

The complete tables with all data for the individual cluster stars are available both from SIMBAD (via anonymous ftp) or upon request from the first author. These tables include the cross identification of objects from the literature, the observed (g_1-y) and a values with their corresponding errors, V magnitudes, the $(B-V)$ as well as $(b-y)$ values from the literature and Δa-values derived from the normality lines of (g_1-y), $(B-V)$ and $(b-y)$, respectively.

Table 3 lists the photometrically peculiar stars. The individual objects are discussed in more detail in the following subsections.

The V versus (g_1-y) and a versus (g_1-y) diagrams for all five open clusters are shown in Fig. 2. Furthermore, the normality lines and the confidence intervals corresponding to 99.9% are plotted. Filled circles indicate the peculiar objects.

2.1. NGC 2439

This distant young open cluster has been poorly investigated now. White (1975) presented photoelectric and photographic Johnson UBV measurements of 183 objects whereas Ramsay & Pollacco (1992) analyzed CCD $-UBVI_c$ colors of 120 stars within the field of NGC 2439. The results of both references agree fairly well, yielding a reddening of $E(B-V) = 0.37$ mag, a distance of $3.98 < d < 4.45$ kpc from the Sun and a very young age (White 1975 lists 20 Myr whereas Ramsay & Pollacco 1992 give only an upper limit of 300 Myr).

We find a well-defined main sequence (Fig. 2) in excellent agreement with White (1975; see Fig. 3 therein). There are probable non-members present which are clearly distinct within the V versus (g_1-y) diagram. These objects coincide with the list of non-members given in Ramsay & Pollacco (1992). Although there are mainly cluster stars within the temperature range of the classical CP stars (B5 to F0) and the detection limit is quite low (0.012 mag), no photometrically peculiar object was detected.

2.2. NGC 3960

An extensive investigation of NGC 3960 was done by Janes (1981) who obtained photoelectric Johnson BV and DDO data. The latter allowed to derive a metallicity of [Fe/H] $= -0.30(6)$ dex which is significant sub-solar. He estimated an age between 0.5 and 1 Gyr (older than the Hyades but younger than NGC 752) and a reddening of $E(B-V) = 0.29$ mag.

All of our observed objects of this open cluster are also included in the work of Janes (1981). He defined an inner region (of radius $2\rlap{.}'75$) and an outer ring concluding that all stars fainter than 16th magnitude are probable non-members.

We find one photometric CP star (No. 2; No. 1 according to Janes 1981) among a sample of 93 objects observed. This object exhibits a very large Δa-index (+0.085 mag). It lies well within the inner region ($V = 14.22$ mag) and is very probably a true member of this cluster. Its dereddened color $(B-V)_0 = +0.19$ mag suggests a spectral type of about A6 (Schmidt-Kaler 1982).

Another object (No. 89; No. 155 according to Janes 1981) has a very large Δa-index (+0.079 mag) by its $(B-V)$ color (based on only one measurement) whereas our (g_1-y) index yields a rather normal one (+0.018 mag). According to our photometry (based on eight individual (g_1-y) measurements) this coolest object within the cluster area (see Fig. 2) is very probably a non-member.

2.3. NGC 6134

Kjeldsen & Frandsen (1989) and Frandsen et al. (1996) performed an extensive search for δ Scuti type pulsators in the field of NGC 6134. They found at least six variables making this cluster an interesting subject for further studies. An overview of all results can be found in Bruntt et al. (1999) who also presented several bona-fide Am candidates and Strömgren $uvby\beta$ photometry.

This rather old cluster with an age of about 690 Myr shows a well defined turn-off point, several giants and

Table 2. Summary of results. In parenthesis are the errors in the final digits of the corresponding quantity.

Name	NGC 2439 C0738−315	NGC 3960 C1148−554	NGC 6134 C1624−490	NGC 6192 C1636−432	NGC 6451 C1747−302
l/b	246/−4	294/+6	335/−0	341/+2	360/−2
$E(B-V)$	0.37	0.29	0.36	0.68	0.70
d [pc]	4200	1700	1400	1700	2100
$\log t$	7.30	8.88	8.84	7.95	8.30
Tr-type	II 3 r	I 2 m	II 3 m	I 2 r	I 2 r
n(obj)	113	93	102	98	146
$\Delta a/(B-V)_0$		+0.085 +0.19		+0.030 −0.06	+0.078 0.08
$V = a + b \cdot (y)$	−8.21(8) 1.000(6)	−8.28(17) 1.009(7)	−8.14(7) 1.000(6)	−8.13(8) 0.997(3)	−8.27(15) 1.001(7)
$a_0 = a + b \cdot (g_1 - y)$	0.869(4) 0.375(7)	0.804(4) 0.274(11)	0.809(2) 0.279(6)	0.786(2) 0.251(5)	0.798(2) 0.343(6)
$a_0 = a + b \cdot (b - y)$			0.618(3) 0.155(5)		
$a_0 = a + b \cdot (B - V)$	0.619(2) 0.126(3)	0.645(5) 0.086(6)		0.603(2) 0.104(3)	0.560(6) 0.146(7)
$3\,\sigma$ [mag]	0.012	0.015	0.009	0.009	0.016
n(frames)	20	17	32	38	12

blue-stragglers (Fig. 2). The turn-off color is at about $(g_1 - y) \approx -0.475$ mag which corresponds to $(b - y)_0 \approx +0.14$ mag or a spectral type of about A8. Only two or three non-members are indicated from the color-magnitude diagram. No peculiar object was found based on a very low detection limit (0.009 mag).

Our field of view includes the following bona-fide Am candidates: No. 598 (in the notation of Bruntt et al. 1999), 619, 832, 919, 1023; and variable stars from the literature: No. 66 (number according to Lindoff 1972), 647, 679, 853 and 906. None of these objects show any peculiar Δa-value in accordance with Maitzen (1976) and Vogt et al. (1998).

We found also no clear evidence for variability of the known variable stars. This is due to the very small amplitudes (below 0.010 mag; Frandsen et al. 1996) and the uneven distribution of our measurements.

However, from our data set we are able to conclude that the objects No. 3 (number according to Lindoff 1972), 735, 1046, 1115 and 1154 are definitely not constant on a level which exceeds more than 10σ of the rms error or typically 0.03 mag. Because of the rather high amplitude, these objects were not included in Fig. 2. Due to the distribution of the observations, no conclusion about the nature of variability can be drawn. In the relevant temperature range one might think of δ Scuti and γ Doradus pulsation as well as variability due to eclipsing binaries. Especially interesting is the case of No. 1154 which is also a bona-fide Am candidate. Explanations of the detected variability as pulsation (only a few Am stars show such a behaviour) or as eclipses (Am stars tend to be found in spectroscopic binary systems) are both very interesting.

2.4. NGC 6192

A remarkable disagreement on the basic properties for NGC 6192 was found in the literature. Kilambi & Fitzgerald (1983) and King (1987) reported a rather old age (1300 Myr) with a reddening of $E(B-V) = 0.26$ mag and a distance of about 1000 pc from the Sun. These results are based on photographic (Kilambi & Fitzgerald 1983) as well as CCD photometry (King 1987). Kjeldsen & Frandsen (1991) contradicted these values and list a reddening of $E(B-V) = 0.68$ mag, an age of 89 Myr and a distance of about 1700 pc from the Sun. They find very good agreement with the individual measurements of King (1987). We have noticed that the photographic measurements of Kilambi & Fitzgerald (1983) only poorly correlate with the CCD ones of King (1987) and Kjeldsen & Frandsen (1991) who used a $(B-V)_0$ versus $(U-B)_0$ diagram whereas King (1987) fitted isochrones to V versus $(B-V)$ in order to derive the reddening. The Q-method (Golay 1974) for the hotter stars does strongly support the findings of Kjeldsen & Frandsen (1991).

We find No. 50 (No. 54 according to King 1987; No. 86, Kjeldsen & Frandsen 1991) as being peculiar with $\Delta a = +0.030$ mag. According to all references and our color-magnitude diagram, this object is a member of NGC 6192. Following the measurements and results from Kjeldsen & Frandsen (1991) we find $(B-V)_0 = -0.06$ mag and an absolute magnitude of $M_V = +0.0(2)$ mag. This is typical for a B8 type, luminosity class V star suggesting that this object might be a late B-type Si star. Note that the values of King (1987) would result in $(B-V)_0 = +0.46$ mag which is typical for a F5 type star and therefore much too cool for a classical CP star.

2.5. NGC 6451

This represents a puzzling case of widely different reddening values and therefore ages and distances found in the literature. Svolopoulos (1966) lists $E(B-V) = 0.08$ mag whereas Kjeldsen & Frandsen (1991) give $E(B-V) = 0.70$ mag as best value. This results in a difference of 560 pc versus 2100 pc and 5 Gyr versus 0.2 Gyr, respectively. Kjeldsen & Frandsen (1991) claim that "due to the well populated color-magnitude diagram we find it difficult to understand the large discrepancy". These are the only two references found in the literature which included an independent estimation of the reddening.

Table 3. Stars of the investigated open clusters with peculiar Δa-values.

Cluster	No_1	No_2	X	Y	V	a	$\sigma(a)$	(g_1-y)	$\sigma(g_1-y)$	Δa	$(B-V)$	Δa
NGC 3960	2	1	20.9	272.4	14.22	0.767	0.014	−0.446	0.009	+0.085	+0.48	+0.081
NGC 6192	50	86	322.4	455.0	13.34	0.697	0.004	−0.473	0.003	+0.030	+0.61	+0.031
NGC 6451	30		118.8	118.6	16.00	0.751	0.008	−0.363	0.006	+0.078		

Col. 1: Cluster name.
Col. 2: Notation sorted after X and Y, respectively (Fig. 1).
Col. 3: Notation according to Janes (1981; NGC 3960), Kjeldsen & Frandsen (1991; NGC 6192).
Col. 4, 5: X and Y coordinates in the finding charts (Fig. 1).
Col. 6: Johnson V magnitude.
Cols. 7, 8: Mean a-index and its standard deviation.
Cols. 9, 10: Mean (g_1-y) value and its standard deviation.
Col. 11: Deviation from cluster line $a_0 = a + b\cdot(g_1-y)$ using the corresponding constants as listed in Table 2.
Col. 12: $(B-V)$ from the literature.
Col. 13: Deviation from cluster line $a_0 = a + b\cdot(B-V)$ using the corresponding constants as listed in Table 2.

Piatti et al. (1998; and other references which can be found therein) used the values of Svolopoulos (1966) to derive a $M_{\rm V}$ versus $(V-I)_0$ diagram for NGC 6451 together with nine other open clusters.

Before we try to disentangle these discrepancies, an overview of the results from the Δa-photometry is presented. Figure 2 shows a well defined main sequence with about 25 probable non-members. Two stars deviate significantly from the normality line: No. 30 and 34. The latter seems to be a bright foreground star with $V = 10.17$ whereas No. 30 seems to be a true member of NGC 6451. None of these objects was measured by Kjeldsen & Frandsen (1991) and Piatti et al. (1998). Depending on the reddening we get $(B-V)_0 = +0.08$ mag or +0.70 mag, respectively. These values correspond either to a spectral type of A2 or G5. The latter is clearly too cool for a classical CP star.

We are not able to decide from our photometry which reddening value fits best all photometric data from our work and the literature. However, the case of NGC 6451 has initialized a study determining the reddening and ages using Δa-photometry (mainly the V or y versus g_1-y diagram) in collaboration with A. Claret.

We have reanalyzed the data from Kjeldsen & Frandsen (1991) and Piatti et al. (1998) since both are based on CCD measurements. The conclusions of Svolopoulos (1966) and Lyngå (1987) are based on estimates from photographic plates which do not take into account any effects by the crowding of the field and result normally in much larger errors than CCD photometry. Note that Kjeldsen & Frandsen (1991) reported problems in calibrating their U and B values to standard ones because the combination of the characteristics for the used filter and the CCD response function was far from the original ones.

We have also detected an apparent inconsistency of the V magnitudes from both references. The values of Piatti et al. (1998) are on the average one magnitude brighter than those of Kjeldsen & Frandsen (1991). For an independent check, the *RGU* measurements from Becker et al. (1978) for NGC 6451 were used. To transform these magnitudes in Johnson V ones, the calibrations from Crawford & Mander (1966) and Buser (1978) were taken

$$V = G + 0.05(U-G) - 0.82(G-R) + 0.21 + \alpha E(G-R)$$
$$G = V + 0.63(B-V) - 0.01(U-B) + \alpha E(B-V)$$

with α (depending on the color) being in the range of 0.1 to 0.3 in the relevant spectral domain and $E(G-R) = 1.39E(B-V)$. These transformations guarantee that the influence of wrong measurements either in the *RGU* or *UBV* system will be minimized. Figure 3 shows the comparison of the data from all three references. We are definitely able to conclude that the V values from Piatti et al. (1998) are too bright by about one magnitude. This finding is based on 160 and 40 stars in common by Piatti et al. (1998) with Kjeldsen & Frandsen (1991) and Becker et al. (1976), respectively. Another independent check via the Guide-Star-Catalogue gives the same consistent result.

From our analysis of all photometric data we believe that a value of 0.70 mag for the reddening of NGC 6451 is probably correct because of additional arguments:

- The Q values (Golay 1974) for the hottest member are between −0.6 and +0.1 which are only compatible with spectral types earlier than A0. This result is independent of the reddening.
- According to Neckel et al. (1980), the interstellar absorption ($A_{\rm V}$) towards NGC 6451 is between 1.2 and 1.9 mag kpc^{-1} close to the edge of a region with $2.6 \le A_{\rm V} < 3.3$ mag kpc^{-1}. Such values only support a distance for NGC 6451 which is larger than 2000 pc.

Taking the newest isochrones from Lejeune & Schaerer (2001) and fitting the photometric data from Piatti et al. (1998; the V measurements were corrected by one magnitude) we get $E(B-V) = 0.60$ mag, $(V-M_{\rm V}) = 13.90$ and an age of about 0.4 Gyr. This is very close to the the results of Kjeldsen & Frandsen (1991) and gives further confidence that the peculiar object detected by our Δa-photometry has a spectral type of about A2.

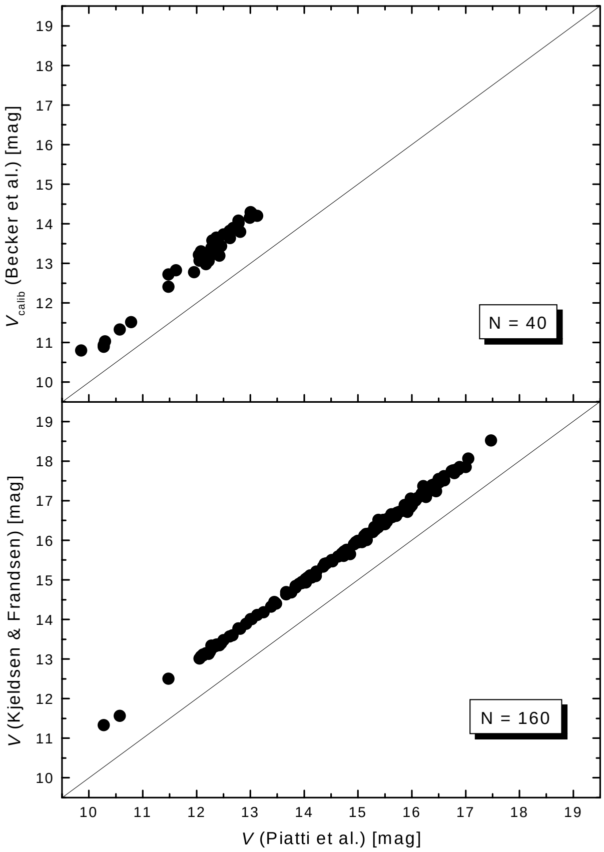

Fig. 3. Comparison of the Johnson V magnitudes for members of NGC 6451 from Piatti et al. (1998) and those listed by Kjeldsen & Frandsen (1991, lower panel) and the transformed ones from the *RGU* photometry by Becker et al. (1978, upper panel). The straight line corresponds to a zero offset.

3. Conclusions

In total, more than 550 objects within the fields of five open clusters were investigated. Three bona-fide CP stars were detected altogether in the open clusters NGC 3960, NGC 6192 and NGC 6451. All three objects seem to be members of the corresponding cluster. For NGC 6192 and NGC 6451 we found widely different reddening values and therefore distances and ages in the literature. From an analysis of published photometric data, we were able to rule out a rather old age for NGC 6451. This is also supported by the finding of one photometric peculiar star in this cluster with a spectral type of about A2.

Five variable objects within the field of NGC 6134 were detected. Since our observations are unfavorably distributed as they span one hour (typical integration times of five minutes) on several nights within 45 days, no conclusion about the kind of variability can be made.

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