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Effective temperatures of magnetic CP stars: semi-fundamental data

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Abstract. A brief discussion of earlier determinations of effective temperatures of chemically peculiar stars is given. It is stressed that the effective temperature is a global parameter, important for stellar structure and evolution studies. It should, however, be used with caution in atmospheric investigations. New determinations of effective temperatures of 27 chemically peculiar stars with characteristics typical of magnetic variables were obtained from a root-mean-square fit of metal enhanced model atmospheres to the observed and de-reddened, when necessary, spectral energy distributions (SED) from UV to red. Metallicity and effective temperature were used as fitting parameters, assuming fixed values of gravity: $\log g = 4$ for main sequence stars and $\log g = 3$ for giants. Equal weights were given to the UV and visual part of SED. The quality of fit was checked for each star by determination of the temperature from the best fitting model atmosphere to the UV part and to the visual part of SED separately. Both temperatures should be close to one another if the global best fitting model satisfactorily describes the full observed SED. This is the case for about a half of the investigated stars but the difference exceeds 750 K for the remaining stars with the extreme values above 2000 K. Possible reasons for such discrepancies are discussed. New, revised calibrations of effective temperature and bolometric correction of magnetic stars in terms of reddening free Strömgren indices are given. It is shown that the investigated stars populate uniformly the main sequence.

Key words: stars: chemically peculiar – stars: fundamental parameters

1. Introduction

By definition, stellar effective temperature $T_{\rm eff}$ is a measure of the total surface brightness. The latter quantity is of fundamental importance in studying stellar structure and evolution. Although the radiation emerging from a star is by no means Planckian it is nevertheless thermal in origin. As a result, the actual kinetic temperature will equal $T_{\rm eff}$ near the depth from which the continuum radiation emerges. It makes $T_{\rm eff}$ a useful parameter in description of a (plane-parallel) stellar atmopshere. In particular, it is used as one of the basic parameters in computations of stellar model atmospheres. In ready-to-use grids of model atmospheres, like that provided by Kurucz (1992) the effective temperature labels, together with surface gravity, all listed models. Additional, important parameter entering computations of a model atmosphere describes chemical composition, e. g. by specifying a factor by which the standard (solar) metallicity is scaled or by introducing detailed chemical abundances for key elements. An approximate similarity of effective and photospheric temperature may, however, be misleading. Let us suppose that we want to interpret spectral features formed at a given optical depth in a star with very unusual chemical composition. In the absence of a correct model atmosphere we have to use a substitute with different, e. g. standard abundances, as a proxy model. If we select a substitute on a sole basis of the proximity of the stellar effective temperature to the model temperature we will very likely obtain erroneous results. The model dependence of temperature on optical depth may be so much different from actual that the temperature in the investigated layers may be off by several hundred kelvin. In such a case a better approach is to select a model which more closely reproduces the temperature in the region of interest. For example, a spectral analysis of weak absorption lines from the Paschen continuum region will very likely give better results if we use a model well reproducing the Balmer jump and the slope of the Paschen continuum rather than the model with effective temperature strictly equal to the stellar effective temperature but with a substantially different chemical composition. To sum up, while the effective temperature is an exact and very convenient measure of the stellar surface brightness (the term "temperature" is intuitive and its value is much easier to remember than the value of the surface flux) its use in the atmospheric context should be done with caution. This is particularly important in case of magnetic chemically peculiar (mCP) stars which show, besides strong, ordered surface magnetic fields, also the most prominent deviations from standard model atmospheres.

Already early spectral and spectrophotometric observations of CP stars revealed substantial deviations of spectral energy distributions (SED) of Si, Cr, Eu or Sr stars from normal stars (Wolff, 1967). Broad band photometry reflected this discrepancy, resulting in color indices of CP stars, which did not follow the two color relation given by normal stars (Wolff, 1967; Stępień, Muthsam 1980). Wolff (1967) determined line blanketing corrections to the observed $U-B$ and $B-V$ indices of a number of CP stars. She concluded that the corrections are rather small except for the coolest stars and that the corrected color indices still do not follow the normal star relation. It was obvious that, besides enhanced spectral lines in visual, there must exist an additional effect influencing SED of CP stars in that region. As it turned out later, this was a strong backwarming effect from UV due to a huge blanketing effect in that part of the spectrum. The increased blanketing in UV was caused by highly enhanced opacity caused by an immense number of strong spectral features (lines and ionization jumps) of overabundant elements.

Key observations demonstrating this effect were obtained with OAO-2 (Molnar, 1973; Leckrone *et al.*, 1974). UV pseudo-continuum of CP stars turned out to be substantially suppressed compared to normal stars with similar visual energy distribution. The UV part of their spectrum can be approximately fitted by an energy distribution of a normal star with a much lower temperature. Leckrone *et al.* (1974) demonstrated that the peculiar energy ditribution of a CP star can qualitatively be reproduced by a model atmosphere with metal opacities increased by a factor of 100. The UV observations showed that effective temperatures of CP stars, particularly of mCP stars, based solely on the visual SED or on visual photometric color indices, are systematically too high, sometimes even by a couple of thousand kelvin, compared to their true values.

A correct value of the stellar effective temperature should be determined from the *total*, integrated emergent energy flux which, in turn, can be calculated from the observed SED and angular diameter of the star (Code *et al.*, 1976). The method cannot be widely used because accurate observations of SED from UV to infrared and angular diameters are available for a limited number of stars only. Such stars usually serve as standards for calibration of other temperature measures of which most useful are color indices observed with different photometric systems. To avoid problems with measuring angular diameters, indirect methods have been suggested, like the infrared flux method (IRFM) in which the diameter is calculated from the ratio of the observed to surface monochromatic flux in infrared, assuming its weak dependence on temperature (Blackwell, Shallis 1977). Since a large grid of realistic model atmospheres computed by Kurucz has become available, the effective temperature of a star can be determined from a fit of the theoretical emergent flux to the observed SED. Model atmospheres are available for a broad range of temperatures, gravities and solar abundances scaled with different factors from 0.001 to 10. With the effective temperature known, the angular diameter can be calculated from the total observed energy flux. Because SED depends only weakly on surface gravity, the simultaneous determination of temperature and gravity is impractical, even in case of stars with known metallicity. Surface gravity is usually determined from other data, e. g. from Balmer lines, photometric index or spectral type.

The purpose of the present investigation is to determine effective temperatures of mCP stars for which the observed UV and visual scans have been published, by fitting metal enhanced model atmospheres to the dereddened (if necessary) SED. Temperatures determined in this way can be used to improve existing calibrations of the effective temperature and bolometric correction from Strömgren photometric color indices. Selection criteria for including a star into our analysis and stellar observational data are described in the next section, together with the method of obtaining the final observed SED. The fitting method of model atmospheres to the observations and the results are given in Section 3, together with the discussion and the revised calibrations.

2. Stellar data

We first took all stars from the *General Catalog of Ap and Am stars* by Renson *et al.* (1991), which possess at least one characteristics of mCP stars, i. e.

surface magnetic field, light or spectrum variations and/or chemical peculiarity typical of these stars. Then we selected those mCP stars for which at least one IUE observation with a large aperture and both, short-wavelength (SW) and long-wavelength (LW) cameras exists, and which have been observed spectrophotometrically in the visual. The following catalogs of visual data were used: Adelman *et al.* (1989), Alekseeva *et al.* (1996, 1997), Breger (1976), Burnashev (1985), Glushnieva *et al.* (1998 a, b) and Kharitonov *et al.* (1988). The final sample contains 27 stars. Table 1 gives the list of them.

Table 1. Investigated stars and final results

HD	$E(B-V)$	[m/H]	$T_{\rm eff}$(final)	ΔT	$\log L$	$R/R_{\odot}$
15089	0	0.0	8250	-250	1.345	2.3
19832	0	0.5	12250	500	1.992	2.1
23387	0	0.0	8250	-1750	1.562	2.1
25823	0	1.0	12500	500	2.451	3.6
26571	0.27	0.0	11750	1500	3.055	8.1
27309	0	1.0	11750	2000	1.953	2.3
34452	0	1.0	13250	3000	2.334	2.9
37470	0.15	0.0	13000	-2250	2.007	1.9
40312	0	0.5	10000	750	2.391	5.2
43819	0	0.5	11000	1000	2.104	3.2
65339	0	0.0	8000	-250	1.472	2.8
92664	0	0.5	14250	1000	2.402	2.7
98664	0	0.0	10250	-250	2.022	3.3
107966	0	0.0	8500	-250	1.724	3.3
108662	0	0.5	9500	750	1.689	2.6
108945	0	0.5	8750	0	1.663	3.0
112413	0	1.0	11250	1000	1.960	2.5
118022	0	0.5	9000	0	1.441	2.2
120198	0	0.5	9750	750	1.563	2.2
124224	0	0.0	12500	1250	2.004	2.2
125248	0	0.5	9500	0	1.519	2.1
133029	0	1.0	10500	1000	1.836	2.4
144844	0.12	0.0	12750	-750	2.229	2.7
152107	0	0.5	8750	-250	1.430	2.3
171782	0.17	1.0	11500	1000	2.079	2.7
196502	0	0.5	8500	250	2.035	4.8
215441	0.26	1.0	14000	750	2.705	4.2

The UV observations were extracted from *IUE Newly Extracted Spectra* (INES) *Catalog* in which the flux in absolute units (cgs) is given every 1.67 Å for

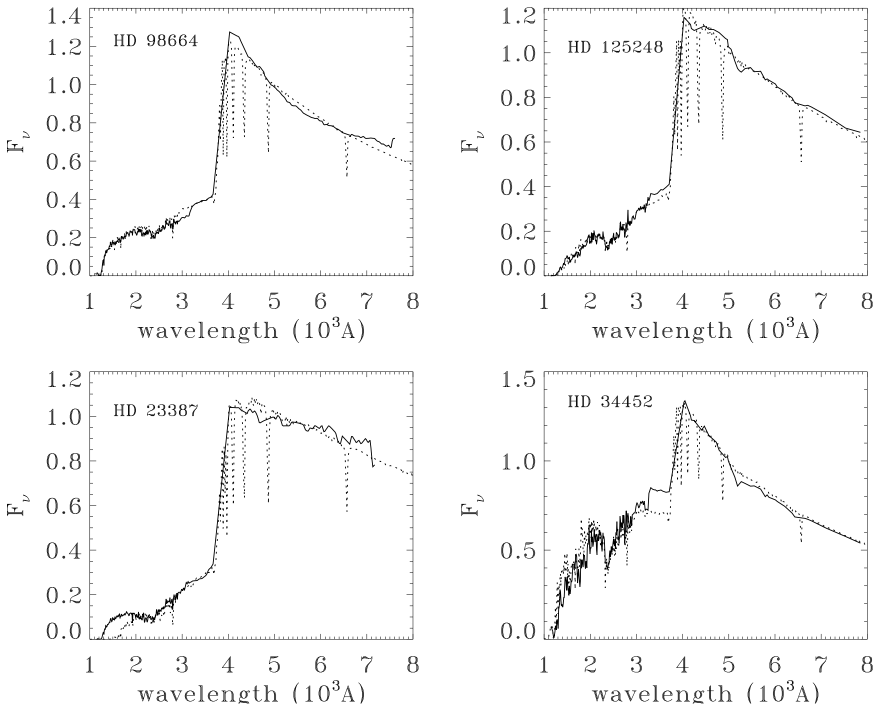

Figure 1. The observed SED (solid lines) with the best fitting models (broken lines). The data are normalized to 5000 AA. Examples of two stars with a good fit (top) and with a poor fit (bottom) are shown

SW cameras and every 2.67 Å for LW cameras. Observations were reduced with the New Spectral Image Processing System (NEWSISP) method. It was assumed, when reducing the observations, that those obtained with the large aperture contain a full stellar flux whereas only an unknown part of the flux is registered through the small aperture because of the vignetting effect. We merged together observations obtained with both apertures, after correcting those obtained with the small aperture for a missing flux. We checked all UV observations for internal consistency and we rejected the discrepant scans. Unfortunately, the only available LW scan of HD 43819 turned out to badly disagree with the SW scan and the visual scan of this star. We retained the star for the further analysis using only SW and visual scans. A similar check on visual scans did not reveal any inconsistencies. The observations from the Catalogs by Adelman *et al.* and Breger were converted into absolute fluxes using Vega calibration (Bohlin, Gilliland 2004)

$$F_\lambda = F_{\mathrm{Vega},\,5556}\left(\frac{5556^2}{\lambda^2}\right)10^{-0.4(V-V_{\mathrm{Vega}}+m_\lambda-m_{5556})}\,, \qquad (1)$$

where F_λ is the stellar flux in absolute units (erg cm^{-2}s^{-1}Å^{-1}), $F_{\mathrm{Vega},\,5556} = 3.46\times10^{-9}$ erg cm^{-2}s^{-1}Å^{-1}, V and $V_{\mathrm{Vega}} = 0.026$ are the magnitudes of the star and Vega in V-band of the UBV system, and m_λ and m_{5556} are the magnitudes of the star at the wavelength λ and at 5556 Å. The observations obtained by the Russian astronomers are given in absolute units so they can directly be analysed with the UV observations.

When a UV spectrum is plotted together with a visual scan, they usually do not merge smoothly. Instead, a gap is often visible between them in the wavelength region around 3200 Åcovered by both sets of observations. Such shifts between UV and visual observations probably result from calibration errors. No attempt was made to remove them.

The observed SED should be corrected for interstellar absorption before fitting the theoretical SED. Unfortunately, standard methods of determination the individual values of the interstellar reddening cannot be applied to mCP stars due to their peculiar photometric indices (Wolff, 1967; Stępień, Muthsam 1980). Other, indirect methods, e. g. based on maps of the distribution of the interstellar matter, can also result in gross errors because interstellar dust has a very patchy structure. Recent investigation of interstellar absorption for many W UMa-type stars by Rucinski and Duerbeck (1997) showed that the reddening of nearby stars had been significantly overestimated by earlier authors. In fact, interstellar reddening is close to zero for nearly all stars closer than 100 pc and rarely exceeds 0.03 for distances up to 200 pc (see also Fruscione *et al.*, 1994). Based on these results we assumed zero reddening for all stars closer than 100 pc. Each star lying further than 100 pc was checked individually. If literature data or maps of interstellar matter suggested $E(B-V) \lesssim 0.03$ we assumed zero reddening. Several stars are, however, significantly reddened and values of $E(B-V)$ up to 0.27 mag can be found in literature. With one exception we accepted the literature values as they are, although some of them are very uncertain. For one star, HD 215441, the fit of the model atmosphere to the published $E(B-V) = 0.20$ was so poor that we decided to determine it together with the effective temperature, adopting metallicity [m/H] = 1.0. The accepted values of $E(B-V)$ are listed in Table 1. The observed SEDs of reddened stars were corrected for interstellar extinction using the curve given by Cardelli *et al.* (1989). As a final step before fitting theoretical SED, the observed fluxes were converted to units used by Kurucz.

3. Results and discussion

The root-mean-square (RMS) method was used to fit the theoretical SED to observations of each star, with equal weights given to UV and visual part of

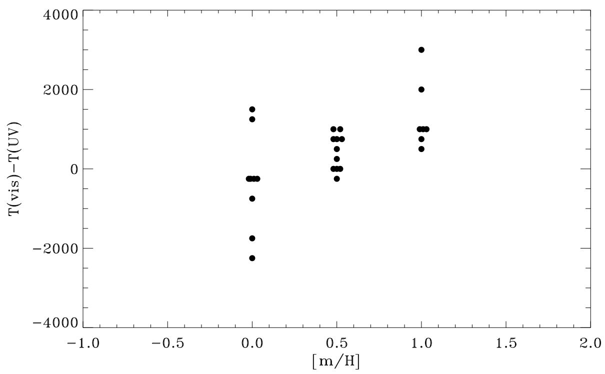

Figure 2. The difference between temperature resulting from the visual and the UV part of SED *versus* metallicity of the model

SED. Only two paramaters, effective temperature and metallicity, were varied when looking for the best fit, with gravity assumed to be equal to $\log g = 4$ for main sequence stars and to $\log g = 3$ for two stars with characteristics of giants. The exception was HD 215441 (see above) for which effective temperature and reddening were used as fitting parameters. An attempt to use three parameter fit resulted in spurious results.

Table 1 lists the final metallicities and effective temperatures, resulting from fits to full SEDs and Fig. 1 shows four examples of the observed SED (solid lines) with the best fitting models overplotted (broken lines). The top part of the figure shows two stars with good fits of models to observations and the bottom part shows two other stars with rather poor fits.

The uncertainty of the best fit, estimated from the shape of the minimum of RMS error is of the order of 200-300 K. It can be seen from Fig. 1, however, that while in some cases the observed SEDs agree very well with the best fitting models, there are also cases where the fit is rather poor. To measure it quantitatively we introduced an independent measure of the quality of fit based on a separate fit of a model to the UV scan of each star and then to the visual scan. Gravity and metallicity were the same as in the global best fitting models to the full SEDs and were kept fixed. Table 1 gives the difference $T(\mathrm{vis}) - T(\mathrm{UV}) = \Delta T$ and Fig. 2 shows its plot versus [m/H]. Note that any possible uncertainties of UV calibration relative to the visual observations (suggested by apparent gaps between both scans visible in some stars) have no influence on temperatures thus found - only the shape of SED matters. In the case of a perfect fit between a global theoretical model and observations, separate fits to UV and visual scan should give identical temperatures or, at most, deviate by a value of the estimated uncertainty from the best fit to the full SED. That means that the difference $|\Delta T| \lesssim 750$ K (i. e. 2-3 times the error) indicates a good or tolerable

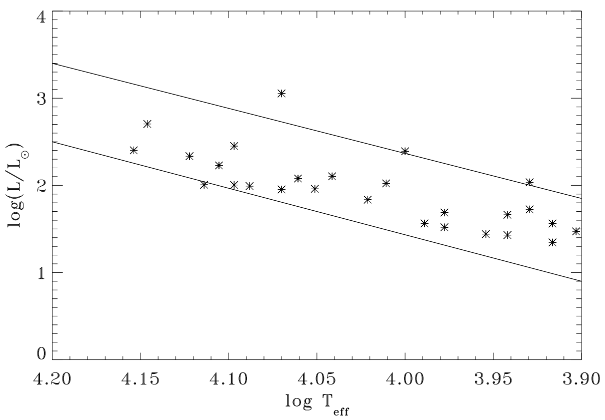

Figure 3. Hertzsprung-Russel diagram with all analysed stars. Solid lines delineate the main sequence

quality of fit. This occurs in majority of stars but in several other stars it exceeds that value, with the most extreme differences reaching -2250 K and 3000 K. A number of factors can influence ΔT, like low quality of observations (visual and/or UV), low number of visual observations or an unusual shape of the observed continuum seen in some stars, which is not satisfactorily reproduced by the models used. As Fig. 2 shows, no apparent trend with metallicity is visible, except that the two largest positive values of ΔT occur for stars with the highest metallicity. Note that large positive differences occur when the models with an insufficient line opacity are fitted separately to UV and to visual scan of a metal rich star (Leckrone *et al.*, 1974). The present results suggest that in some stars, models with metallicity increased even by a factor of ten seem to be insufficiently blanketed to reproduce correctly the observations. Until models with chemical compositions accurately corresponding to the observed abundances are available, a set of models with solar abundances scaled by a factor of 30 (or, perhaps, even a factor of 100) would highly be desirable.

Uncertainty of the final temperature results from the following sources: a limited accuracy of observations, possible mismatch of UV and visual part of SED, large discrepancies between actual and accepted chemical abundances and uncertain reddening corrections. Our calculations show that the best fitting temperature increases by about 1 % per 0.01 mag increase of $E(B-V)$. It is difficult to assess an importance of each of the above sources for individual stars. The resulting accuracy varies very likely between about 300 K and 1000 K with about 600 K as a realistic average accuracy.

New values of effective temperatures can be used to revise the temperature calibration in terms of the Strömgren reddening-free index $[u-b]$

$$\Theta = 0.317 + 0.028[u - b] + 0.102[u - b]^2 \,, \tag{2}$$

where $\Theta = 5040/T_{\rm eff}$. A similar calibration in terms of the index $[c_1]$ gives

$$\Theta = 0.333 + 0.024[c_1] + 0.200[c_1]^2 \,. \tag{3}$$

Note that, contrary to the earlier calibrations (e.g. Napiwotzki *et al.*, 1993; Stępień, 1994) which were linear, the present one is quadratic in Strömgren indices.

Bolometric corrections (BC) of the analyzed stars can be computed from the apparent visual and apparent bolometric magnitudes, obtained from their total integrated fluxes with the use of the formula given by Code *et al.* (1976). The calibration of BC in terms of the effective temperature is given as

$$BC = 18.67 - 4.73 \log T_{\rm eff} \,, \quad 3.94 < \log T_{\rm eff} < 4.16 \,, \tag{4}$$

and $BC \approx 0$ for $3.90 < \log T_{\rm eff} < 3.94$.

With the total integrated fluxes and effective temperatures known one can compute stellar angular diameters and then, using distances to the stars, the linear stellar radii and absolute luminosities (see Table 1). When plotted in the Hertzsprung-Russell diagram, the stars uniformly populate the main sequence (Fig. 3).

The new determinations of effective temperatures agree well with the older ones (Stępień, 1994), so the revised calibrations are also not much different from the old ones, except that they are more accurate, and, in case of temperature calibration, they show a significant curvature in Strömgren indices.

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