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On the effective temperatures, surface gravities, and optical region fluxes of the CP stars

S.J. Adelman[1,2] **and K.E. Rayle**[1]

[1] Department of Physics, The Citadel, 171 Moultrie Street, Charleston, SC 29409, United States of America
[2] Guest Investigator, Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 W. Saanich Drive, Victoria BC, V8X 4M6 Canada

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Abstract. We determined effective temperatures and surface gravities for 17 magnetic Chemically Peculiar (mCP) stars by comparing optical region spectrophotometry and Hγ profiles with the predictions of ATLAS9 model atmospheres. Although solar composition models can fit the energy distributions of the normal and many Mercury-Manganese stars, they cannot match the optical energy distributions of the mCP stars, especially the λ5200 broad, continuum regions. The role of metallicity and microturbulence to provide appropriate energy distributions which fit those observed for the mCP stars is investigated. Using metal-rich models with the opacity distribution functions for microturbulent velocities of 4 and 8 km s^{-1}, their λ5200 broad, continuum features are often fit as part of this process. For some stars it is impossible to fit simultaneously both this feature and the line blanketing in the Hγ region. This suggests that this continuum feature is produced by elements other than those which contribute most of the general line blanketing. A systematic difference in the temperatures found by the photometric and spectrophotometric approaches is discovered for the hotter mCP stars. An investigation of 10 Mercury-Manganese stars shows a similar effect. This may be due to the photospheric compositions becoming less solar with increasing temperature.

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

1. Introduction

Adelman et al. (1995) (hereafter Paper 1) found effective temperatures and surface gravities for five magnetic Chemically Peculiar (mCP) stars by matching the predictions of ATLAS9 metal-rich model atmospheres (Kurucz 1993) with optical region spectrophotometry and Hγ profiles. For four stars the theoretical continua were also able to match their λ5200 broad, continuum features (depressions). These model atmospheres contain much improved representations of the line opacities compared with previous models. Adelman & Pyper (1993 and references therein) used this feature in particular to differentiate the mCP from normal stars as did Maitzen (1976), for example, using photometry. Longward of Hα the spectrophotometric data systematically began to be brighter than the models, a systematic also seen in some normal stars. The derived temperatures showed considerable differences compared with values in literature based upon using uvbyβ photometry (Napiwotzki et al. 1993) and other methods (see, e.g, Gerbaldi et al. 1989). The current algorithms based on photometry for the mCP stars are somewhat questionable since the flux distributions and colors of mCP stars can be quite different from those of the normal stars. Further the λ5200 broad, continuum, which was shown to be at least in part produced by differential line blanketing and thus is in part an indicator of metallicity, is not directly considered. Unfortunately the model predictions were not able to reproduce the λ4200 and λ6300 broad, continuum features.

2. The effect of the magnetic field on the fluxes

In Paper 1, a figure demonstrated that as the metallicity increased for models with T_{eff} = 8400 K, log g = 3.30 the fluxes exhibit an increase in the size of the λ5200 feature. This also occurs at other temperatures and surface gravities. Most investigators believe that the mCP stars are indeed metal rich, but are cautious about the degree of enhancement due to the effects of the magnetic field. The Zeeman effect produced by the stellar magnetic field desaturates strong lines and strengthens those lines which are above the linear part of the curve of growth. For lines with Zeeman patterns having many components, one can treat the effects of a weak magnetic field as pseudo-microturbulence. But very sensitive lines exhibit the Paschen-Back effect even for moderately strong magnetic field strengths.

Paper 1 did not account for the effects of the magnetic field on the fluxes of magnetic CP stars. ATLAS9 uses Opacity Distribution Functions (odfs) to model the metal line opacity. To calculate valid odfs for mCP stars is complicated. As the magnetic field strength varies over the photosphere, a proper calculation probably requires several odfs for a variety of field strengths and compositions as well as an integration over the visible hemisphere. Further the photosphere of a mCP star may not be spherical.

Nevertheless, let us try to include magnetic field affects on the line opacity in an approximate manner. According to the

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Send offprint requests to: S.J. Adelman (adelmans@citadel.edu)

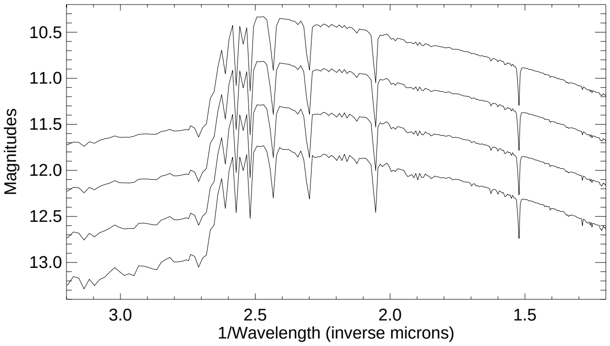

Fig. 1. The optical region fluxes of ATLAS9 model atmospheres with $T_{\rm eff}$ = 10000 K, log g = 4.00, and log Z = +1.0 odfs. The fluxes correspond from top to bottom to microturbulences of 0, 2, 4, and 8 km s^{-1}. The offset between pairs of models is 0.5 mag. As the microturbulence increases so does the size of the λ5200 feature near 1.9 μ^{-1} and the Lyman continuum becomes more depressed and exhibits more features.

radiation diffusion scenario (Michaud & Proffitt 1993), the atmospheres of the mCP stars should be quiescent. Thus the true microturbulence should be zero. But when we examine the spectra of most mCP stars and attempt to find microturbulences by standard techniques, we find non-zero values due to line broadening produced by the Zeeman effect acting as a pseudo-microturbulence. The magnetic field redistributes the line opacity so that it is more uniform with wavelength and tends to close opacity holes. Such effects are likely to be most important in the spectral regions where most of the flux is emitted and for hot stars this is the ultraviolet. The use of scaled solar odfs also may be non-optimal due to the abnormal compositions. Further the distribution of opacity with wavelength is unique for each atomic species. Effects of this sort can be explored using ATLAS12 (Kurucz 1996) models and might be important especially for some remaining details.

Fig. 1 shows predicted optical region energy distributions for ATLAS9 model atmospheres with $T_{\rm eff}$ = 10000 K, log g = 4.00, and log Z = +1.0 odfs. The fluxes from top to bottom correspond to microturbulences of 0, 2, 4, and 8 km s^{-1}, respectively. The offset between fluxes for pairs of models is 0.5 mag with the scale being correct for the 0 km s^{-1} model. As the microturbulence increases so does the size of the λ5200 feature near 1.9 μ^{-1} and the Lyman continuum becomes more depressed and exhibits additional structure. In addition the Balmer continuum brightens slightly (about 0.1 magnitude over the range of exhibited microturbulence) and the mean line strength increases.

Hence to fit the energy distribution of a mCP star, one can adjust both the metallicity and the microturbulence. One is constrained since the spectrum synthesized from the model should match that of the star. If the elements which produce the λ5200 feature and the elements which produce most of the observed lines are not the same and are enhanced by sufficiently different amounts, then the matching process may be able to reveal such effects. Each element is enhanced by a different average amount and these anomalies are affected by the changing strength of the magnetic field over the photosphere. In some spectrum variables lines of different elements are known to vary in strength out of phase with one another. To model such effects, it may be necessary to use an opacity sampling model atmospheres program such as ATLAS12 (Kurucz 1996) and to integrate the predicted fluxes over the surface.

3. Effective temperatures and surface gravities

For surface temperature and surface gravity determinations, 17 mCP stars, with fluxes consistent with the Hayes & Latham (1975) calibration of Vega mainly from the catalogs of Breger (1976) and Adelman et al. (1989) were studied. The fluxes longward of Hα were given lower weights than other values due to the senior author's previous difficulties in obtaining simultaneous fits to them and other spectrophotometric values. For this investigation the spectrophotometry for each star was selected to be the mean fluxes to represent the average star.

Hγ profiles came from 20 Å mm^{-1} spectrograms obtained with either Reticon or CCD detectors at the Dominion Astrophysical Observatory (DAO). The stellar exposures were flat fielded with the exposures of an incandescent lamp placed in the Coudé mirror train as viewed through a filter to eliminate first order light. A central stop removed light from the beam in the same manner as the secondary mirror of the telescope. The spectra were rectified using the interactive computer graphics program REDUCE (Hill et al. 1982) after which a 3.5% scattered light correction (Gulliver et al. 1996) was applied. As Balmer line profile variability has not been demonstrated to be significant in most mCP stars, we assumed that the observed Hγ profile is typical of each star.

Kurucz's ATLAS9 (1993) code calculates fully line blanketed NLTE plane parallel model atmospheres. From converged model atmospheres, one can calculate the fluxes using ATLAS9 and the Hγ region using the synthetic spectrum code SYNTHE (Kurucz & Avrett 1981). For comparison with observations the synthesized spectra were convolved with the measured stellar rotational velocity of the star and the instrumental profile of the short camera of the coudé spectrograph of the DAO 1.22-m telescope. Trends in recent elemental abundance studies indicate for normal main sequence band stars with $T_{\rm eff} \geq$ 10500 K that their microturbulence is 0 km s^{-1}, for those with $T_{\rm eff}$ between 10500 and 9500 K 1 km s^{-1}, and for those with $T_{\rm eff} \leq$ 9500 K 2 km s^{-1} (Adelman 1998 and references therein).

For initial temperature and surface gravity estimates, the homogeneous uvbyβ values of Hauck & Mermilliod (1980) were used whenever possible with the program of Napiwotzki et al. (1993) based on the work of Moon & Dworetsky (1985). Using solar composition models, we compared fluxes and Hγ observations with predictions. Some of the best fits were fine while others were abysmal. Then we used models with greater than solar metallicity to fit the continuum especially the λ5200 feature and adjusted the microturbulence as necessary. In matching the observed and predicted Hγ regions we tried to also have similar levels of metal line blanketing which was not always possible.

Table 1 shows effective temperatures and surface gravities. The photometric values are not rounded. The stars are listed

Table 1. Effective temperature and surface gravities of magnetic CP stars

Star	HD			spectrophoto.	and $H\gamma$					
Name	Number	uvbyβ		solar	models	enhanced	metallicty	models		T([c$_1$)]
		$T_{\rm eff}$	log g	$T_{\rm eff}$	log g	$T_{\rm eff}$	log g	log Z	ξ(km s^{-1})	(K)
56 Ari	19832	13623	4.17	13150	4.05	12850	4.00	+0.5	2	12600
CU Vir	124224	13210	4.28	13100	4.15	12750	4.00	+0.5	2	12280
HR 5597	133029	11760	4.10	11300	4.00	11000	3.90	+1.0	8	10888
17 Com A	108662	10994	4.21	11100*	4.35	10800+	4.25	+1.0	8	10300
HR 6958	170973	11676	3.69	11000*	3.50	10750+	3.50	+1.0	8	10760
HR 6176	149822	11493	3.94	10900	4.10	10750	4.00	+1.0	8	10590
84 UMa	120198	11234	4.07	10500	4.19	10400	4.00=	+1.0	8	10260
78 Vir	118022	9720	4.22	9500	4.10	9750+	4.00	+1.0	8	10040
HR 6326	153882	9240	3.80	9500	3.75	9500	3.75	+1.0	8	...
ϵ UMa	112185	9543	3.59	9350	3.70	9500	3.60=	+1.0	8	...
χ Ser	140160	9210	4.04	9100	4.10	9000	4.00=	+0.5	4	...
						9100	4.10‘	+0.2	2	...
73 Dra	196502	8837	4.22	8300*	3.75	9000	3.65=	+1.0	8	...
21 Com	108945	8791	3.92	8500	3.75	8700	4.00	+0.5	4	...
HR 8216	204411	8528	3.52	8400	3.75	8500	3.25=	+0.5	4	...
β CrB	137909	8097	4.28	8100	4.25@*	8300	4.50@	+1.0	8	...
				8300	4.25!*	8300	4.50!	+1.0	8	...
γ Equ	201601	7871	4.36	8000	4.00@*	8000	4.50@	+0.5	4	...
				8000	4.00!*	8000	4.50!	+0.5	4	...
10 Aql	176232	7760	3.80	8000	4.00@	7800	4.25@	+0.5	4	...
				8000	4.00!	7800	4.50!	+0.5	4	...

Footnotes:* = Poor Fit, + Fair Fit, = synthetic $H\gamma$ profile metal lines too strong, ‘ $H\gamma$ profile lines fine, but the λ5200 feature not fit, @ convection calculated via mixing length theory, ! convection calculated according to Canuto & Mazzitelli (1991, 1992)

in approximately decreasing effective temperature order. When the line blanketing for $H\gamma$ became large and locating the continuum became difficult, then relatively metal line free regions in the line profile were used as fitting guides. Fig. 2 shows the $H\gamma$ profile of 10 Aql, which is an example of a cooler mCP stars. In hotter stars the metal lines become weaker and the $H\gamma$ profile becomes stronger and dominates. For good matches, the synthetic spectra of both the $H\gamma$ and metal lines lie essentially on top of such profiles and cannot be distinguished at the usual figure resolution. No corrections were made for reddening as these stars should be sufficiently nearby for such corrections to be minimal. In Paper 1 HR 8216 was found to have $T_{\rm eff}$ = 8400 K, log g = 3.20, log Z = +0.5, ξ = 2 km s^{-1}, values close to those of this paper while for γ Equ $T_{\rm eff}$ = 7700 K, log g = 4.20, log Z = +0.5, ξ = 2 km s^{-1}. Its temperature is 300 K cooler than adopted here. The later comparison indicates the difficulties in fitting $H\gamma$ profiles in heavily line blanketed stars.

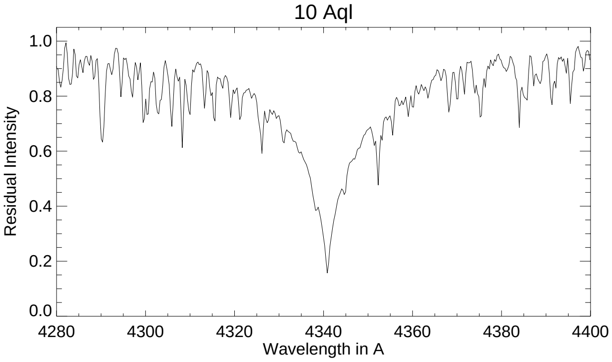

Fig. 2. The observed $H\gamma$ profile of 10 Aql, which is an example of the heavily metal line blanketed profiles seen in the cooler mCP stars. Near λ4311, λ4322, λ4329, and λ4379 are less line blanketed regions of the profile which act as fitting guides in matching observed and synthetic spectra. The $H\gamma$ profile was extracted from DAO spectrogram W48955557.

In Fig. 3 we illustrate some of the fits for the spectrophotometry. That for 56 Ari is similar to that for CU Vir. HR 5597 is reasonably well fit. But for HR 6958 as for 17 Com A, the fit is for the Lyman continuum and the Balmer continuum from about $H\gamma$ through most of the λ5200 feature. Beyond the longward part of the λ5200 feature, the star is systematically brighter than the model. The $\lambda\lambda$4000-4300 region in the star is presumably more heavily line blanketed than the model. For χ Ser fits for enhanced metallicity models are given for both matching the λ5200 feature and the $H\gamma$ profile line strengths. To fit satisfy both criterion will require the use of non-solar scaled odfs. The resulting temperatures and surface gravities will likely lie between the solar cases and the enhanced metallicity values. For the hottest mCP stars, the photometric effective temperature estimates are greater than those from spectrophotometry. But near 9500 K the agreement is much better and this trend continues for stars as cool as 8500 K.

Cooler than this value the efficiency of the convection may come into play. Smalley & Kupka (1997) argued that the tur-

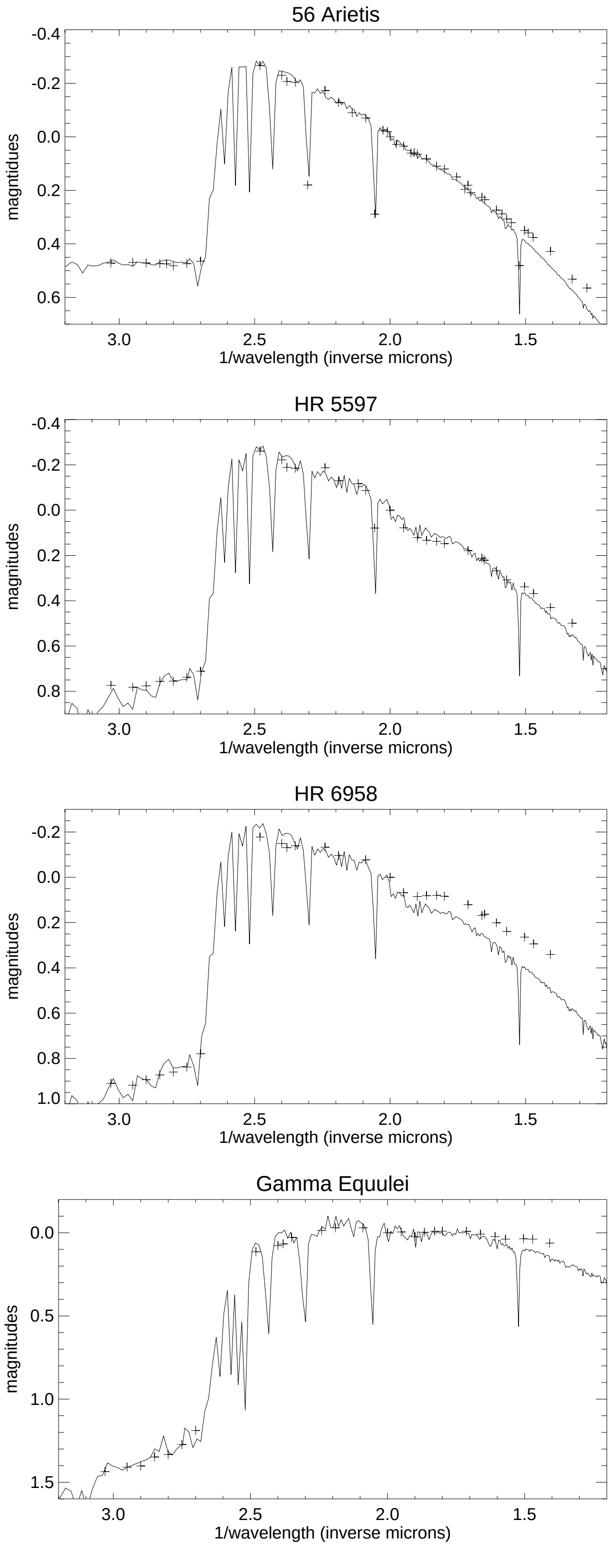

Fig. 3. Observed energy distributions of four magnetic CP stars compared with the predictions of ATLAS9 model atmospheres. For 56 Ari the fluxes of a $T_{\rm eff}$ = 12850 K, log g = 4.00, log Z = +0.5, ξ = 2 km s^{-1} model are shown, for HR 5597 of a $T_{\rm eff}$ = 11000 K, log g = 3.90, log Z = +1.0, ξ = 8 km s^{-1} model, for HR 6958 of a $T_{\rm eff}$ = 10750 K, log g = 3.50, log Z = +1.5, ξ = 8 km s^{-1} model, and for γ Equ of a $T_{\rm eff}$ = 8000 K, log g = 4.50, log Z = +0.5, ξ = 4 km s^{-1} model.

bulent convection theory of Canuto & Mazzitelli (1991, 1992) should be more realistic than mixing-length theory (Castelli et al. 1997). Adelman et al. (2000) found the coolest effective temperatures for which solar composition models utilizing both theories predict the same flux distribution and Hγ profile. The values are 7725 K for log g =3.00, 7850 K for log g = 3.25, 8000 K for log g = 3.50, 8150 K for log g = 3.75, 8300 K for log g = 4.00, and 8475 K for log g = 4.25. As β CrB has values close to this line of demarcation and both γ Equ and 10 Aql are cooler, we found effective temperatures and surface gravities for these three stars using both mixing length and Canuto & Mazzitelli theory.

As convection should not occur in the presence of sufficiently strong magnetic fields, in some cooler mCP stars the efficiency of the convection acting in their photospheres might be less than that for normal stars with similar effective temperatures and surface gravities. If this occurs, then mixing length theory, which corresponds to less efficient convection than that of Canuto & Mazzitelli, may be a better representation of convection in these stars. For the 3 coolest mCP stars studied, the differences between the results for both convection theories is not too large. The temperatures found via mainly the Hγ profiles tend to be slightly larger than those found from uvbyβ photometry. The surface gravity determinations which come from the fluxes increase with metallicity. Fig. 4 shows the difference in effective temperature $\Delta T_{\rm eff}$ between the photometric (T(uvbyβ)) and spectrophotometric (T(sp))temperatures for the mCP stars as a function of T(uvbyβ). The least squares fit is

$$\Delta \mathrm{T_{eff}} = 0.1587\mathrm{T(uvby}\beta) - 1376\,\mathrm{K}.$$

Alternatively

$$\mathrm{T(uvby}\beta) = 1.1984\,\mathrm{T(sp)} - 1704\,\mathrm{K}.$$

In addition there is on the average a 0.09 dex decrease in log g from the photometric values for the spectrophotometric-Hγ determination.

If we compare the temperatures (T[c_1]) fitted by Napitowski et al. (1993) for the hotter mCP stars based on [c_1] (see Table 1), then better agreement results. For these stars on average

$$\mathrm{T(uvby}\beta) - \mathrm{T(sp)} = 583 \pm 341\,\mathrm{K}$$

compared with

$$\mathrm{T([c_1])} - \mathrm{T(sp)} = 167 \pm 255\,\mathrm{K}$$

and

$$\mathrm{T([c_1])} - \mathrm{T(sp)} = 0.8517\mathrm{T(sp)} + 1485\mathrm{K}.$$

This indicates that in the T([c_1]) values some of the effects due to the greater line blanketing and the broad, continuum features are included.

If the strength of the λ5200 feature is in part related to that of the integrated magnetic field as we have suggested, then a photometric measure of its strength such as that of Δa (Maitzen 1976) would possibly be useful in defining a photometrically determined temperature. Around the mean systematic offset in

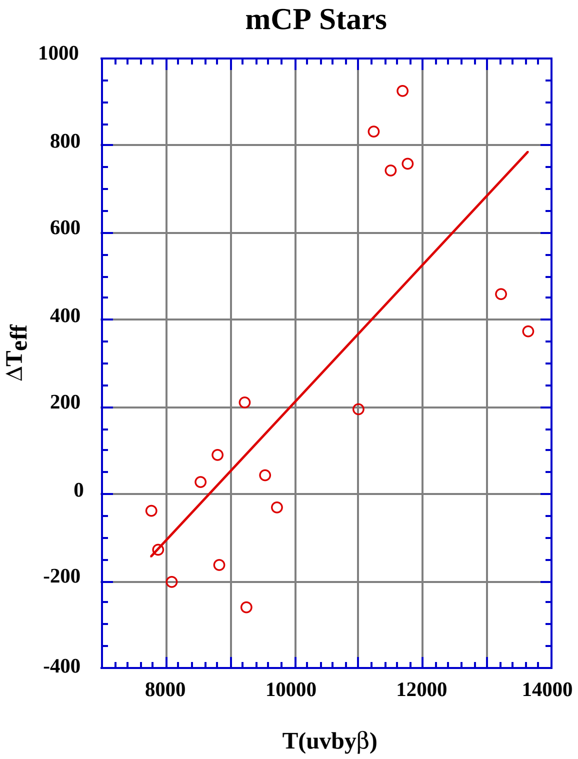

Fig. 4. For the mCP stars the difference between the effective temperature determined from photometry and that from spectrophotometry and the Hγ profile is plotted as a function of the former temperature. The tendency for the difference to increase with temperature is seen although it is probably more complex than the simple regression we adopted.

temperature between the photometric and the spectrophotometric and Hγ profile values there is some scatter which plausibly is due to a range in magnetic field strengths and configurations. A likely origin of the mean trend is the increasing tendency of the photospheric composition to become more metal-rich and non-solar with increasing effective temperature. If this suggestion is valid, then a similar effect might be seen in the Mercury-Manganese stars.

4. The Mercury-Manganese stars

The Mercury-Manganese (HgMn) stars are a group of non-magnetic Chemically Peculiar stars corresponding to normal middle through late B main sequence band stars. Their abundance anomalies range from near solar to very unsolar. Those of the trace elements minimally affect their energy distributions. But those of iron-peak elements may have more important consequences especially when their abundances approach that of iron. One of their most notable anomalies is the tendency of the Mn abundances to increase from near solar in the cooler stars with $T_{\rm eff}$ near 10000 K and to being substantially greater than solar among the hotter stars with $T_{\rm eff}$ near 13,000 K (Adelman 1992a). Further many HgMn stars are members of binary systems. For this study we studied single stars and those whose

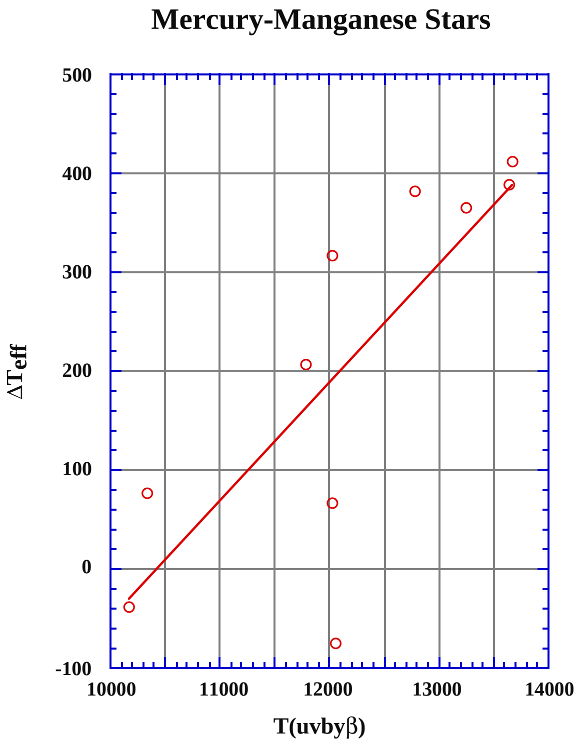

Fig. 5. For the HgMn stars the difference between the effective temperature determined from photometry and that from spectrophotometry and the Hγ profile as a function of the former temperature. As for the mCP stars, the tendency for the difference with temperature is seen. Additional values are highly desirable.

companions have not been detected or contribute very little to the optical region fluxes.

We determined the effective temperatures and surface gravities of HgMn stars as for the mCP stars using for the most part solar composition model atmospheres. Corrections were applied for reddening when indicated by the photometry using the values in Schild (1977). As high quality photometry is available for many class members, calibrations of effective temperatures and surface gravities are possible in many photometric systems. In some cases the relationships used are those for normal main sequence band stars without considering whether this is really appropriate.

Table 2 shows the same kind of systematic offset between the photometric and the spectrophotometric temperatures seen in the mCP stars which further suggests that the similar processes are at work. Fig. 5 shows the difference in effective temperature $\Delta T_{\rm eff}$ between the photometric and spectrophotometric temperatures for the HgMn stars as a function of T(uvbyβ). The least squares fit is

$$\Delta T_{\rm eff} = 0.1197\,{\rm T(uvby}\beta) - 1247\,{\rm K}.$$

In addition there is on the average a 0.04 dex decrease in log g from the photometric values for the spectrophotometric-Hγ determination which is about half as great as that for the mCP stars (γ CrV was not included in this mean value).

Table 2. Effective temperature and surface gravities of Mercury-Manganese Stars

Star Name	HD Number	uvbyβ $T_{\rm eff}$	log g	spectro. $T_{\rm eff}$	and Hγ log g	log Z	spectro. source	Reddening E(b-y)	T([c_1]) (K)
HR 6096	147550	10160	3.85	10200	3.85	0.0	A2	0.07	9600
ν Cnc	77350	10330	3.65	10250	3.75	0.0	A1	0.00	9666
ϕ Her	145389	11780	3.95	11575	4.05	0.0	AP3	0.02	10930
				11575	4.05	0.2			
53 Tau	27295	12015	4.20	11700	4.25	0.0	AP	0.00	11200
υ Her	144206	12015	3.70	11950	3.70	0.0	AP	0.01	11090
γ CrV	106625	12050	3.35	12125	3.70	0.0	DW	0.00	11080
μ Lep	33904	12780	3.80	12400	3.70	0.0	HYL	0.01	11800
HR 7664	190229	13240	3.45	12875	3.50	0.0	KUB	0.00	12210
				12875	3.60	0.2			
β Tau	35497	13640	3.65	13250	3.65	0.0	SPO	0.01	12530
κ Cnc	78316	13660	3.80	13250	3.75	0.0	AP	0.02	12550

Spectrophotometric Sources: A1 = Adelman (1981), A2 = Adelman (1992b), AP = Adelman & Pyper (1979), AP3 = Adelman & Pyper (1983), DW = Davis & Webb (1974), HYL = Hyland (1967), KUB = Kubiak (1973), SPO = Schild et al. (1971)

Table 2 also contains the temperatures of the HgMn stars based on [c_1] of Napitowski et al. (1993). For these stars on average

$$\mathrm{T(uvby\beta) - T(sp)} = 209 \pm 188\,\mathrm{K}$$

compared with

$$\mathrm{T([c_1]) - T(sp)} = -692 \pm 157\,\mathrm{K}$$

which indicates that the normal star relations based on uvbyβ agree better than those based on [c_1]. This probably reflects that the line blanketing of the HgMn stars is more similar to the normal stars than the mCP stars.

5. Discussion

Napiwotzki et al. (1993) claim fitting errors of order ±200 K in $T_{\rm eff}$ and ±0.2 dex in surface gravity among the middle B to early F star. Hence the use of photometric relations for normal stars has appeared to work for the cooler mCP and HgMn stars as the errors are similar to those for the fitting errors. But the use of such relations for hotter class members is inappropriate without using corrections similar to those found in this paper. When these corrections are ignored, systematic errors occur for mCP and HgMn stars with $T_{\rm eff} \geq$ about 10000 K and 12000 K, respectively. As the effective temperatures are too large, so will be many of the abundances. Some investigators have minimized these effects by deriving differential corrections similar to those of this paper and then applying them to stars with only photometrically determined effective temperatures and surface gravities.

There are still some mCP and HgMn stars with good quality spectrophotometry in the literature for which Hγ profiles can be observed. Values derived from this data can help better define the relations shown in Figs. 4 and 5. In addition investigations using non-solar composition models should help. Although ultraviolet and infrared data can each play a role in defining such values, that the absolute calibration of fluxes in the optical region is so much better than those of these two regions means that the comparisons between theory and observations are best done here at present. Spectrophotometric fluxes with a resolution of at least 20 Å from $\lambda\lambda$3300-9000 with nearly continuous coverage and errors not greater than 2% are required for establishing a more reliable temperature scale for these stars with non-solar photospheric compositions. To obtain such data will require a building a spectrophotometer with a CCD as a detector.

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