The 5200 Å flux depression of chemically peculiar stars: 
I. Synthetic Δa photometry - the normality line.

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ABSTRACT

The Δa photometric system provides an efficient observational method to identify and distinguish magnetic and several other types of chemically peculiar (CP) stars of spectral types B to F from other classes of stars in the same range of effective temperatures. We have developed a synthetic photometric system which can be used to explore the capability of model atmospheres with individual element abundances to predict photometric Δa magnitudes which measure the extent of the flux depression around 5200 Å found in different types of CP stars. In this first paper, we confirm the observed dependency of the Δa index as a function of various colour indices sensitive to the effective temperature of stars as well as its average scatter expected from surface gravity variations within the main sequence band. The behaviour of the so-called “normality line” of Δa systems used in photometric observations of CP stars is well reproduced. The metallicity dependence of the normality line of the Δa system was computed for several grids of model atmospheres where the abundances of elements heavier than He had been scaled ±0.5 dex with respect to the solar value. We estimate a lowering of Δa magnitudes for CP stars within the Magellanic Clouds by ∼ −3 mmag relative to those in the solar neighbourhood assuming an average metallicity of [Fe/H] = −0.5 dex. Using these results on the metallicity bias of the Δa system we find the observational systems in use suitable to identify CP stars in other galaxies or distant regions of our own galaxy and capable to provide data samples on a statistically meaningful basis. In turn, the synthetic system is suitable to test the performance of model atmospheres for CP stars. This work will be presented in follow-up papers of this series.

Key words: stars: atmospheres — stars: chemically peculiar

1 INTRODUCTION

The chemically peculiar (CP) stars of the upper main sequence have been targets for astrophysical studies since the discovery of these objects by the American astronomer Antonia Maury (1897). Most of this early research was devoted to the detection of peculiar features in their spectra and photometric behaviour. The main characteristics of the classical CP 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 Si, Cr, Sr, Eu, and for other heavy elements.

Babcock (1947) discovered a global dipolar magnetic field in the star 78 Virginis followed by a catalogue of similar stars (Babcock 1958) in which also the variability of the field strength in many CP stars — including even a reversal of magnetic polarity — was discovered. Stibbs (1950) introduced the Oblique Rotator concept of slowly rotating stars with non-coincidence of the magnetic and rotational axes. This model reproduces variability and reversals of the magnetic field strength. Due to the chemical abundance concentrations at the magnetic poles also spectral and related photometric variabilities are easily understood, as well as radial velocity variations of the appearing and receding patches on the stellar surface.

Preston (1974) divided the CP stars into the following groups:
• CP1: Am/Fm stars without a strong global magnetic field; weak lines of Ca\textsc{ii} and Sc\textsc{ii}, otherwise strong over-abundances;
• CP2: “classical” CP stars with strong magnetic fields (they are also known as the magnetic CP or mCP stars);
• CP3: HgMn stars, basically non-magnetic;
• CP4: He-weak stars, some of these objects show a detectable magnetic field.

Kodaira (1969) was the first who noticed significant flux depressions at 4100 Å, 5200 Å, and 6300 Å in the spectrum of HD 221568. Jamar (1977, 1978) investigated similar features in the ultraviolet region at 1400 Å, 1750 Å, and 2750 Å. All features were found to be only visible in magnetic CP stars.

Maitzen (1976) introduced the narrow band, three filter $\Delta a$ system in order to investigate the flux depression at 5200 Å. It samples the depth of this flux depression by comparing the flux at the center (5220 Å, $g_2$), with the adjacent regions (5000 Å, $g_1$ and 5500 Å, $g$) using a band-width of 130 Å (for $g_1$ and $g_2$) and the band-width of 230 Å for the Strömgren $y$ filter. The respective index was introduced as:

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

Since this quantity is slightly dependent on 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 $a$-value and the $a$-value of non-peculiar stars of the same colour. It was shown (e.g. Vogt et al. 1998) that virtually all peculiar stars with magnetic fields (CP2 stars) have positive $\Delta a$ values up to $+75$ mmag whereas Be/Ae and $\lambda$ Bootis stars exhibit significantly negative ones (Maitzen & Pavlovski 1989a,b,c). Extreme cases of the CP1 and CP3 group may exhibit marginally peculiar positive $\Delta a$ values (Maitzen & Vogt 1983).

Several attempts have been made to explain the origin of this feature. Adelman & Wolken (1976) and Adelman, Shore & Wolken (1976) investigated bound-free discontinuities, Jamar, Macau-Hercot & Praderie (1978) proposed autoionisation transitions of Si\textsc{ii}, whereas enhanced line absorption was discussed by Maitzen (1976) and Maitzen & Muthsam (1980). The latter presented a comparison of synthesised flux distributions and observed spectrophotometry (the first attempt in this direction was by Leckrone, Fowler & Adelman 1974). From their synthetic spectra they recovered a narrow and deep feature at about 5175 Å and a broad component centred at about 5275 Å. They were not able to reproduce the flux depression for effective temperatures higher than 8000 K. More recently, Adelman et al. (1995) have used model atmospheres of Kurucz (1993a,b) with enhanced metallicity (i.e. a solar element abundance distribution where all elements heavier than He had been scaled by $+0.5$ or $+1.0$ dex) and concluded that at least part of the 5200 Å feature in magnetic CP stars may be due to differential line blanketing. In a follow-up work, Adelman & Rayle (2000) have extended this study to a larger group of stars and found that solar composition models may successfully predict the flux distribution of normal and many CP3 (HgMn) stars, while they fail to do so for a number of CP2 stars, i.e. the group of stars showing the largest flux depression in the 5200 Å region and thus the largest magnitudes in $\Delta a$.

One of the main conclusions drawn from these previous works has been the necessity to build specific model stellar atmospheres for CP stars using state-of-the-art opacity data. The increase in available computer power and advances in computational algorithms during the last two decades have now brought this problem into the realm of workstations and personal computers. Moreover, stellar atmosphere modelling can take advantage of data bases for atomic line transitions devoted to stellar atmosphere applications such as Kurucz (1992) and the VALD project (Kupka et al. 1999; Ryabchikova et al. 1999). Among the current projects for the computation of model atmospheres there are several which can calculate models with individual abundances on workstations or personal computers. Two of them are based on an opacity sampling approach. ATLAS12 by Kurucz (1996), for which a first application was presented by Castelli & Kurucz (1994), is particularly suitable for B to K type stars at or close to the main sequence. The marcs project in Upsala (Bengt Gustafsson and his group) is aimed at the cool part of the Hertzsprung-Russell diagram and can produce model atmospheres for stars with spectral types later than A0 (Gustafsson et al. 2003). However, for the computation of small grids of model atmospheres with individual abundances, which are required when varying $T_{\text{eff}}$ or log($g$) during the initial analysis of a single star or several sufficiently similar stars, the opacity distribution function (ODF) approach remains preferable due to its higher computational efficiency. Piskunov & Kupka (2001) have presented a new software toolkit based on this approach using a modified version of the ATLAS9 code of Kurucz (1993b). It is suitable for spectral types from early B type to early F type stars at or close to the main sequence.

Our study has been initiated to synthesise and reproduce the characteristics of the 5200 Å flux depression which is measured via the $\Delta a$ photometric system with the currently available stellar atmosphere models. Our general aim is to explain the various aspects and characteristics of the $\Delta a$ photometric system (and thus the 5200 Å flux depression), i.e. the dependency on the metallicity, surface gravity and effective temperature.

The new synthetic photometric $\Delta a$ system is introduced in Sect. 2. We discuss the chosen filter system and its properties with respect to systems that have been used for observations. We compare the $\Delta a$ calibration relations obtained from grids of standard model atmospheres with observed relations as a function of several photometric indicators of $T_{\text{eff}}$. We also discuss luminosity and metallicity effects and compute the expected zero point shift of the normality line $a_0$ of $\Delta a$ photometry when applying the latter to the Magellanic Clouds. Following the standard used in the literature we give values for $\Delta a$ in units of mmag throughout this paper, while other photometric quantities are given in mag with normalisations as described in Sect. 2. Whenever the unit of mmag is used, it is explicitly mentioned so in the text to avoid confusion. In the concluding Sect. 3 we summarise the success of the synthetic $\Delta a$ system in reproducing the normality line and the usefulness of $\Delta a$ photometry to study CP stars in environments different from the solar neighbourhood. We also provide an outlook for the next
papers of this series in which the software and methods of Piskunov & Kupka (2001) will be used. In two follow-up papers we will discuss the capability and limitations of homogeneous model atmospheres with individual abundances for reproducing observed \( \Delta \alpha \) indices of different types of CP stars.

2 SYNTHETIC PHOTOMETRY

2.1 The synthetic \( \Delta \alpha \) filter system

Relyea & Kurucz (1978) have discussed in detail how to calculate synthetic colours from model atmosphere fluxes computed with the ATLAS code. The main idea is to convolve the emergent surface fluxes predicted from model atmospheres with several functions representing filter transmission, relative absorption of all other devices in the optical path (including telescope mirrors), and detector sensitivity.

Figure 1 shows the response functions of our synthetic photometric system. The steep decay of the response function of a 1P21 RCA photomultiplier tube (PMT) and a typical mirror reflection efficiency function (the latter two are taken from the UVBY code of Kurucz 1993b).

We note that all \( \Delta \alpha \) measurements used for comparisons in this paper were observed within the classical photomultiplier system. The new CCD \( \Delta \alpha \) system (Maitzen, Faunzen & Rode 1997; Bayer et al. 2000; Maitzen et al. 2001; Faunzen & Maitzen 2001, 2002; Faunzen et al. 2002) in turn has been modified in order to compensate for the different response functions of a photomultiplier and a CCD. A classical photomultiplier is almost insensitive at approximately 6000 Å whereas a CCD is very sensitive in the red region. This implies an almost linear increase of the response function from \( g_1 \) to \( y \). In the new CCD system, the FWHM of the \( g_1 \) and \( y \) filters are 222 Å and 120 Å, respectively. This guarantees that the total flux of each filter after the convolution with the response function is comparable with that one of the "old" system.

2.2 Calibration relations

The overall success of the ATLAS9 model atmospheres of Kurucz (1993b) to reproduce photometric colours and spectrophotometric fluxes of standard stars of spectral types B and A (Castelli & Kurucz 1994; Smalley & Dworetsky 1995; Castelli, Gratton & Kurucz 1997; Castelli, Gratton & Kurucz 1997; Castelli 1998) and also for some of the CP stars (Adelman & Rayle 2000) promotes them as a logical choice when testing a synthetic photometric system. We have thus computed several grids of ATLAS9 model atmospheres with the Stellar Model Grid Tool (SMGT; see Heiter et al. 2002 for a description) using the line opacities from Kurucz (1993a) and the ATLAS9 code of Kurucz (1993b), unaltered except for the convection treatment (Smalley & Kupka 1997; Heiter et al. 2002). In fact, both Smalley & Kupka (1997) and Heiter et al. (2002) recommend the use of a convection model in ATLAS9 which predicts inefficient convection for mid to late A stars (\( T_\text{eff} \leq 8500 \) K). We thus used the model of Canuto & Mazzitelli (1991) which allows a better reproduction of Strömgren colours of A stars than the original models of Kurucz (1993b), as shown in Smalley & Kupka (1997). For models with \( T_\text{eff} > 8500 \) K, where convection has only negligible influence on temperature gradients and colours, our models are virtually identical to those from the original grids published by Kurucz (1993b). Anyway, from a comparison we did with model atmospheres based on different convection models we conclude that for any of the convection treatments available for ATLAS9 (cf. Castelli et al. 1997; Heiter et al. 2002) the \( \alpha \) values change only by 0 to \(+3 \) mmag for the coolest models in our grids and remain completely unaltered for models with \( T_\text{eff} > 8500 \) K. Thus, no important bias is introduced into our calibration tests by selecting a particular convection model. The ATLAS9 grids of Kurucz (1993b) ones have a spacing of \( \Delta \log(g) = 0.5 \) dex which is slightly too coarse for our purpose. Hence, we also included intermediate models in our computations by using a spacing of \( \Delta \log(g) = 0.25 \) dex.

We studied a \( \log(g) \)-range from 2.5 dex to 4.5 dex and a \( T_\text{eff} \)-range from 7000 K to 15000 K (with a spacing of 250 K as in Kurucz 1993b). Model atmospheres assuming one of the following three metallicities were investigated: \(-0.5, 0, \) and \(+0.5 \) dex, where \([M/H] = 0\) dex represents solar abundance and elements heavier than He are scaled by \(+0.5 \) dex in the other cases. A constant value of 2 km s\(^{-1}\) as in the
effective temperature, surface gravity, and metallicity. For the ∆a index as a function of various experimental indicators of $T_{\text{eff}}$. For (B−V) and (g1−y) the entire temperature range is displayed while a cut-off was introduced for the other two cases through requiring that (b−y) ⩾ −0.02 (i.e. $T_{\text{eff}} \leq 11000$ K) and [u−b] ⩽ 1.38 (i.e. $T_{\text{eff}} \geq 9250$ K). Models with log($g$) = 4 dex have been connected with straight lines to provide a proxy for the normality line $a_0$ of the synthetic photometric system. Note that the output colours have been rounded to 1 mmag accuracy as in Kupka (1993b). The actual run of the colours is continuous and smaller magnitude differences can hardly be assigned a real physical meaning within the current state of modelling.

For our comparison of the synthetic ∆a system to observational ones we have used the results for Galactic field stars (Maitzen & Vogt 1983; Vogt et al. 1998). More than 1140 bright normal, peculiar and related stars have been observed within four different ∆a systems. These four systems are mainly distinguished by slightly different filter transmission curves (Fig. 3 in Maitzen & Vogt 1983). The differences for the ∆a values were found to be in the range of 2 to

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standard grid of Kurucz (1993b) was used for the microturbulence.

To transform the observational colours into the frame of observed colours Kurucz (1993b) corrected the zero-point of his synthetic uvby system so as to match c1, m1, and (b−y) of Vega. A similar procedure is necessary to compare calculated a values from our synthetic Δa system directly to observations. We have added 0.6 to the synthetic a value computed from convolving the effective transmission functions with the fluxes from ATLAS9 model atmospheres.

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3 mmag. They find the following relation for the normality line:

$$a_0 = G_0 + G_1(b - y) + G_2(b - y)^2$$

with $G_0 = 0.594$, and where $0.086 < G_1 < 0.105$ as well as $-0.050 < G_2 < -0.150$ hold for $-0.120 < (b - y) < +0.200$. The 1σ level around the normality line was found to be between 2.9 and 5.1 mmag. These values are a superimposition of the internal measurement errors and the (observed) natural bandwidth. On the other hand, the colours from model atmospheres ranging the main sequence band from log($g$) of [3.5,4.5] dex for all models with a $T_{\text{eff}}$ of [7000,15000] K and solar metallicity, and for which $(b - y) \geq -0.02$, yield a $G_0 = 0.591$ (with less than 0.5 mmag error), while $G_1 = 0.0985 \pm 0.0056$ and $G_2 = -0.044 \pm 0.030$, when fitting a least square parabola through the model colours (see Fig. 2). Hence, the $(b - y)$ dependence of the experimental $\Delta a$ systems investigated in Maitzen & Vogt (1983) is reproduced very well.

For the $[u - b]$ relation, Maitzen (1985) lists $G_1 = 0.024$ for 22 bright unreddened stars with a 1σ level of 4.5 mmag. For this correlation, the results in Fig. 2 imply a more flat dependence of $G_1 = 0.0098 \pm 0.0018$ (and a $G_2$ of $-0.0022 \pm 0.00097$). However, the rather small slope is very sensitive to the precise definition of the sample: including giants with log($g$) $\geq 2.5$ dex would raise $G_1$ to 0.0161, whereas reducing the range of $[u - b]$ from an upper limit of 1.38 to 1.20 while keeping only the main sequence band models with log($g$) $\geq 3.5$ dex, as in the first case, would increase it to $G_1 = 0.0211 \pm 0.0028$. Thus, within the overall uncertainties expected for such kind of a weak dependence on $[u - b]$ the latter is reproduced sufficiently well.

Figure 2 also shows the correlation of $a$ with the temperature indicators $(B - V)$ and $(g_1 - y)$. Their dependency can easily be studied as before, but is unlikely to reveal more information beyond the uncertainties introduced by the colour transformation required to compare the different filter systems used in observations and the synthetic systems of Kurucz (1993b).

### 2.3 Luminosity effects

Because each of the colour relations presented in Fig. 2 is also affected by surface gravity within the range of effective temperatures populated by the CP stars, we have looked at the direct dependence of $a$ on $T_{\text{eff}}$ as well (see Fig. 4). Clearly, models with lower surface gravity have higher $a$ values. The effect of surface gravity on the $a$ index is largest for the late B stars with effective temperatures around $7300 \pm 500$ K. The width of the band of standard stars as induced by surface gravity for a given metallicity is between 2 and 5 mmag. This confirms the results of the previous subsection and is in agreement with the observational data quoted therein.

We note here that the step size in log($g$) for model sequences shown in both Fig. 4 and 5 is 0.25. However, as the output of the photometric indices has been truncated to 1 mmag, it turns out that the $\Delta a$ dependence on log($g$) is too weak to show up more prominently. Hence, many models overlap in the Figures due the assumed output accuracy. The sensitivity of $\Delta a$ to log($g$) slightly depends on $T_{\text{eff}}$ and metallicity, as the number of apparent points in Figs. 4 and 4 reveals as well.

### 2.4 Metallicity effects

Metallicity has an effect on the $a$ index which is actually more important than that of luminosity (surface gravity). Fig. 4 compares the main sequence band for solar metallicity with models having over- and underabundances of $\pm 0.5$ dex for all elements heavier than He. We conclude that an under-abundance of $0.5$ dex as in the Magellanic Clouds (Dirsch et al. 2000) yields a shift of the normality line of $-3$ mmag. Notice that Maitzen, Paunzen & Pintado (2001) found the first extragalactic CP stars in the Magellanic Cloud using...
the \( \Delta a \) system. The size of this shift is quite constant over the entire \( T_\odot \) range relevant for CP stars and also within the entire luminosity range expected for the main sequence band. On the other hand, an overabundance of +0.5 dex yields a larger shift of between +3 and +6 mmag with a maximum for the late B stars. This behaviour gives already some hint on the nature of the flux depression at 5200 Å in agreement with Adelman et al. (1995) and Adelman & Rayle (2000) who found that line opacities of ATLAS9 models with metal overabundances of +0.5 and +1.0 dex predict some extra line blanketing in this region. In turn, due to the good agreement of ATLAS9 model fluxes in this wavelength region with observations for mildly peculiar stars, which have underabundances or overabundances of up to about 0.5 dex (cf. Castelli & Kurucz 1994; Adelman & Rayle 2000), and due to the satisfactory agreement of our synthetic \( \Delta a \) system with systems used in observations (see previous subsections), we can draw an important conclusion: application of \( \Delta a \) photometry to the Magellanic Clouds will lead only to a small bias, with a size of about –3 mmag relative to the observations made for the solar neighbourhood, and the same will hold for more remote targets that have a similar metallicity range.

3 CONCLUSIONS AND OUTLOOK

In this first paper of our series we have established a synthetic photometric \( \Delta a \) system and confirm the observed dependency of the \( a \) index as a function of various colour indices sensitive to the effective temperature and surface gravity variations within the Strömgren \( uvby\beta \) and Johnson \( UBV \) photometric systems. Several calibration relations are presented to confirm that the new synthetic \( \Delta a \) system provides a normality line and features an average scatter along the main sequence for normal type stars which is very close to the observed relations, if fluxes from ATLAS9 model atmospheres are used as input data for the synthetic photometric system. The metallicity dependence of the normality line of the \( \Delta a \) system was computed for several grids of model atmospheres for which the abundances of elements heavier than He had been scaled by \( \pm 0.5 \) dex in order to test for the effects of over- and underabundances. We estimate a lowering of \( \Delta a \) by \( \sim –3 \) mmag assuming an average metallicity of [Fe/H] = –0.5 dex compared to the Sun. This is a typical value as found for Magellanic Clouds for which the first CP stars have already been detected using the \( \Delta a \) system. Thus, \( \Delta a \) photometry is a viable tool to identify CP stars in samples with metallicities slightly different from the solar ones and it is well suited to draw statistically meaningful conclusions about their distribution. It is hence a recommendable method to find CP stars in other galaxies, too.

We intend to publish two follow-up papers. In these papers we will present model atmospheres computed with individual abundances for a representative sample of CP as well as \( \lambda \) Bootis stars. For these objects we will either confirm or redetermine the input parameters (effective temperature, surface gravity, overall metallicity and microturbulence) found in the literature through comparisons with photometric, spectrophotometric, and high resolution spectra \((R \approx 20000)\) spectroscopic data. The final models obtained from this procedure will be used to compute synthetic \( \Delta a \) values which will be compared with individual photoelectric observations. The observed behaviour of \( \Delta a \) will be shown to be very well reproduced for several types of CP stars. Furthermore, a detailed statistical analysis of the relative abundances for each star will be given. This will illustrate which species contribute in the different filters.

The first follow-up paper (paper II) will discuss the models for Am and cool CP2 stars with effective temperatures below about 10000 K. The second one will deal with a discussion of hotter CP stars with spectral types earlier than A0 (paper III). The atmospheres of these objects are different from those of A stars. Among others, convection cannot play an essential role any more and the effects of stratification become even more important than for cooler objects.

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