

On the detection of chemically peculiar stars using Δa photometry^{*}

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Received 7 March 2005 / Accepted 3 June 2005

Abstract. We have summarized all Δa measurements for galactic field stars (1474 objects) from the literature published over more than two decades. These measurements were, for the first time, compiled and homogeneously analyzed. The Δa intermediate band photometric system samples the depth of the 5200 Å flux depression by comparing the flux at the center with the adjacent regions with bandwidths of 110 Å to 230 Å. Because it was slightly modified over the last three decades, we checked for systematic trends for the different measurements but found no correlations whatsoever. The Δa photometric system is most suitable to detecting magnetic chemically peculiar (CP) stars with high efficiency, but is also capable of detecting a small percentage of non-magnetic CP objects. Furthermore, the groups of (metal-weak) λ Bootis, as well as classical Be/shell stars, can be successfully investigated. In addition, we also analyzed the behaviour of supergiants (luminosity class I and II). On the basis of apparent normal type objects, the correlation of the 3σ significance limit and the percentage of positive detection for all groups was derived. We compared the capability of the Δa photometric system with the $\Delta(V1 - G)$ and Z indices of the Geneva 7-color system to detect peculiar objects. Both photometric systems show the same efficiency for the detection of CP and λ Bootis stars, while the indices in the Geneva system are even more efficient at detecting Be/shell objects. On the basis of this statistical analysis it is possible to derive the incidence of CP stars in galactic open cluster and extragalactic systems including the former unknown bias of undetected objects. This is especially important in order to make a sound statistical analysis of the correlation between the occurrence of these objects and astrophysical parameters such as the age, metallicity, and strength of global, as well as local, magnetic fields.

Key words. stars: chemically peculiar – stars: early-type – techniques: photometric

1. Introduction

The classical chemically peculiar (CP) stars of the upper main sequence (luminosity classes V and IV) are targets of detailed investigations since their “discovery” by Maury (1897). They are excellent test objects for astrophysical processes like diffusion, convection, and stratification in stellar atmospheres in the presence of rather strong magnetic fields. These mechanism can be studied depending on the age and metallicity of individual objects, which was a major setback of the stellar evolution theory.

There is a wide variety of peculiar stars in the spectral domain from B0 (30 000 K) to F5 (6500 K). Preston (1974) divided the CP stars into four different groups selected on the basis of the presence of strong magnetic fields and the kind of the surface elemental peculiarity. Later on, small peculiar groups like the λ Bootis stars were also investigated (Paunzen et al. 2002a) and classified as an individual subgroup.

The prerequisite for investigating larger samples of CP stars (including the generally fainter open cluster members) is an

unambiguous detection. Looking into catalogues of CP stars, especially the magnetic ones, it immediately becomes obvious that there are many discrepancies even at classification dispersions. The reasons for discrepant peculiarity assessments are mainly to be found in the differences in observing material (density of spectrograms, widening of spectra, dispersion, focussing), but also intrinsic variability of peculiar spectral features (e.g. silicon lines).

Besides the use of (very time consuming and magnitude limited) high dispersion spectroscopy, photometry has shown a way out of this dilemma, especially through the discovery of characteristic broad band absorption features, the most suitable of them located around 5200 Å. Kodaira (1969) was the first notice to significant flux depressions at 4100 Å, 5200 Å, and 6300 Å in the spectrum of the CP star HD 221568. These flux depressions are very likely enhanced by the effects of magnetic radiative transport phenomena.

Nearly three decades ago, Maitzen (1976) introduced the narrow-band, three filter Δa photometric system in order to investigate the flux depression at 5200 Å, which samples the depth of this feature by comparing the flux at the center

^{*} Complete Table 4 is only available in electronic form at <http://www.edpsciences.org>

Table 1. The number of individual Δa measurements from the given reference. The used filter systems are according to Table 2.

Ref.	$N_{\text{obs.}}$	System
Maitzen (1976)	168	1
Maitzen (1980a)	10	2
Maitzen (1980b)	8	2
Maitzen & Seggewiss (1980)	21	2
Maitzen (1981)	20	2
Maitzen & Vogt (1983)	342	3
Maitzen & Pavlovski (1989a)	16	4
Maitzen & Pavlovski (1989b)	31	4
Pavlovski & Maitzen (1989)	40	4
Schnell & Maitzen (1994)	3	5
Schnell & Maitzen (1995)	14	5
Maitzen et al. (1997)	6	6
Maitzen et al. (1998)	131	7
Vogt et al. (1998)	803	3

(5220 Å, g_2) with the adjacent regions (5010 Å, g_1 and 5500 Å, y) using bandwidths of 110 Å to 230 Å. The respective index was introduced as:

$$a = g_2 - (g_1 + y)/2.$$

Since this quantity is slightly dependent on the temperature (increasing towards lower temperatures), the intrinsic peculiarity index had to be defined as

$$\Delta a = a - a_0[(b - y); (B - V); (g_1 - y)],$$

i.e. the difference between the individual a -values and those of non-peculiar stars for the same color. The locus of the a_0 -values has been called the normality line.

Since its introduction in 1976, many papers presenting Δa photometry of galactic field and especially open clusters have been published. Until the late 90s, all observations were performed with photomultipliers.

All but one (Vogt et al. 1998) publication about Δa photometry of galactic field stars were explicitly devoted to chemically peculiar stars or related groups selected on the basis of several relevant catalogues. Superficial “normal” type objects were only observed in order to define the normality line for the specific set of data.

For the first time, we have combined all available Δa data of bright galactic field stars that have been published in the literature over more than two decades, in order to make a sound statistical analysis of detection probabilities for all kinds of peculiar objects, as well as luminosity class I/II supergiants. This is especially important for observations in open clusters (Paunzen et al. 2002b) and even in the Magellanic clouds (Maitzen et al. 2001). The knowledge of how many peculiar stars for a certain detection limit are expected in comparison with the actually observed number, serves as important information for a statistical analysis, such as the incidence of CP stars that depend on different local environments.

2. Selection, preparation, and homogenization of the data

We used the following sources of Δa photometry for galactic field stars: Maitzen (1976, 1980a, 1980b, 1981),

Table 2. Filter systems used for the Δa measurements, the units are Å.

System	g_1		g_2		y	
	λ_c	$\lambda_{1/2}$	λ_c	$\lambda_{1/2}$	λ_c	$\lambda_{1/2}$
1	5020	130	5240	130	5485	230
2	5010	130	5215	130	5485	230
3	5020	130	5240	130	5505	230
4	5026	111	5238	138	5466	230
5	5017	120	5212	120	5494	228
6	5027	222	5205	107	5509	120
7	5017	110	5212	120	5473	188

Maitzen & Seggewiss (1980), Maitzen & Vogt (1983), Maitzen & Pavlovski (1989a,b), Pavlovski & Maitzen (1989), Schnell & Maitzen (1994, 1995), Maitzen et al. (1997, 1998) and Vogt et al. (1998). The number of individual measurements are given in Table 1. Some references already list $(b - y)_0$ magnitudes, these were used for this study. Objects were only included which have Strömgren indices available.

All but Maitzen et al. (1997, CCD) were conducted with photomultipliers and classical aperture photometry (one star at one time). The different filter sets of these observations are listed in Table 2. The only important difference is the filter set used by Maitzen et al. (1997) together with the CCD equipment. This new CCD photometric Δa system was successfully applied to open clusters of the Milky Way (Paunzen et al. 2002b) and the Large Magellanic Cloud (Maitzen et al. 2001). Although the bandwidths of g_1 and y were exchanged, the overall values of Δa are in very good agreement with those of the photoelectric system.

The Johnson, Geneva, and Strömgren (if not listed in the original source of the Δa photometry) colors were taken from the General Catalogue of Photometric Data (GCPD, Mermilliod et al. 1997). Usually, the reddening for objects within the solar neighborhood is estimated using photometric calibrations in the Strömgren $uvby\beta$ system (Strömgren 1966; Crawford & Mander 1966; Crawford 1975, 1979; Hilditch et al. 1983). The validity of these procedures for chemically peculiar stars was shown, for example, in Maitzen et al. (2000). However, these relations have to be used with some caution when applied to magnetic CP2 stars, because all calibrations are primarily based on the β index. But due to variable strong magnetic fields, the β index can give erratic values (Catalano & Leone 1994). Another effect taken into account is a “blueing” effect, which occurs in bluer colors due to stronger UV absorption than in normal type stars, which can be erratically interpreted as strong reddening (Adelman 1980). An independent way to derive the interstellar reddening is to use galactic reddening maps, which are derived from open clusters as well as from galactic field stars. For this comparison, we used the model proposed by Chen et al. (1998) to derive the interstellar reddening for all program stars. The values from the calibration of the Strömgren $uvby\beta$ and the model by Chen et al. (1998) agree within an error of the mean of ± 1.9 mmag for the complete sample. The normality line is shifted by

$E(g_1 - y) = 0.55E(b - y)$ to the red and by a small amount $E(a)$ to higher a -values (Maitzen 1993)

$$a(\text{corr}) = a(\text{obs}) - 0.07E(b - y).$$

In order to check this procedure, we used the raw data of Maitzen (1976) to derive the normality line of these data. He used a combined normality line for the $(b - y)$ and $(b - y)_0$ values under the assumption that the reddening in the solar neighborhood is negligible. Our results confirm his A_0 parameter with a slight adjustment of the A_2 value from 0.06 to 0.066, which means a correction of Δa in the order of only one mmag. This leads to confidence in our dereddening procedure.

As the next step, we checked the intrinsic consistency of the different reference for objects in common since the filter systems are slightly different (Table 2). Besides a possibly wrong identification or typographical errors, the variability of Δa itself has to be taken into account. Several chemically peculiar stars show variability in correlation with strong magnetic fields and rotation. These variations were also detected in the Δa photometric system (Maitzen & Vogt 1983, Fig. 11). There is also the outstanding case of Pleione (Maitzen & Pavlovski 1987). This Be/shell star shows a strong positive Δa value (+36 mmag) as it undergoes its shell phase.

The published $(b - y)_0$ and Δa values were checked in this respect and no significant trends were found. All references agree, in a statistical sense, within one sigma of the correlation coefficients. We found no significant outliers. Therefore, the values of objects with more than one measurement were averaged without using any weights, resulting in 1474 individual galactic field stars (which almost doubles the sample used by Vogt et al. 1998) with an available Δa value. This sample consists of “normal” type and peculiar stars of all kinds.

3. Analyzing the sample

With the sample of 1474 galactic field stars, a statistically sound analysis was performed. Figure 1 shows the distribution of the galactic coordinates for the sample. There is a clustering of objects between $190^\circ < l < 280^\circ$ (third galactic quadrant) because of the systematic investigation in the southern hemisphere by Vogt et al. (1998). In this region, the reddening is almost negligible for distances up to 500 pc (Chen et al. 1998). But no unknown bias has been introduced, because the chemically peculiar stars are distributed uniformly in the solar neighborhood (Gómez et al. 1998).

The sample covers $-0.15 < (b - y)_0 < 0.4$ mag (Fig. 2), which corresponds to the spectral range from B0 to F8 (Crawford 1975, 1978). The peak of the distribution is at $(b - y)_0 = -0.05$ mag or B8 at the main sequence. At this spectral type, the number of CP2 stars reaches an intrinsic maximum. The Johnson V distribution shows two maxima around $V = 6$ mag and 8 mag and extends from $1.5 < V < 10.5$ mag. The first peak is a consequence of the systematical investigation of all bright stars by Vogt et al. (1998) whereas the second one is due to the chosen sample by Maitzen & Vogt (1983). They have investigated the list of astrophysically interesting stars by Bidelman & MacConnell (1973), which was published prior to

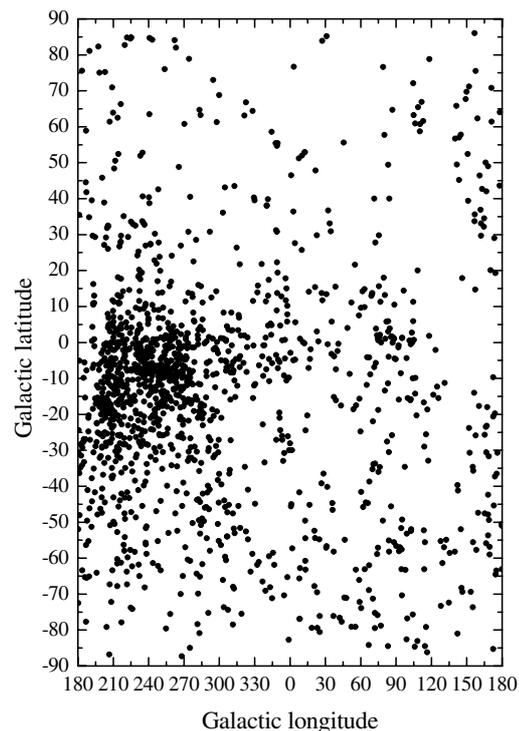


Fig. 1. The galactic distribution of our sample including 1474 individual objects. There is a clustering of objects at $190^\circ < l < 280^\circ$, the almost reddening free (up to 500 pc from the Sun) third galactic quadrant.

the Michigan spectral survey, while both are based on the same spectroscopic material.

There are three stars in the sample that exhibit positive Δa values, for which we were not able to designate a distinctive membership in a certain class of CP stars. Certainly, these three objects deserve further interest:

- HD 68161: Eggen (1980) lists a photometric spectral type of B7III, whereas the spectroscopic type is B8Ib/II (Houk & Swift 1999). This is a strong indication that this star is of CP2 type, because the silicon lines are also used to derive the luminosity classification.
- HD 202671: classified as B6(8)III SrTi He-w (Bychkov et al. 2003), it seems to be a transition object of the CP3 and CP4 group.
- HD 225253: we found several deviating classifications in the literature, B8III (Jaschek et al. 1969), B8IV/V p(mild) (Maitzen 1980a), and B7 UV gallium (Jaschek & Jaschek 1987). With a Δa value of +18 mmag, this object is obviously chemically peculiar.

3.1. The normal type objects

The selection of apparent normal type objects is a rather difficult task because of undetected peculiarities of all kinds which

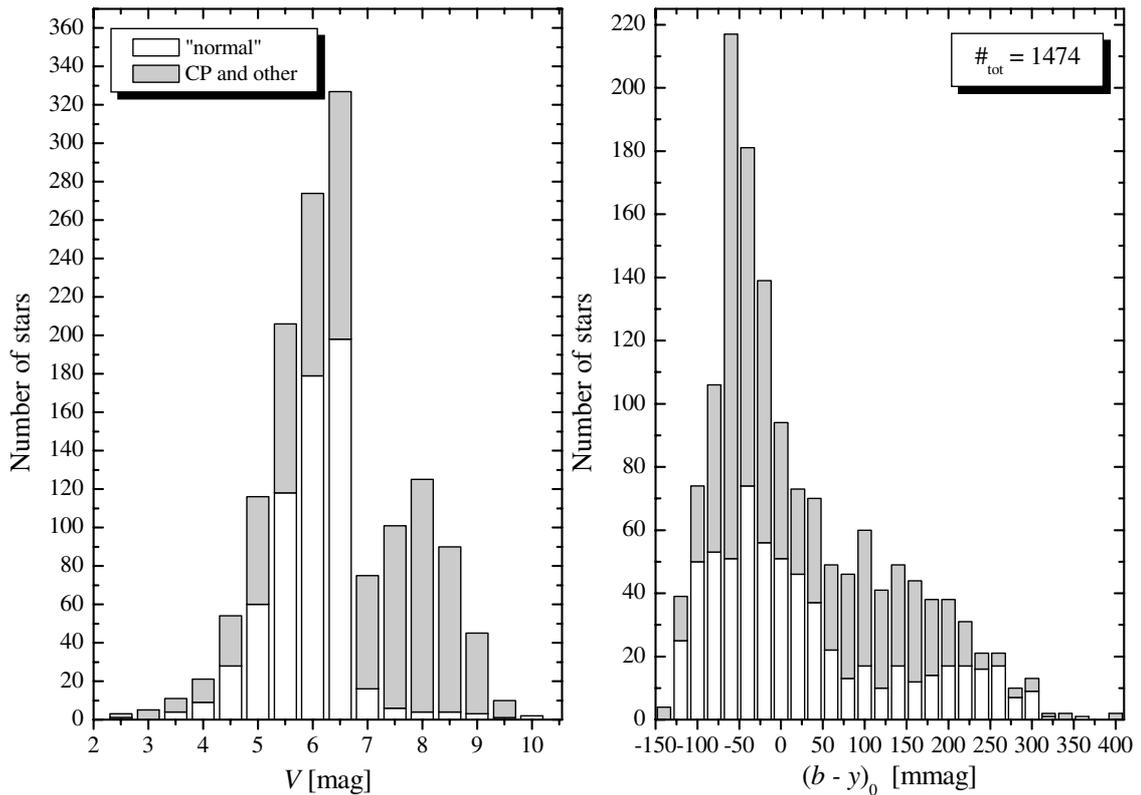


Fig. 2. The distribution of Johnson V and Strömgren $(b - y)_0$ of the sample divided into “normal” type and “other” (all objects included in Renson 1991, Table 3 and Sect. 3.2) stars.

might introduce an unknown bias. We chose all objects not listed in the catalogue by Renson (1991), because he compiled the stars which have been identified as peculiar at least once in the literature, even though they might turn out to be “normal” after all. As a next step, stars classified as λ Bootis (Paunzen et al. 2002a), Be/shell stars, and super giants of luminosity classes I and II were excluded. For this purpose the spectral classifications given in the Michigan catalogues of two-dimensional spectral types (Houk & Swift 1999, and references therein) and the extensive list of Skiff (2003) were used. Known binary systems of all kinds were not automatically excluded.

In total, 633 objects with luminosity classes V, IV, and III were selected on this basis. These stars were divided into subsamples according to their $(b - y)_0$ values with a bin size of 20 mmag, which corresponds to ± 1 spectral subclass. For each subsample we calculated the mean Δa value and the corresponding root mean square scatter for all objects within it. Figure 3 shows the results, with mean values uniformly distributed around zero. The straight lines $\pm 13 \pm 0.01(b - y)_0$ are linear fits through the mean values adding 3σ in both directions. The mean value of σ is 4.8(8) mmag in the interval from $-0.13 < (b - y)_0 < 0.31$ mag. This is in line with the values listed in Maitzen (1976) and Vogt et al. (1998). The detection limit for our sample increases from ± 12 to ± 16 mmag towards cooler objects (Fig. 3). There are two main reasons for this behaviour: 1) $g_1 - y$ is no longer only an indicator of the effective temperature because of significantly increasing line

blanketing (like $b - y$) and 2) the strong general increase in metallic lines towards later spectral types. Since most of the “normal” type stars are brighter than $V = 7$ mag (Fig. 2), we checked if the detection limit changes if only fainter “normal” objects are used. Although we are confronted with poor number statistics, no correlation was found.

The observed scatter around the normality line has several causes. Besides the instrumental limitations (e.g. photon noise and variable sky transparency), which account for about 3 mmag (Maitzen 1976), the intrinsic variations due to the natural bandwidth of the main sequence is important. Kupka et al. (2003) investigated a synthetic Δa photometric system based on modern stellar atmospheres and the filter transmission curves of “System 3” in Table 2. Their models are in the temperature range from 7000 to 15 000 K and surface gravities from 2.5 to 4.5 dex. They found a natural bandwidth of about 4 mmag within these models. A metallicity range from -0.5 to $+0.5$ dex creates an overall bandwidth ($=2\sigma$) of 10 mmag (see their Figs. 3 and 4). This is more or less exactly the value we find for our sample of normal type, galactic field stars. In open clusters for which the metallicity is rather uniform, lower detection limits are expected if neglecting strong differential reddening. Paunzen et al. (2002b) reported 3σ detection limits for five open clusters between 7 and 9 mmag for objects with $9 < V < 18$ mag. Again, this proves the high efficiency, as well as accuracy, of CCD Δa photometry in order to detect chemically peculiar objects.

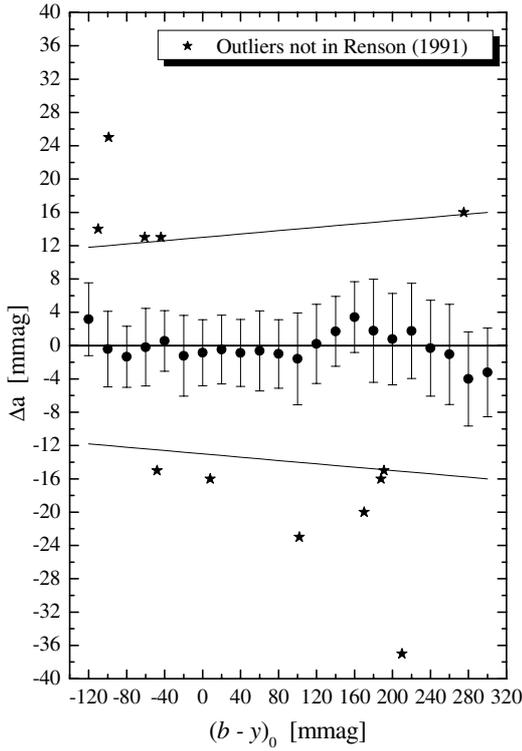


Fig. 3. The mean values and the corresponding root mean square scatter for all normal type objects with Δa measurements. The straight lines are the 3σ fits through the errors, whereas the asterisks denote the outliers of objects not included in the catalogue of Renson (1991) discussed in Sect. 3.2.

Table 3. Limits in mmag for detecting the individual groups of objects. For example 49% of all CP1 stars can be detected with a 3σ limit of +5 mmag. In addition, the mean group $\overline{\Delta a}$, the maximum values for group members Δa_m , and the number N of well-established members for the analysis are listed.

	+5	+10	+15	+20	$\overline{\Delta a}$	Δa_m	N
CP1	49%	17%	8%	1%	+3.2	+22	78
CP2	98%	93%	90%	79%	+32.5	+79	108
CP3	80%	10%	–	–	+5.3	+11	10
CP4	94%	94%	77%	35%	+18.8	+36	17
I/II	61%	28%	17%	11%	+5.4	+19	18
	–5	–10	–15	–20			
λ Boo	95%	65%	35%	20%	–16.2	–35	20
Be	41%	12%	5%	–	–1.5	–19	59

The results of the statistics for the different groups are listed in Table 3. The detection rates as functions of the corresponding 3σ limits are shown in Fig. 4.

3.2. Outliers not included in Rensons catalogue

Twelve objects (five with positive and seven with negative Δa values) are located outside the 3σ limit (Fig. 3) and are not

included in Renson (1991). First of all, we discuss the seven objects with negative Δa values in more detail:

- HD 2834 ($(b - y)_0 = +8$ mmag, $\Delta a = -16$ mmag): a known spectroscopic binary system that is also part of a visible double system.
- HD 4158 (+210, –37): a metal weak, cool star classified as hF3mF0V (wk met) by Paunzen (2001). HD 6173 (+102, –23): although previously thought to be a member of the λ Bootis group, it was classified as A0III_n by Paunzen et al. (2001).
- HD 38043 (+170, –20): classified as blue giant by Norris et al. (1985).
- HD 97937 (+188, –16): a metal weak (F0V m–1.5), intermediate Population II type object (Gray 1989).
- HD 114911 (–48, –15): a young, early type quadruple system which exhibits X-ray emission (Hubrig et al. 2001).
- HD 217792 (+191, –15): a Cepheid type variable within a spectroscopic binary system. The five objects with positive Δa values lie only marginally (exception: HD 193237) above the 3σ limit (Fig. 3):
- HD 31726 (–110, +14): a B1V star which exhibits rather normal silicon line strengths (Massa 1989).
- HD 49028 (–61, +13): a close visual binary system with a B7III and a F3V Fe–2 component (Corbally 1984).
- HD 65908 (–44, +13): Bowyer et al. (1995) reported a clear detection in the far-ultraviolet for this star which might indicate a previously unknown binary nature.
- HD 73451 (+275, +16): a known spectroscopic binary system with an early A type and a G type component (Cowley et al. 1969).
- HD 193237, P Cygni, (–99, +25): Rather outstanding, its true nature is still uncertain. Although classified as supernova, there are strong indications that this object might have undergone a superoutburst typical of luminous blue variables (Chu et al. 2004). This shows the potential of Δa photometry to detect such objects which is especially important for studying open clusters of the Milky Way and extragalactic systems.

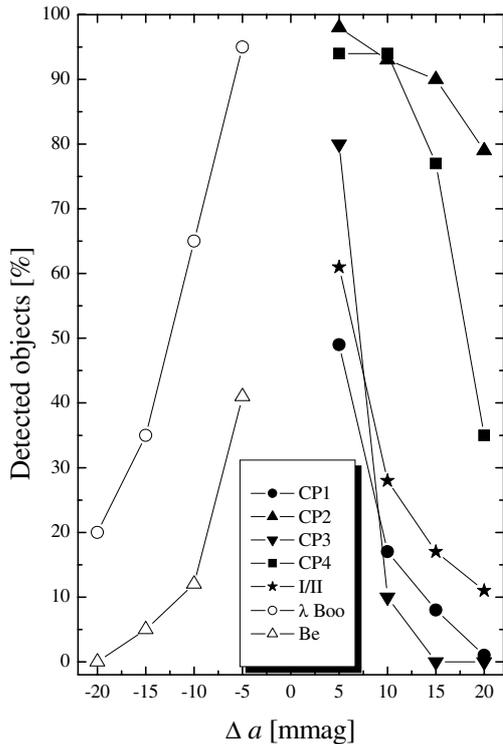
3.3. CP1 stars

The Am/Fm stars (CP1) are preferably found within close binary systems. The main characteristics of this group are the lack of magnetic fields, the apparent underabundance of calcium and scandium compared to the Sun, overabundances of Fe-peak elements, and very low rotational velocities. Almost all CP1 stars seem to be rather evolved with ages above 400 Myr (Künzli & North 1998).

The observed abundance pattern is explained by the diffusion of elements together with the disappearance of the outer convection zone associated with the helium ionization because of gravitational settling of helium (Michaud et al. 1983). They predict a cut-off rotational velocity for such objects (≈ 90 km s^{–1}), above which meridional circulation leads to a mixing in the stellar atmosphere.

Table 4. Confirmed chemically peculiar stars from Renson (1991), the type of peculiarity was taken from the literature. The complete table is only available in electronic form.

Renson	HD	$(b-y)_0$	Δa	Spec.	Renson	HD	$(b-y)_0$	Δa	Spec.	Renson	HD	$(b-y)_0$	Δa	Spec.
30	315	-71	31	Si	15910	58292	-27	34	Si	28370	98486	-60	23	Si
760	2957	-20	36	CrEu	16240	59435	284	25	SrCrSi	29270	101600	22	21	Si
1480	5601	-56	49	Si	16550	60559	-62	23	Si	29330	101724	-78	16	Si
1580	6164	-12	40	SiCrEu	16840	61382	-23	23	Si	29780	103302	4	33	SrCrEu
1620	6322	-23	22	SrCrEu	17100	-	-19	46	Si	29820	103457	-7	35	Si
1760	6783	-57	53	Si	17150	62530	-31	34	EuCr	29830	103498	-9	46	CrEuSr
2110	8783	72	23	SrEuCr	17160	62535	-35	40	Si	30330	104810	-65	19	Si
4060	16145	28	35	CrSrEu	17180	62556	35	18	EuCr	30460	105379	27	16	SrCr

**Fig. 4.** The detection probability of the different investigated groups as listed in Table 3.

In our sample, there are 78 well established CP1 stars yielding a slightly positive mean value (+3.2 mmag) and quite extreme values (+22 mmag) for some members (e.g. HD 116235, HD 184552, and HD 204541). But the detection capability is only 17% for a limit of +10 mmag (Table 3). Some of the most outstanding objects have already been discussed by Vogt et al. (1998). Kupka et al. (2003) present detailed synthetic Δa values for the CP1 group concluding that the 5200 Å flux depression is only marginally detectable for these objects. This means that the most significant elements contributing to this feature (e.g. Chromium) are not strongly enhanced in CP1 stars.

Table 4 lists only one CP1 object with a significant positive Δa value: HD 196655, which was classified as probable Am star by Bidelman (1985).

3.4. CP2 stars

This is the largest group of chemically peculiar stars already described by Maury (1897). The main characteristics of the classical CP2 stars are: peculiar and often variable line strengths, quadrature of line variability with radial velocity changes, photometric variability with the same periodicity, and coincidence of extrema. Slow rotation was inferred from the sharpness of spectral lines. Overabundances of several orders of magnitude compared to the Sun were derived for heavy elements such as silicon, chromium, strontium, and europium.

The strong global magnetic fields exhibit variability of the field strength including even a reversal of magnetic polarity leading the Oblique Rotator concept of slowly rotating stars with non-coincidence of the magnetic and rotational axes. This model produces variability and reversals of the magnetic field strength similar to a lighthouse. Due to the chemical abundance concentrations at the magnetic poles spectral and the related photometric variabilities are also easily understood, as are radial velocity variations of the appearing and receding patches on the stellar surface (Deutsch 1970).

Most of the Δa observations were dedicated to this group because of the high efficiency at detecting CP2 stars. This is also reflected by the results listed in Table 3. About 93% of all CP2 objects can be detected with a limit of +10 mmag, whereas the mean value is +32.5 mmag with an extreme value of +79 mmag. This sample includes all well-established CP2 stars classified in Renson (1991) and marked with an asterisk. We have not subdivided the sample into hotter Si and cooler CrEu(Sr) objects, because the definition is not quite clear yet (Bychkov et al. 2003).

In Table 4 we list 296 CP2 stars which are included in Renson (1991) but not marked as “well established”. These objects are obviously magnetic chemically peculiar stars because of the significant positive Δa value belonging to the given subgroup. Although several of these stars have already been assigned to the CP2 group, we see our result as further proof of membership.

3.5. CP3 stars

The HgMn (CP3) stars are generally non-magnetic, slow rotating, B type stars with large overabundances (up to five orders of magnitudes) of mercury and manganese. There are several mechanisms which play a major role in understanding these extreme peculiarities: radiatively driven diffusion, mass loss, mixing, light induced drift, and possible weak magnetic fields.

However, there is no satisfactory model which explains the abundance pattern, yet (Adelman et al. 2003).

All CP3 stars listed by Adelman et al. (2003) with Δa measurements (10 objects) have been taken for our analysis. The mean value of all objects is +5.3 mmag but with a very low maximum of +11 mmag (Table 3). The detection limit drops from 80% to 10% for +5 and +10 mmag, respectively (Fig. 4). This is comparable to the values found for the CP1 group.

3.6. CP4 stars

As defined by Preston (1974), the CP4 stars comprise helium weak, B type objects. They have strong magnetic fields (as the CP2 group) which produce elemental surface inhomogeneities together with photometric variations. Several objects also show emission in the optical spectral range and signs of mass loss (Wahlgren & Hubrig 2004). The percentage of detection (94%) at +10 mmag is even higher than that of the CP2 group leading to the conclusion that almost all magnetic chemically peculiar stars can be detected with the Δa photometric system.

Within our sample, there are also four helium rich objects: HD 37017 ($\Delta a = +2$ mmag), HD 37479 (+10), HD 64740 (−1), and HD 209339 (−20). Zboril et al. (1997) analyzed a sample of 17 helium rich objects and concluded that several stars exhibit strong emission together with stellar activity. This might be the reason for such a wide range of positive, as well as negative, Δa values were observed similar to Be/shell stars.

3.7. λ Bootis stars

This small group comprises non-magnetic, late B- to early F-type, Population I, luminosity class V stars with apparently solar abundances of the light elements (C, N, O, and S) and moderate to strong underabundances of Fe-peak elements (Paunzen et al. 2002a). Only a maximum of about 2% of all objects in the relevant spectral domain are believed to be λ Bootis type stars. Two papers by Maitzen & Pavlovski (1989a,b) were dedicated to a systematical analysis of bona-fide group members that were selected from a catalogue by Renson et al. (1990).

However, the group definition at this time was not clear, and their sample included objects which definitely not belong to this group. In our analysis, true members of this group listed by Paunzen et al. (2002a), together with HD 84948, were included. The latter is a spectroscopic binary system which includes two λ Bootis type objects (Iliev et al. 2002).

The group of λ Bootis stars is an especially excellent example of how Δa photometry can preselect candidates for spectroscopic observations, for example, in young open clusters. Paunzen (2001) presents spectral classification of 708 stars selected to be good photometric candidates only on the basis of Strömberg indices. From those, only 26 turned out to be new members of the λ Bootis group.

Within our analysis, we found twenty well-established members of the λ Bootis group with Δa measurements. The group mean value is −16.2 mmag, and a maximum of −35 mmag (Table 3) shows the high efficiency of this

photometric system. Even with a detection limit of −10 mmag, almost 2/3 of all bona-fide λ Bootis stars can be detected.

3.8. Supergiants

The only notice about a positive detection of supergiants was given by Vogt et al. (1998), who investigated two cool supergiants and found a substantial positive deviation from the normality line.

We have restricted our analysis to objects classified as luminosity class I or II in the literature. It has to be emphasized that such objects are, in general, easily sorted out within color-magnitude diagrams of different photometric systems. However, Claret et al. (2003) show that isochrones with the Δa photometric system together with the location of objects with respect to the normality line are capable of sorting out foreground and background objects very efficiently.

Analysis of supergiants in open clusters is important in several respects. Most of these giants are within binary systems and exhibit variability. Furthermore, their membership is crucial for isochrone fitting because of the sensitivity of the determined age on the existence of a “giant clump” (Eigenbrod et al. 2004). Since all known chemically peculiar stars have luminosity classes IV or V (Gómez et al. 1998), supergiants selected by their location in a color-magnitude diagram with a significant positive Δa value can be easily tested for membership in an open cluster. In total, eighteen supergiants from O9.5II (HD 47432) to F4Iab (HD 61715) are included in the investigated sample with a mean value of +5.4 and a maximum value of +19 mmag (Table 3).

3.9. Be/shell stars

These stars are defined as B type dwarfs which have shown hydrogen emission in their spectra at least once. Due to an equatorial disk produced by stellar winds, emission arises quite regularly. In addition, photometric variability on different timescales is a common phenomenon caused by the formation of shock waves within those disks. But nonradial pulsation and variability due to rotation are also observed (Porter & Rivinius 2003).

The phases of emission are replaced by shell and normal phases of the same object. This episode was analysed for the case of Pleione using Δa photometry by Pavlovski & Maitzen (1989). In the shell phase it reached a Δa value of +36 mmag, which dropped to +4 mmag within one year. However, the behaviour of Pleione seems quite extreme and outstanding, because no other similar object has been detected so far (Vogt et al. 1998). The contamination of classical chemically peculiar stars due to Be stars in a shell phase is, therefore, only marginal.

Since Pavlovski & Maitzen (1989) already presented a paper with measurements of 40 apparent Be/shell type stars, our sample is rather large, 59 objects in total. The mean value is close to zero (−1.5 mmag) with extremes of −19 mmag (emission phase) and +36 mmag (shell phase).

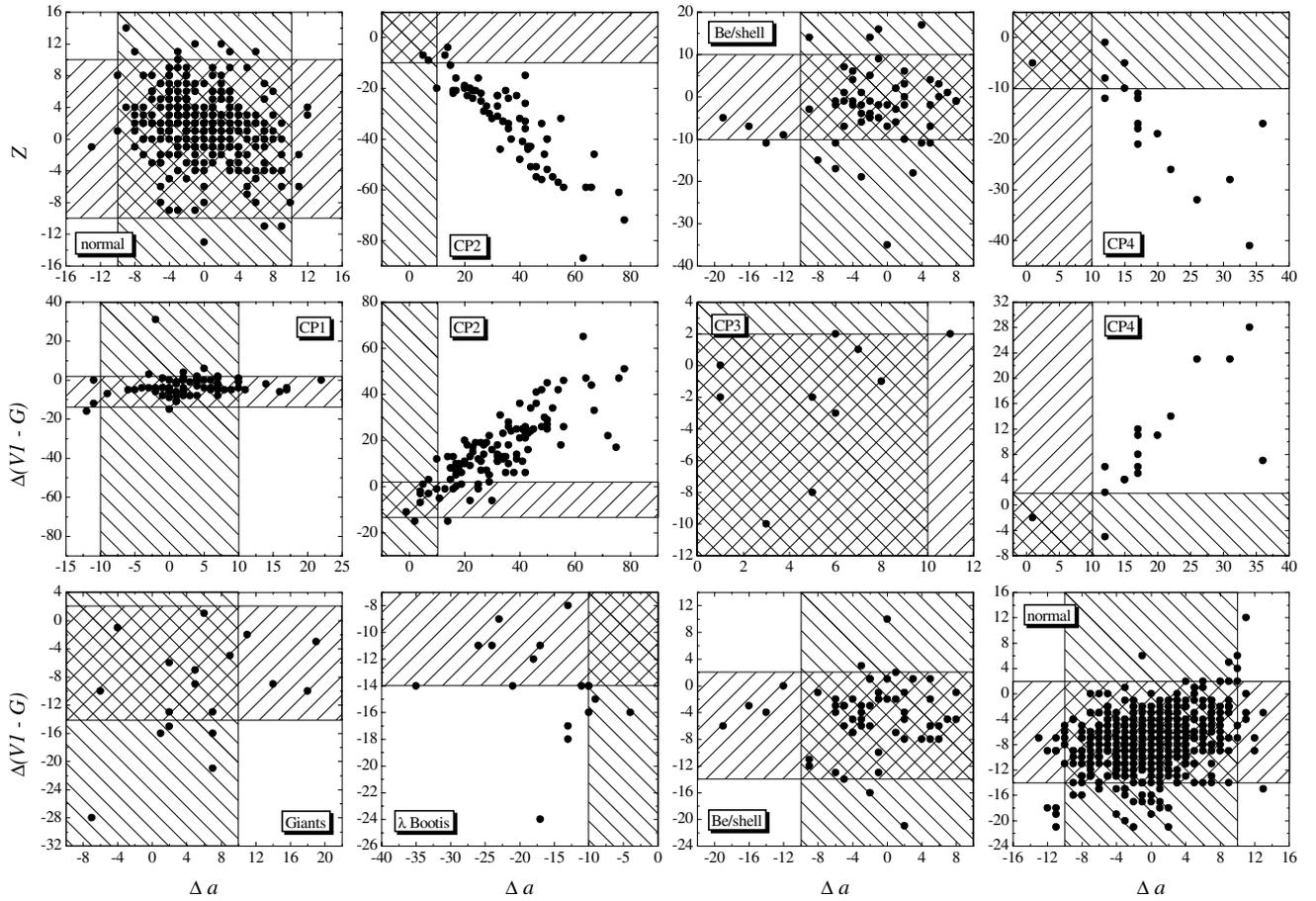


Fig. 5. Comparison of the detection capability of the Δa and Geneva $\Delta(V1 - G)$, as well as Z indices for all groups discussed in this paper. No objects of the CP1 and λ Bootis group are within the range of valid Z values, defined for stars hotter than A0. Because neither Z nor $\Delta(V1 - G)$ show significant deviating values for CP3 objects, both diagrams are identical, so we display only the $\Delta(V1 - G)$ versus Δa diagram. Since Z is not affected by gravity, the plot for supergiants was omitted. Areas with the different patterns denote the regions where the respective indices are insensitive to peculiarity. The detailed statistics of these data are listed in Table 5.

The negative Δa values found are probably caused by emission of iron and magnesium lines in the spectral region from 5167 to 5197 Å (Hanuschik 1987), which fall exactly within the g_2 filter and its bandwidth (Table 2).

3.10. Comparison with the Geneva $\Delta(V1 - G)$ and Z indices

Besides the Δa index, the $\Delta(V1 - G)$ and Z indices within the Geneva 7-color photometric system (Golay 1972; Cramer 1999) are the most suitable for detecting CP stars. The only difference between these indices is the limitation of Z to spectral types hotter than approximately A0 (Cramer 1999). Hauck & North (1982, 1993) investigated the properties of $\Delta(V1 - G)$ in the context of magnetic CP stars. Here we will recall the definition of $\Delta(V1 - G)$ and Z as

$$\begin{aligned} \Delta(V1 - G) &= (V1 - G) - 0.289 \cdot (B2 - G) + 0.302 \\ Z &= -0.4572 + 0.0255 \cdot U - 0.1740 \cdot B1 \\ &\quad + 0.4696 \cdot B2 - 1.1205 \cdot V1 + 0.7994 \cdot G. \end{aligned}$$

The $V1$ and G filters are centered at 5408 and 5814 Å (bandwidths of about 200 Å), respectively. The Geneva 7-color photometric system is the most homogeneous one because unique filter sets together with the same type of photomultipliers were used throughout its history. We took the sample as described in Sect. 3 and searched for all objects with available Geneva photometry.

The zero point of the $\Delta(V1 - G)$ index represents the upper limit of the sequence of normal type objects and not its mean value. This was done by using the upper envelope for normal type, luminosity class V to III objects, based on a linear fit for the correlation of $(V1 - G)$ with $(B2 - G)$ as given by Hauck (1974) which introduces a negative shift. The rightmost lower panel of Fig. 5 shows exactly this behavior. Only very few normal type stars exceed $\Delta(V1 - G) > +2$ mmag, whereas many normal type objects clearly have values lower than -10 mmag with a mean value of -7.6 mmag for the complete sample. We therefore introduced heuristic significance limits of $+2$ and -14 mmag for $\Delta(V1 - G)$, which brings the level of normal type objects lying outside these limits to

Table 5. A comparison of the detection capability of the Δa and Geneva $\Delta(V1 - G)$, as well as Z indices for the objects with available Geneva 7-color photometry. No objects of the CP1 and λ Bootis group are within the range of valid Z values (defined for stars hotter than A0). The results are shown graphically in Fig. 5.

	N_{tot}	$N_{\Delta(V1-G)}$		$N_{\Delta a}$		$N_{\Delta(V1-G)}$ [%]	$N_{\Delta a}$ [%]
		-	+	-	+		
CP1	71	2	4	3	6	8	13
CP2	108	2	89	-	98	84	91
CP3	10	-	-	-	1	-	10
CP4	17	-	14	-	16	82	94
I/II	18	5	-	-	4	28	22
λ Boo	17	11	-	12	-	65	71
Be	56	3	2	4	-	9	7
normal	601	27	5	9	8	5	3

	N_{tot}	N_Z		$N_{\Delta a}$		N_Z [%]	$N_{\Delta a}$ [%]
		-	+	-	+		
CP2	66	-	62	-	63	94	95
CP3	10	-	-	-	1	-	10
CP4	17	-	12	-	16	71	94
Be	56	9	4	4	-	23	7
normal	324	3	7	1	4	3	2

almost the same percentage as for the Δa photometric system (Table 5). A very strict significance limit of +10 mmag for $\Delta(V1 - G)$ was set by Hauck & North (1982) to avoid contamination of CP objects.

The Z index is virtually independent of temperature and gravity effects for stars hotter than A0 or $(b - y)_0 = 0$ mag. Cramer (1999) lists a limit of ± 10 mmag for apparent peculiarity.

Table 5 and Fig. 5 show the results. The Δa and Geneva 7-color photometric systems are able to detect magnetic CP objects (CP2 and CP4) with more or less the same statistical significance. The slope for the CP2 stars is 0.60(6) and a negligible zero point using only the objects, which are significant peculiar Δa and $\Delta(V1 - G)$ values (Fig. 5), as well as $-0.89(7)$ for Z , respectively. For the CP4 stars we get a slope of 1.26(14) and $-1.31(18)$, not taking the one deviating object (HD 174638) into account, respectively.

For λ Bootis stars the detection capability is similar to that of Δa . But for the Be/shell stars, the $\Delta(V1 - G)$ and Z indices are even more sensitive. For the giants, an interesting behaviour was found. While four stars exhibit significant positive Δa values, five stars have significant negative $\Delta(V1 - G)$ ones, but no positive value was found.

4. Conclusions

All Δa measurements for galactic field stars, 1474 objects in total, of the literature were, for the first time, compiled and homogeneously analyzed. This intermediate band photometric system samples the depth of the 5200 Å flux depression by comparing the flux at the center with the adjacent regions. Although it was slightly modified over the last three decades, no systematic trend of the individual measurements was found.

This photometric system is most suitable for detecting magnetic CP stars with high efficiency (up to 95% of all relevant objects). But it is also capable of detecting a small percentage of non-magnetic CP objects. Furthermore, the groups of (metal-weak) λ Bootis, as well as classical Be/shell stars, can be traced with the help of this photometric system. In addition, we investigated the behaviour of supergiants (luminosity class I and II). On the basis of apparent normal type objects, the correlation of the 3σ significance limit and the percentage of positive detection for all groups was derived. This is especially important for observations in open clusters of the Milky Way and even the Magellanic Clouds. As a next step, we compared the capability of the Δa photometric system with the $\Delta(V1 - G)$ and Z indices of the Geneva 7-color system to detect peculiar objects. Both photometric systems show the same efficiency for detection of magnetic CP and λ Bootis stars; the indices in the Geneva system are even more efficient concerning the Be/shell objects.

On the basis of this statistical analysis, it is possible to derive the incidence of CP stars in galactic open cluster and extragalactic systems, including the former unknown bias of undetected objects.

It seems worthwhile to investigate whether the formation of magnetic peculiar objects occurs in the same proportion to “normal” stars for all degrees of metallicity. Stellar models then have to explain chemically peculiar stars taking different metallicities, ages, and magnetic field strengths into account as found for different individual galactic open clusters.

Acknowledgements. We would like to thank P. North for pointing on a serious error in treating the Geneva measurements and for several comments that improved this paper significant. This work benefited from the Fonds zur Förderung der wissenschaftlichen Forschung, projects P17580 and P17920, as well as the City of Vienna (Hochschuljubiläumsstiftung project: Δa Photometrie in der Milchstrasse und den Magellanschen Wolken, H-1123/2002). Use was made of the SIMBAD database, operated at the CDS, Strasbourg, France. This research made use of NASA’s Astrophysics Data System.

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