1 Summary

This book describes the history, characteristics, observations, results and future prospects of the Δa photometric system. Up to now, it successfully produced countless scientific output since its development and first appearance on the astronomical scene initiated by Hans-Michael Maitzen in 1976.

It was intended to study the typical and unique flux depression at 5200 Å found in mainly magnetic chemically peculiar stars of the upper main sequence. Therefore the most important measurement is through the g_2 filter centred at this wavelength region. In addition, one needs the information about the continuum flux of the same object. Originally, the g_1 (centred at 5000Å) and Strömgren y (5500Å) was used to get the continuum flux. In principle, any other filters such as Johnson $BVRI$ can be used. However, the closer it is measured to the 5200Å region and the narrower the used filters are, the results become more accurate. The a index is then defined as the flux in g_2 compared to the continuum one. Because there is a general increase of opacity around 5200Å with decreasing temperature, one has to normalize a with the index a_0 of a non-peculiar star of the same temperature, to compare different peculiar (or deviating) stars with each other (Δa index).

With this photometric system it is possible to measure any peculiarities, such as abnormal absorption and emission lines, in the region of 5200Å. Soon, it was used to investigate metal-weak, Be/shell and supergiants in the Galactic field and open clusters.

At the end of the 1980ies, the highly developed photomultiplier technology, slowly but surely, was replaced by the CCD technology. It took a few years until CCDs reached the same accuracy as photomultipliers for the same exposure time and target brightness.

The first CCD Δa observations which were performed 1995 with the same telescope, the 61 cm Bochum telescope at La Silla, by the same person, Hans-Michael Maitzen, who initiated in 1971 the observations of CS Vir in g_1 and g_2. The results of the first CCD observations, data for 25 Galactic field stars with known spectroscopic peculiarity types, were published in 1997. After that, CCD observations of open clusters, the Large Magellanic Cloud and Globular clusters were successfully secured.

This book goes one step further showing that the Δa photometric system and the study of its corresponding spectral region from 4900 to 5700Å is able to contribute significant new insights at many fields of astrophysics. The list of objects which are potential targets is long: cool-type Population

I and Population II objects, supergiants, emission type objects, all type of galaxies, and so on.

These research fields can be investigated by 1) new observations; 2) archival data not used so far, for example cool-type objects in star cluster fields and 3) data from other surveys which employ similar filters. For sure, all three approaches will be extensively utilized in the future.

2 The early history of the Δa photometric system

The roots of the Δa photometric system date back to the year 1969. The invention and development of it is closely tied to ao. Univ.-Prof. i.R. tit. Univ.-Prof. Dr. Hans-Michael Maitzen (HMM). The interested reader is referred to his article "Two decades of Δa photometry" published by Maitzen (1998) which includes a comprehensive overview of the history until then.

Here, a very short overview is given because it sheds more light on the original intentions which are still state-of-the-art today.

In 1969, HMM got a position at the newly founded astronomical institute of the Ruhr-University of Bochum, Germany. Soon, the at that time, head of the institute, the late Prof. Theodor Schmidt-Kaler invited him to perform photometric observations at the Bochum 61 cm telescope at ESO (La Silla). He started the observations in May 1969, only less than two months after the official opening of the observatory on 23. March 1969. He monitored magnetic stars (CP2) from the catalogue by Babcock (1958) as suggested to him by the late Prof. Karl Rakos. This was to confirm the variability of these stars by means of Johnson UBV photometry. The "key star" for the further historical development was CS Vir (HD 125248), a classical CP2 object. HMM found not only, as expected, a decrease of the variability amplitude from U to B, but also the V light curve exhibited either half the period of U and B, or as we know today, a double wave variation due to the variable continuum backwarming produced by strong line absorption at shorted wavelengths.

These results were published by Maitzen & Rakos (1970). As next step, photometric observations in the Strömgren system and spectroscopy of CS Vir was done. Because no filter covered the wavelength interval where the transition from a single to a double wave variation occurred, he decided to order two new interference filters (g_1, $\lambda_c = 5020$ Å and g_2, $\lambda_c = 5240$ Å, both with FWHM = 130 Å). These filters are already very close to those used today (Sects. 9 and 14.1.1). From their colour appearance to the human eye, Prof. Schmidt-Kaler suggested to name them *giftgrün* (poisonous green, g_1) and *lindgrün* (yellowish green, g_2) which was rejected for practical reasons. The first observations with these filter were conducted in 1971 in order to trace the light variability of CS Vir but not in the way, the Δa photometric system is used nowadays. The most important result for the birth of the system was the detection of the characteristic flux depression at 5200Å by Kodaira (1969) which can be measured via

g_2. This prompted HMM to substantiate the feature by a more extended photometric campaign of different CP stars (not only magnetic ones) and apparent normal type ones. Using the already available Strömgren y filter, he defined the normality line, and the final Δa parameter. The foundation paper then appeared more than 40 years ago (Maitzen, 1976a).

3 The diagnostic tools of the Δa photometric system

Here, an overview of the characteristics and diagnostic tools of the Δa photometric system is given. One has to refer to many consecutive Sections where these tools are applied and discussed in more detail. Some of the information given here might be repeated there because of the necessity to clarify some points within the context. However, it was tried to minimize such duplicities.

Basically, the Δa photometric system consists of one filter which measures the 5200Å region (g_2) and an additional information about the continuum flux of the same object. This can be either achieved by measuring the flux at the adjacent spectral regions, for example with the filters g_1 (5000Å) and $g_3 = y$ (5500Å), but also by any other effective temperature ($T_{\rm eff}$) sensitive colour, $B-V$, $b-y$, or $B2-V1$ to give some examples. The latter were indeed successfully applied, for example, Maitzen et al. (1986) used $b-y$, whereas Maitzen (1993) also employed $B-V$ colours.

With these measurements, the index a can be calculated as

$$a = g_2 - \frac{g_1 + y}{2} \qquad (1)$$

$$a = g_2 - \frac{b + y}{2} \qquad (2)$$

$$a = g_2 - \frac{B + V}{2} \qquad (3)$$

In principle, the positioning of the continuum filters minimizes the influence of $T_{\rm eff}$ on the peculiarity index. The closer it is measured to the 5200Å region and the narrower the used filters are, the results become more accurate. One has to avoid, for example, the hydrogen or helium lines for the continuum measurement because they are very much sensitive to the projected rotational velocity and the surface gravity.

In Sect. 10, Table 9 lists several different filters which were used in the past for different purposes to obtain observations. There is a general increase of opacity around 5200Å with decreasing temperature (Sect. 14.1).

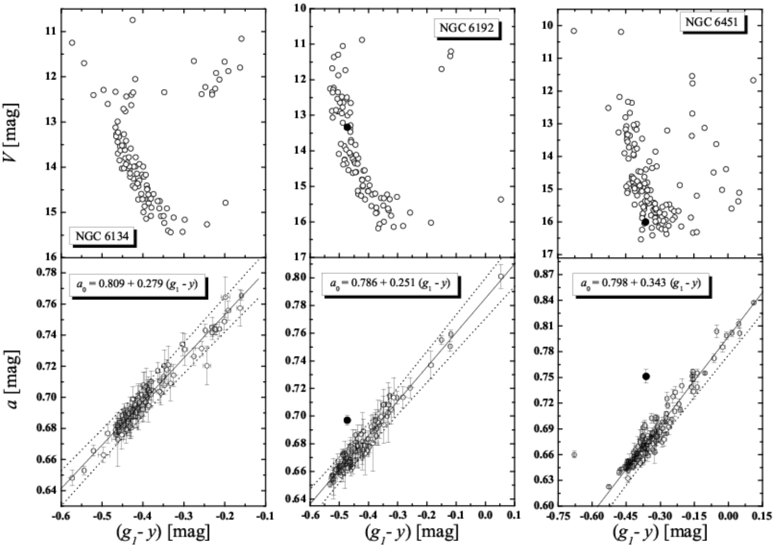

Figure 1: The two basis diagnostic tools of the Δa photometric system for three open clusters: the normality line a_0 versus $(g_1 - y)$ and colour-magnitude $M_{\rm V}$ versus $(g_1 - y)$ diagrams together with isochrones.

Therefore, one has to normalize a with the index a_0 of a non-peculiar star of the same temperature, to compare different peculiar (or deviating) stars with each other. The photometric peculiarity Δa index is therefore defined as

$$\Delta a = a - a_0[(g_1 - y); (b - y); (B - V))]. \tag{4}$$

The first diagnostic tool is the *normality line* which comprises of the location of the a_0-values in respect to a $T_{\rm eff}$ sensitive colour. Assuming that all stars exhibit the same interstellar reddening, peculiar objects deviate from the normality line more than 3σ (Fig. 1).

From observations, it is known that the normality line is shifted by $E(b-y)$ to the red and by a small amount $E(a)$ to higher a-values (Maitzen, 1993). It has to be emphasized that correlations between the amount of reddening for different photometric systems exist (Sect. 12.1.2, Yuan et al., 2013), for example $A_V = 3.1E(B-V) = 4.3E(b-y)$. These correlations can be used to transform the reddening values between the different photometric systems. The ratio of the shifts

$$f = E(a)/E(b-y) \tag{5}$$

can be determined from the deviation of a reddened cluster normality line from the unreddened relationship. On the other hand, assuming a mean f-value (≈ 0.05) and iterating the formula

$$a(\mathrm{corr}) = a(\mathrm{obs}) - fE(b-y) \tag{6}$$

one can determine reddening values by the Δa-photometry of clusters. The effect has only to be taken into account for $E(b-y) > 0.3$ mag and a non uniform reddening distribution.

More of a problem is the estimation of differential reddening within a star cluster (Bonatto et al., 2012), for example. In principle, several methods can be applied (Sects. 12.1.2 and 12.2.2) to overcome this problem:

- to deredden each individual object using the Strömgren $uvby\beta$ photometric system and its calibrations
- to use the Q-method for the Johnson UBV photometric system

An a versus $(g_1 - y)_0$ or $(b-y)_0$ or $(B-V)_0$ diagram should then be able to further strengthen the membership of objects to the investigated star cluster since fore- and background deviate significantly from the normality line. These deviations are in generally ten times higher than those observed for the most prominent CP stars.

The second diagnostic tool is a y versus $(g_1 - y)$ diagram. Instead of y, any other magnitude, for example, V, R, I, and so on, can be taken. This is just a classical colour-magnitude diagram (CMD) for the Δa photometric system. With the knowledge of the reddening and the distance, the absolute magnitude M_{V}, and using the bolometric correction (B.C.) as well as the absolute magnitude of the Sun, the luminosity $\log L/L_{\odot}$ can be calculated (Gómez et al., 1998).

In Sect. 13, a grid of isochrones with different initial chemical compositions for the Δa system is presented. There, it is shown that the accuracy of fitting isochrones to Δa data without the knowledge of the cluster parameters is between 5 and 15 %. This efficient tool has been already widely used for star clusters and the LMC (Sects. 17 and 19).

Figure 1 shows M_{V} versus $(g_1 - y)$ diagrams (upper panels) together with isochrones for three open clusters. The capability to sort out non-members and to estimate the cluster parameters are evident.

4 Other indices measuring the 5200Å region

One has to differentiate between indices which measure the flux in the 5200Å region directly and those which measure the metallicity (line blan-

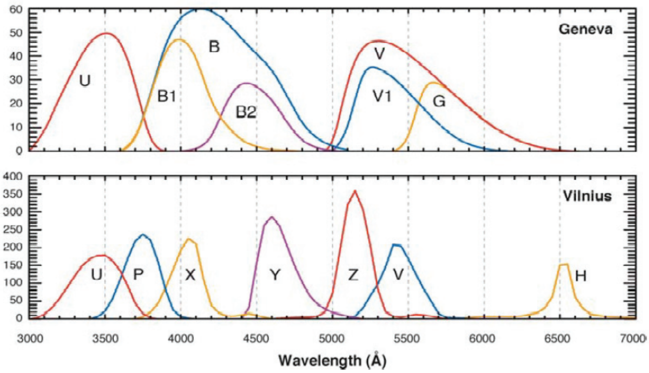

Figure 2: The filter transmission curves of the Geneva 7-colour (upper panel) and Vilnius (lower panel) system taken from Bessell (2005).

keting). The latter are capable to detect most extreme CP stars because of their prominent overabundances. Those are, for example, the m_1, Δm_1, and $[m_1]$ in the Strömgren system as well as m_2 and δm_2 in the Geneva 7-colour system (Golay, 1974).

Another interesting approach was published by Masana et al. (1998). They defined a reddening-depended peculiarity index Δp as a linear combination of all Strömgren $uvby\beta$ colours. They found a detection rate of up to 50% for early (hot) CP2 stars. However, this approach was not systematically followed after the original paper has been published. It would be very interesting to use the new photometric catalogue by Paunzen (2015) to update and upgrade this method.

Besides the Δa photometric system (Sect. 3), a few other indices are available which measure the flux in the 5200Å region. These are described in more detail in the following.

The $\Delta a'$ index by Adelman (1979): it basically works in the same way as the "classical Δa index", but was especially designed for his spectrophotometric data. It is defined as

$$a' = m_{5264} - [m_{4785} + 0.453 \cdot (m_{5840} - m_{4785})]. \quad (7)$$

The measurements at 4785 and 5840Å, which were both made at locations significantly bluer than g_1 and redder than y, represent a wavelength base for the continuum that is larger by a factor of two than in Δa photometry. The depression itself is represented by the 5264Å value. Like the a index, the a' index is slightly dependent on the colour of the star and therefore has to be normalized by the index of non-peculiar stars with the same colour.

The $\Delta(V1-G)$ *and* Z *indices of the Geneva 7-colour system*: The Geneva 7-colour photometric system (Fig. 2) is the most homogeneous one because unique filter sets together with the same type of photomultipliers were used throughout its history (Golay, 1994). However, unfortunately, no new observations are available for it because the original instrumentation is not existing any more. The $\Delta(V1-G)$ index is the first measurement for peculiarity derived from the Geneva 7-colour photometric system. The $V1$ and G filters are centred at 5408 and 5814Å (bandwidths of about 200Å), respectively. Hauck (1974) was the first to propose this index as peculiarity parameter. It is defined as

$$\Delta(V1-G) = (V1-G) - 0.289 \cdot (B2-G) + 0.302. \quad (8)$$

On average, normal stars have $\Delta(V1-G)$ values of -5 mmag (Sect. 11.11). 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 this negative shift. Consequently, a very strict significance limit of $+10$ mmag for $\Delta(V1-G)$ was set by Hauck & North (1982) to avoid contamination of CP objects.

Besides the $\Delta(V1-G)$ index, Z within the Geneva 7-colour photometric system is most suitable for detecting CP stars. Originally, Cramer & Maeder (1979) defined a three-dimensional grid $[XYZ]$ for hot stars on the basis of the seven available filters (Fig. 2). The X parameter is oriented along the main sequence (MS) of O- and B-type, whereas the Y is in the direction of high luminosity stars. The Z parameters is normal to the $[XY]$ plane. It is defined (Cramer, 1999) as

$$Z = -0.4572 + 0.0255 \cdot U - 0.1740 \cdot B1 + 0.4696 \cdot B2 - 1.1205 \cdot V1 + 0.7994 \cdot G \quad (9)$$

The Z index is virtually independent of temperature and gravity effects for stars hotter than A0 or $(b-y)_0 < 0$ mag. Furthermore, the only stars showing a significant deviation in the Z direction, are the CP stars. Later on, Cramer & Maeder (1980) showed that Z is correlated with the measured magnetic field of CP stars. This is line with the corresponding synthesized photometry (Sect. 14.9.2). Cramer (1999) lists a limit of ± 10 mmag for apparent peculiarity (Sect. 11.11).

As the Δa index (Sect. 5.1), $\Delta(V1-G)$ and Z also vary over the rotational period of CP2 stars (Muciek et al., 1984). However, the variations (± 3 mmag) are less than those for the Δa index.

The different diagrams of the Vilnius system: The Vilnius system (Fig. 2) was developed independently from the Geneva 7-colour system but for similar reasons, namely, to derive temperatures, luminosities, and peculiarities in reddening and composition from photometry alone. The colours are normalized by the condition $U-P = P-X = X-Y = Y-Z = Z-V = V-S$ for unreddened O-type stars. Therefore, all colours for normal stars are positive. Reddening free indices are constructed as for the Geneva 7-colour and Strömgren systems. Interesting enough, the Z filter was placed on the Mg I triplet as well as the MgH molecular band. It is also sensitive to the luminosity classes of G- to M-type stars (Straižys et al., 1986). Straižys & Žitkevičius (1977) proposed four diagrams to separate CP from normal type stars. They defined the following index

$$Q_{\mathrm{Y}ZS} = Y - Z - 0.538 \cdot (Z - S) \qquad (10)$$

which is, in principle, independent of interstellar reddening. If a star exhibits $Q_{\mathrm{Y}ZS} < -0.03$ mag it can be considered as CP object. They found that 56% of CP stars (denoted as Ap stars in their work) have such values with the classical hot Si stars show the largest and the HgMn (CP3) the smallest deviations. It turned out that strongly reddened and cool type CP stars can not be unambiguously detected. Also, this index fails to detected CP1 stars which is similar to the situation within the Δa photometric system (Sect. 11.3). However, CP1 stars can be detected in the Vilnius system on the basis of CMDs including the U filter. Later on, North et al. (1982) discussed the capabilities of a joint Vilnius and Geneva 7-colour (VILGEN) system to detect CP stars. They improved the detection capability of $\Delta(V1-G)$ by using the Vilnius Z filter (not to be confused with the Geneva Z index) instead of $V1$. In addition, they defined four peculiarity indices (PECx). Using these indices, 54% of magnetic Ap (CP2 and CP4) stars were detected. Since then, no new corresponding investigation has been published employing this extended system.

5 The variability of the Δa index

If one looks very closely on the brightness of any arbitrary chosen star, one will find variability on different time scales. The detection limit of the amplitude only depends on the instrumentation and accuracy of the measurements. The Sun, as the closest star, shows variability with periods from minutes (not visible by eye) to several years (sunspots). Variable stars are divided into two categories: intrinsic variables, in which internal physical changes, such as pulsations or eruptions, are the driving mechanism, and extrinsic variables, in which the light output fluctuates due to planet transits, eclipses or stellar rotation (Percy, 2007). The further classification is rather complex; originally it was based on a star's light-curve characteristics, amplitude, and periodicity (or the lack of it). Many astrophysical theories, for example pulsation, diffusion, and evolutionary models, can be tested with variable stars (Handler, 2013).

It is also well known that the amplitude of almost all types of variability is depending on the observed wavelength region. For example, CP stars exhibit larger amplitudes in the UV than in the IR region (Krtička et al., 2012). Therefore, it was several times tested if and how the variability of stars influences the 5200Å region and the Δa index. The knowledge of this behaviour is essential to estimate the percentage of missed positive (or negative) detections, for example.

5.1 CP stars

Here, the published results of the analysis of the variability behaviour for 17 well established CP stars is presented. Let us recall that the main characteristics of this group are (Sect. 6): peculiar and often variable line strengths, quadrature of line variability with radial velocity changes, photometric variability with the same periodicity and coincidence of extrema. Stibbs (1950) introduced the Oblique Rotator concept of slowly rotating stars with non-coincidence of the magnetic and rotational axes. This model reproduces the photometric variability by the appearing and receding patches on the stellar surface similar to Sun spots.

Table 1 lists the spectral types (Skiff, 2016), dereddened $(b-y)$ colours (Sect. 10), averaged quadratic effective magnetic field $\langle B_\mathrm{e}\rangle$ (Bychkov et al., 2009), the rotational period P, the observed Δa range, and the mean absolute Δa value of the sample. It was chosen to list here the $\langle B_\mathrm{e}\rangle$ values by Bychkov et al. (2009) because they compiled a homogeneous sample of measurements. For the definition of $\langle B_\mathrm{e}\rangle$ and its correlation with the magnetic field modulus, for example, the reader is referred to Bychkov et al. (2003). Briefly, the effective magnetic field B_e of a star is a complex average over the stellar disc of the projection of the local vector of magnetic intensity on the line of sight, and can be measured as the splitting of circularly polarized components of spectral lines.

Table 1: The spectral types (Skiff, 2016), dereddened $(b-y)$ colours (Sect. 10), averaged quadratic effective magnetic field $\langle B_{\rm e}\rangle$ (Bychkov et al., 2009), the rotational period P (references see text), the observed Δa range (references see text), and the mean absolute Δa value (Sect. 10). For some objects, the mean absolute Δa value could be higher than the given range because there is an offset between different applied filter systems (see Section 7 in Hensberge et al., 1981).

HD	HIP	Spec	$(b-y)_0$ [mag]	$\langle B_{\rm e}\rangle$ [G]	P [d]	$\Delta a_{\rm range}$ [mmag]	Δa [mmag]
3980	3277	Ap SrEuCr	+0.079	780(25)	3.9516	+39 ... +49	+38
5601	4488	Ap Si	−0.056	1192(100)	1.11	+52 ... +66	+49
19712	14736	A2p CrEu	−0.060	2268(225)	2.1945	+44 ... +62	+43
25267	18673	B9p Si	−0.070	241(91)	1.21	+30 ... +50	+36
30466	22402	B9p SiCr	+0.025	1716(354)	2.7795	+42 ... +57	+50
30849	22340	Ap SrCrEu	+0.166		15.865	+12 ... +37	+30
38823	27423	A5p Sr	+0.151	1509(111)	8.635	+06 ... +16	+19
50169	32965	Ap SrCrEu	−0.035	1218(70)	1.729	+65 ... +67	+78
52847		Ap CrEuSr	+0.102			+53 ... +58	+62
53116	34049	Ap SrEu	−0.046		11.978	+38 ... +63	+50
55540		Ap CrEu	−0.068			+66 ... +71	+70
56022	34899	Ap SiSr	−0.022	202(117)	0.9184	+18 ... +26	+16
72968	42146	A0p SrCr	−0.039	445(181)	11.305	+12 ... +21	+50
81009	45999	A2p SrCrEuSi	+0.086	1431(204)	33.984	+29 ... +37	+35
111133	62376	A0p SrEuCr	−0.057	807(143)	16.31	+43 ... +73	+56
116458	65522	Ap CrSrEu	−0.036	1926(273)	126.18	+14 ... +32	+54
126515	70553	A2Vp SrSiCr	−0.038	1859(360)	129.95	+33 ... +74	+52

Note that the $g_1, g_2, g_3/y$ filters, for example, used by Hensberge et al. (1981) are slightly different than those used by Maitzen (1976a). Therefore, there is an offset between these systems (see Section 7 in Hensberge et al., 1981). In Sect. 10, mean absolute Δa values from different sources are presented. These values can be, for some objects, higher than those derived by the references mentioned in the following. However, the aim of this analysis is, if the individual CP stars would have been detected independent of the knowledge about the observed phase of variability. This is the most general case possible. Or in other words, is the expected minimum Δa value over the phase still above the detection limit (Sect. 10). In the following, the results of the individual stars, listed in Table 1, are discussed in more detail.

HD 3980: Nesvacil et al. (2012) performed a spectrum analysis in order to determine atmospheric parameters for Doppler imaging. They detected also horizontal inhomogeneities (stratification) in the stellar atmosphere. However, no obvious correlation between theoretical predictions of diffusion in CP stars and the abundance patterns could be found. The rotational period of 3.9516 d was deduced by Maitzen et al. (1980). They also investigated the behaviour of the Δa index over the rotational period (+39 … +49 mmag).

HD 5601: Besides the classification as CP star, not many investigations were devoted to it. Joshi et al. (2009) unsuccessfully search for rapid oscillations (periods below 25 minutes) whereas Hensberge et al. (1981) estimated a rotational period of close to one day. The Δa index varied for ±7 mmag on a very high absolute level.

HD 19712: The rotational periods published by Hensberge et al. (1981, 2.1945(2) d) and Dubath et al. (2011, 2.0422 d) are slightly different. The latter is based on the Hipparcos photometry (Høg et al., 2000). However, Hensberge et al. (1981) noticed that one of their apparent constant comparison star, HD 20319, seems to be a low amplitude variable. Speckle interferometry (Horch et al., 2006) revealed that HD 20319 is a close binary system with a separation of about 1". The variability of this object could be due to binarity. For HD 19712, the variations of Δa range from +44 to +62 mmag.

HD 25267: Glagolevskij & Nazarenko (2015) presented a detailed analysis of the magnetic field geometry for this star with its period slightly longer than one day. The rather large variability of the Δa index (Hensberge et al., 1981) can be possibly explained by the strong dipole shift across the axis when the magnetic poles are located close to each other (Glagolevskij & Nazarenko, 2015).

HD 30466: It is a double wave photometric variable CP2 star (P = 2.7795 d) with an averaged quadratic effective magnetic field of about 1.5 kG (Bychkov et al., 2009). The measured Δa values over the rotational period are between +42 and +57 mmag (Maitzen, 1976b) which are well above detection limit.

HD 30849: This star was often used as a "standard object" which does not show any rapid oscillation (Balmforth et al., 2001). It is one of the coolest CP star investigated for variations in the Δa index. The rotational period of about 15.865 d (Hensberge et al., 1982) is well established. The lower measured Δa of +12 mmag (Hensberge et al., 1981, 1982) is close to the defined detection limit.

HD 38823: Hensberge et al. (1981) found a rotational period of 8.635 d for this cool CP star with a rather strong averaged quadratic effective magnetic field (1.5 kG, Bychkov et al., 2009). The maximum observed Δa index of +19 mmag (Sect. 10) is not very high, probably because of its rather low $T_{\rm eff}$ and the decreasing sensitivity of Δa in this regime (Sect. 14.9.2). In certain phases of the rotational cycle, HD 38823 would have