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On the anomaly of Balmer line profiles of A-type stars

Fundamental binary systems*

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Abstract. In previous work, Gardiner et al. (1999) found evidence for a discrepancy between the $T_{\rm eff}$ obtained from Balmer lines with that from photometry and fundamental values for A-type stars. An investigation into this anomaly is presented using Balmer line profiles of stars in binary system with fundamental values of both $T_{\rm eff}$ and $\log g$. A revision of the fundamental parameters for binary systems given by Smalley & Dworetsky (1995) is also presented. The $T_{\rm eff}$ obtained by fitting Hα and Hβ line profiles is compared to the fundamental values and those obtained from *uvby* photometry. We find that the discrepancy found by Gardiner et al. (1999) for stars in the range 7000 K $\lesssim T_{\rm eff} \lesssim$ 9000 K is no longer evident.

Key words. stars: general – stars: atmospheres – convection – stars: binaries: eclipsing – stars: fundamental parameters

1. Introduction

Balmer lines are an important diagnostic of stellar atmospheric structure since they are formed at a wide range of depths within the atmosphere. In addition, the depth of formation of Hα is higher than that of Hβ, thus observations of these profiles provide useful diagnostics (e.g. Gardiner 2000). Balmer profiles are relatively insensitive to surface gravity for stars cooler than ~8000 K (Gray 1992; see also Heiter et al. 2002). In addition, Balmer profiles are sensitive to the treatment of atmospheric convection (van't Veer-Menneret & Megessier 1996; Castelli et al. 1997; Gardiner 2000; Heiter et al. 2002). For stars hotter than ~8000 K, the profiles are sensitive to both effective temperature and surface gravity. However, provided we know surface gravity from some other means (e.g. from eclipsing binary systems), we can use them to determine effective temperature.

In previous work, Smalley & Kupka (1997, hereafter SK97) found no significant systematic problems with *uvby* and fundamental (and standard) stars. In fact, *uvby* was found to be very good for obtaining $T_{\rm eff}$ and $\log g$. Using Hα and Hβ profiles, Gardiner et al. (1999, hereafter GKS99) found that both the Canuto & Mazzitelli (1991, 1992) and standard Kurucz (1993) mixing-length theory without overshooting (MLTnoOV) (see Castelli et al. 1997) are both in agreement to within the uncertainties of the fundamental stars. Overshooting models were always clearly discrepant. However, GKS99 found some evidence for significant disagreement between *all* treatments of convection and fundamental values around 8000 ~ 9000 K. In this region the effects of $\log g$ cannot be ignored. In GKS99, most of the $T_{\rm eff}$ stars do not have fundamental values of $\log g$. Thus, possible $\log g$ bias could have occurred. In this paper, we use binary systems with fundamental values of $\log g$, determine revised fundamental values of $T_{\rm eff}$ and compare the results with those from Balmer lines.

Binary systems with fundamental values of $\log g$, with in some cases fundamental values of $T_{\rm eff}$, were discussed by Smalley & Dworetsky (1995, hereafter SD95). Their list was limited to four systems, mainly due to lack of trigonometric parallax measurements. Fortunately, the Hipparcos mission (ESA, 1997) has provided trigonometric parallaxes for all of the binary systems considered by SD95. Thus we re-evaluated 15 of those systems, using the methods of SD95, with

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slight modifications and a discussion of the sources of uncertainty.

Theoretical Balmer line profiles are compared to observations and the required values of $T_{\rm eff}$ are derived which when used in a model atmosphere will predict the correct profiles. We have considered three models of convection: the standard mixing-length theory ATLAS9 models (Kurucz 1993; Castelli et al. 1997), with and without approximate convective overshooting, and modified ATLAS9 models based on the turbulent convection theory proposed by Canuto & Mazzitelli (1991, 1992) and implemented by Kupka (1996).

2. Effective temperatures of binary systems

Eclipsing binary systems provide ideal test stars for comparing to models, since they enable us to obtain fundamental values of $T_{\rm eff}$ and $\log g$. We can obtain fundamental values of $T_{\rm eff}$ provided we know the apparent angular diameter (θ) and total integrated (bolometric) flux at the Earth ($f_\oplus$). In the case of binary systems, where there are no direct measurements of angular diameters (θ), we can obtain them from the stellar radius (R) and the parallax (π) of the system (for details see SD95). Since the final $T_{\rm eff}$ is twice as sensitive to θ than $f_\oplus$, it is critically important to obtain good values of θ, which requires both accurate stellar radii measurements and accurate distance determinations.

Available spectrophotometry was taken from various sources (see Table 1), supplemented by 13-colour photometry fluxes from Johnson & Mitchell (1975). All fluxes were placed on the Hayes & Latham (1975) absolute flux scale. Unfortunately, only four stars had enough spectrophotometry. Many others, however, have at least UBV or $UBVRI$ colours, which can be used to estimate the optical flux. Near-infrared fluxes were taken from the Gezari et al. (1987), 2MASS (Skrutskie et al. 1997) and DENIS (Epchtein et al. 1999) catalogues and placed on the Mountain et al. (1985) absolute flux scale.

Using a method similar to Petford et al. (1988), the total integrated flux in the optical region can be obtained. Theoretical UBV or $UBVRI$ colours were compared to the observed values. The model which gave best agreement with the observations was then integrated from 3300–10 000 Å. While this method is not truly fundamental, the final integrated fluxes are not that sensitive to the choice of models. An uncertainly of 10% was adopted to accommodate errors in the photometry and model fluxes.

In a few cases, not even UBV colours are available. However, these systems have Strömgren *uvby* photometry and hence $(B-V)$ can be obtained from $(b-y)$ using the relationship found by Crawford & Barnes (1970). Petford et al. (1988) found that the $(B-V)$ index could be used to obtain the integrated flux from 3800–9000 Å, to within about 3% of that from reticon fluxes. Hence, in the absence of other observations, the Petford et al. empirical relationship is used, with an adopted uncertainty of 10%, to be consistent with that adopted for fluxes obtained from UBV and $UBVRI$ photometry.

Reddening has been determined using UVBYBETA (Moon 1985) and converted to $E(B-V)$ using the relationship $E(B-V) = 1.35E(b-y)$ from Crawford (1975). Where necessary, the observed fluxes were de-reddened using the dereddening routine from DIPSO (Howarth et al. 1997).

Table 1. Sources of flux measurements for binary systems.

Star	HD	Flux sources
12 Per	16739	S2/68 B85 JM G87
CD Tau	34335	S2/68 UBV 2MA
UX Men	37513	$(b-y)$ 2MA
β Aur	40183	IUE J76 B85 K88 JM G87
WW Aur	46052	S2/68 $UBVRI$ 2MA
PV Pup	62863	$(b-y)$ 2MA
RS Cha	75747	UBV
HS Hya	90242	UBV 2MA DEN
RZ Cha	93486	$(b-y)$ DEN
γ Vir	110379	IUE M78 B85 G92 K88 JM G87
DM Vir	123423	$(b-y)$
V624 Her	161321	IUE $UBVRI$ 2MA
V1143 Cyg	185912	S2/68 UBV
MY Cyg	193637	UBV
δ Equ	202275	S2/68 B85 JM G87

Key: IUE INES data from the IUE satellite, S2/68 Starlink STADAT data base (see Thompson et al. 1978, Carnochan 1979), J76 Jamar et al. (1976), M78 Macau-Hercot et al. (1978), B85 Burnashev (1985), G92 Glushneva et al. (1992), K88 Kharitonov et al. (1988), G87 Gezari et al. (1987), JM Johnson & Mitchell (1975), 2MA Skrutskie et al. (1997), DEN Epchtein et al. (1999).

Following SD95, having obtained the combined $f_\oplus$ of the system, we can determine the $f_\oplus$ for each component by assuming that the difference in $f_\oplus$ between the two components is given by the observed magnitude difference, Δm_V. This is a reasonable approximation for a system with nearly identical components, but not necessarily valid for systems with markedly different spectral types. In these cases, we must apply the bolometric correction to obtain the difference in bolometric magnitudes in order to assign the appropriate $f_\oplus$ to each component. Bolometric corrections (BC) were calculated using the polynomials given by Flower (1996). Table 2 lists the values of fundamental radii and $\log g$ values and the observed Δm_V and gives the results of θ, $f_\oplus$ and $T_{\rm eff}$ for each system. In most cases the values obtained using the Hipparcos distances are in agreement with that obtained from other means (e.g. Infrared Flux Method, *uvby* photometry, etc.) and other determinations (e.g. Jordi et al. 1997; Ribas et al. 1998). Three systems are anomalous. Two of them, PV Pup and DM Vir, have large uncertainties in their parallax measurements. The other system, HS Hya, appears to have a very good Hipparcos parallax. Torres et al. (1997) argue that an hitherto undetected third star in the system is likely to have affected the trigonometric parallax. Hence, these systems will not be used in our analysis.

Several of the systems considered here have measured infrared colours which enables us to employ the Infrared Flux Method (IRFM) developed by Blackwell & Shallis (1977) to determine the mean $T_{\rm eff}$ of the binary system, which can be compared to the "combined" $T_{\rm eff}$ obtained using the fundamental method. The results from the IRFM are presented in Table 3. In most cases there is good agreement with the

Table 2. Fundamental values of $T_{\rm eff}$ for binary stars. The "combined" $T_{\rm eff}$ values are given in *italics*.

Star	π ($10^{-3}''$)	Δm_V		Radii	$\log g$	Sp. Types	θ ($10^{-3}''$)	$f_\oplus$ (10^{-6} W m^2)	$T_{\rm eff}$
HD 16 739	40.52 ± 1.25	0.57 ± 0.04		BSF98			*0.788 ± 0.034*	*310. ± 20.0*	*6220 ± 168*
12 Per			A	1.58 ± 0.05	4.16 ± 0.03	F8V	0.596 ± 0.026	195. ± 12.8	6371 ± 176
			B	1.37 ± 0.04	4.24 ± 0.03	G2V	0.517 ± 0.022	115. ± 5.06	6000 ± 143
HD 34 335	13.66 ± 1.64	0.17 ± 0.14		RJT99			*0.305 ± 0.037*	*45.0 ± 5.00*	*6177 ± 410*
CD Tau			A	1.798 ± 0.017	4.087 ± 0.010	F6V	0.229 ± 0.028	24.3 ± 3.06	6110 ± 415
			B	1.584 ± 0.020	4.174 ± 0.012	F6V	0.201 ± 0.024	20.7 ± 1.61	6260 ± 397
HD 37 513	9.93 ± 0.62	0.15 ± 0.10		AND91			*0.171 ± 0.011*	*14.0 ± 2.00*	*6151 ± 293*
UX Men			A	1.347 ± 0.013	4.272 ± 0.009	F8V	0.124 ± 0.008	7.48 ± 1.12	6171 ± 302
			B	1.274 ± 0.013	4.306 ± 0.009	F8V	0.118 ± 0.007	6.52 ± 0.54	6130 ± 233
HD 40 183	39.72 ± 0.78	0.17 ± 0.14		NJ94			*1.411 ± 0.032*	*4500. ± 379.*	*9077 ± 217*
β Aur			A	2.769 ± 0.031	3.930 ± 0.010	A1V	1.023 ± 0.023	2430. ± 250.	9131 ± 257
			B	2.627 ± 0.029	3.962 ± 0.010	A1V	0.971 ± 0.022	2070. ± 139.	9015 ± 182
HD 46 052	11.86 ± 1.06	0.19 ± 0.23		AND91			*0.294 ± 0.027*	*108. ± 12.0*	*7827 ± 419*
WW Aur			A	1.883 ± 0.038	4.187 ± 0.019	A5m	0.208 ± 0.019	58.7 ± 8.65	7993 ± 470
			B	1.883 ± 0.038	4.143 ± 0.018	A7m	0.208 ± 0.019	49.3 ± 5.01	7651 ± 401
HD 62 863	8.10 ± 5.88	0.05 ± 0.27		AND91			*0.162 ± 0.118*	*43.0 ± 6.00*	*8372 ± 3053*
PV Pup			A	1.542 ± 0.018	4.257 ± 0.010	A8V	0.116 ± 0.084	22.0 ± 4.07	8361 ± 3060
			B	1.499 ± 0.018	4.278 ± 0.011	A8V	0.113 ± 0.082	21.0 ± 2.41	8383 ± 3053
HD 75 747	10.23 ± 0.46	0.01 ± 0.16		AND91			*0.302 ± 0.015*	*88.0 ± 9.00*	*7342 ± 266*
RS Cha			A	2.137 ± 0.055	4.047 ± 0.023	A8V	0.203 ± 0.011	44.2 ± 5.56	7525 ± 307
			B	2.338 ± 0.055	3.961 ± 0.021	A8V	0.223 ± 0.011	43.8 ± 3.21	7178 ± 225
HD 90 242	11.04 ± 0.88	0.17 ± 0.09		TOR97			*0.181 ± 0.014*	*14.0 ± 1.40*	*5985 ± 282*
HS Hya			A	1.275 ± 0.007	4.326 ± 0.006	F5V	0.131 ± 0.010	7.55 ± 0.80	6028 ± 290
			B	1.216 ± 0.007	4.354 ± 0.006	F5V	0.125 ± 0.010	6.45 ± 0.40	5936 ± 255
HD 93 486	5.43 ± 0.63	0.00 ± 0.14		AND91			*0.162 ± 0.019*	*15.0 ± 2.00*	*6440 ± 432*
RZ Cha			A	2.264 ± 0.017	3.909 ± 0.009	F5V	0.114 ± 0.013	7.50 ± 1.11	6440 ± 444
			B	2.264 ± 0.017	3.907 ± 0.010	F5V	0.114 ± 0.013	7.50 ± 0.60	6440 ± 396
HD 110 379	84.53 ± 1.18	0.00 ± 0.04		POP80			*1.502 ± 0.179*	*1960. ± 157.*	*7143 ± 450*
γ Vir			A	1.35 ± 0.16	4.21 ± 0.017	F0V	1.062 ± 0.127	978. ± 80.5	7143 ± 451
			B	1.35 ± 0.16	4.21 ± 0.017	F0V	1.062 ± 0.127	978. ± 41.3	7143 ± 433
HD 123 423	2.91 ± 1.25	0.00 ± 0.14		LAT96			*0.068 ± 0.029*	*6.00 ± 1.00*	*7928 ± 1735*
DM Vir			A	1.763 ± 0.017	4.108 ± 0.009	F7V	0.048 ± 0.021	3.00 ± 0.53	7928 ± 1740
			B	1.763 ± 0.017	4.106 ± 0.009	F7V	0.048 ± 0.021	3.00 ± 0.28	7928 ± 1714
HD 161 321	6.93 ± 0.74	0.79 ± 0.12		AND91			*0.242 ± 0.026*	*89.0 ± 9.00*	*8222 ± 489*
V624 Her			A	3.030 ± 0.034	3.834 ± 0.010	A3m	0.195 ± 0.021	60.0 ± 6.44	8288 ± 497
			B	2.209 ± 0.034	4.024 ± 0.014	A7V	0.142 ± 0.015	29.0 ± 2.55	8092 ± 474
HD 185 912	25.12 ± 0.56	0.07 ± 0.11		AND91			*0.441 ± 0.012*	*110. ± 11.0*	*6418 ± 184*
V1143 Cyg			A	1.346 ± 0.023	4.323 ± 0.016	F5V	0.315 ± 0.009	56.8 ± 6.32	6441 ± 201
			B	1.323 ± 0.023	4.324 ± 0.016	F5V	0.309 ± 0.009	53.2 ± 3.38	6393 ± 136
HD 193 637	3.79 ± 0.87	0.03 ± 0.16		AND91			*0.109 ± 0.025*	*12.2 ± 1.22*	*7434 ± 877*
MY Cyg			A	2.193 ± 0.050	4.008 ± 0.021	F0m	0.077 ± 0.018	6.17 ± 0.76	7459 ± 891
			B	2.193 ± 0.050	4.014 ± 0.021	F0m	0.077 ± 0.018	6.00 ± 0.43	7408 ± 865
HD 202 275	54.11 ± 0.85	0.00 ± 0.07		POP80			*0.869 ± 0.025*	*420. ± 30.0*	*6393 ± 147*
δ Equ			A	1.22 ± 0.03	4.34 ± 0.02	F7V	0.614 ± 0.018	210. ± 16.5	6393 ± 156
			B	1.22 ± 0.03	4.34 ± 0.02	F7V	0.614 ± 0.018	210. ± 8.90	6393 ± 115

Key: BSF98 Barlow et al. (1998); RJT99 Ribas et al. (1999); NJ94 Nordström & Johansen (1994b); AND91 Andersen (1991); TOR97 Torres et al. (1997); POP80 Popper (1980); LAT96 Latham et al. (1996).

fundamental values. However, for three systems there is significant disagreement:

PV Pup: as noted above the fundamental value is unreliable, but the IRFM value is also significantly hotter than that obtained from *uvbyβ* photometry (7140 K). Thus, we conclude that the IRFM result is unreliable, possibly due to the uncertainty of the optical flux, which was obtained from $b-y$ alone.

γ Vir: the IRFM result is cooler than the fundamental value, but both agree to within the relatively large errorbar of the fundamental value. Interestingly, SD95 obtained a value of $T_{\rm eff}$ = 6750 ± 470 K using the van Altena et al. (1991) trigonometric parallax, which is in excellent agreement with the IRFM.

V624 Her: the IRFM is cooler than the fundamental value. The fundamental value is, however, in agreement with Popper (1984) and Ribas et al. (1998).

Having obtained fundamental $T_{\rm eff}$ values for the binary systems, we now present observations of the Balmer lines of these systems and the results of fitting profiles using models with differing treatments of convection. We will also refer to the IRFM values and values of $T_{\rm eff}$ obtained from *uvby* photometry.

Table 3. Effective temperatures obtained from the Infrared Flux Method (IRFM) for the binary systems. The values are the "combined" flux $T_{\rm eff}$.

Star	HD	$T_{\rm eff}$
12 Per	16739	6275 ± 229
CD Tau	34335	5985 ± 203
UX Men	37513	6204 ± 244
β Aur	40183	8858 ± 221
WW Aur	46052	7795 ± 227
PV Pup	62863	7759 ± 313
HS Hya	90242	6256 ± 181
RZ Cha	93486	6404 ± 260
γ Vir	110379	6747 ± 189
V624 Her	161321	7710 ± 218
δ Equ	202275	6293 ± 162

3. Observations

The Hα and Hβ observations were made at the Observatorio del Roque de los Muchachos, La Palma using the Richardson-Brealey Spectrograph on the 1.0 m Jacobus Kapteyn Telescope (JKT) in 1997 October/November. A 2400 l mm^{-1} holographic grating was used and a 1124 × 1124 pixel Tek CCD, giving a resolution of 0.4 Å FWHM. Further Hα and Hβ observations were made at the Mount Stromlo Observatory, Australia in February 2000 using the Cassegrain Spectrograph on the ANU 74 inch telescope. A 1200 l mm^{-1} blazed grating was used, giving a resolution of 0.35Å FWHM. Additional Hβ profiles were taken from the work of SD95.

The data reduction of the profiles taken in 1997 and 2000 was performed using the Starlink ECHOMOP software package (Mills et al. 1997). In most cases the final spectra had a signal-to-noise ratio in excess of 100:1. Instrumental sensitivity variations were removed from the Hα profiles by comparing to observations of stars with intrinsically narrow Balmer profiles, for example early-B or O type stars and G type stars, and the Hβ profiles were normalized such that the observed profile of Vega agreed to a model with $T_{\rm eff}$ = 9550 K, log g = 3.95, [M/H] = −0.5 (Castelli & Kurucz 1994) and the standard profiles of Peterson (1969).

4. Effective temperatures from Balmer line profiles

The observed Balmer line profiles are fitted here to model spectra to compare the derived $T_{\rm eff}$ with that from fundamental methods. One of our main aims is to investigate the performance of different models of convection. The following convection models were used, using solar-metallicity Kurucz ATLAS models:

1. Standard ATLAS9 (Kurucz 1993) models using mixing length theory (MLT) without convective overshooting. The value of the MLT parameter α is the standard value of 1.25. These will be referred to as MLT_noOV 1.25 models in this paper.
2. Standard ATLAS9 models using MLT without convective overshooting. The value of the MLT parameter α is 0.5. These will be referred to as MLT_noOV 0.5 models.
3. Standard ATLAS9 models using MLT with approximate overshooting. The value of the MLT parameter α used is 1.25. These will be referred to as MLT_OV 1.25 models.
4. Standard ATLAS9 models using MLT with approximate convective overshooting. The value of the MLT parameter α used is 0.5. These will be referred to as MLT_OV 0.5 models.
5. Modified ATLAS9 models using the Canuto & Mazzitelli (1991, 1992) model of turbulent convection. These will be referred to as the CM models.

The synthetic spectra were calculated using UCLSYN (Smith 1992; Smalley et al. 2001) which includes Balmer line profiles calculated using the Stark-broadening tables of Vidal et al. (1973) and metal absorption lines from the Kurucz & Bell (1995) linelist. This routine is based on the BALMER routine (Peterson 1969; Kurucz 1993). The spectra were rotationally broadened as necessary and instrumental broadening was applied with $FWHM$= 0.4 Å to match the resolution of the observations. The synthetic spectra were normalized at ±100 Å to match the observations. The values of $T_{\rm eff}$ were obtained by fitting model profiles to the observations using the least-square differences. A microturbulence of 2 km s^{-1} was assumed throughout for both the model atmosphere line opacities and spectrum synthesis.

Two stars, HD 46 052 and HD 161 321, are Am stars, with [M/H] = 0.23 and 0.29, respectively, calculated from the δm_0 calibrations, derived by Berthet (1990) and Smalley (1992). For these stars Balmer profile fits using the solar abundance grid model atmospheres gave results for $T_{\rm eff}$ which were around 50 ∼ 100 K hotter, compared to models with the appropriate [M/H].

The Balmer line profiles become increasingly less sensitive to log g below ∼8000 K thus any errors in the values of log g used will have no significant effect on the results. Hotter than ∼8000 K the Balmer profiles become progressively more sensitive to log g, making it important to have a fundamental value of log g with a small error. For example, at 8000 K, a change in assumed log g of 0.5 dex would have the effect to changing the temperature of the model profile an observation is fit to by ∼150 K.

The best fitting values of $T_{\rm eff}$ for the binary stars are given in Table 4, for the 5 convection models listed above. Figures 1 and 2 show the variation of $\Delta T_{\rm eff}$ = $T_{\rm eff}$(Balmer) − $T_{\rm eff}$(fund) against $T_{\rm eff}$(fund) for Hα and Hβ, respectively. To within the uncertainties, the CM results show no significant variation with $T_{\rm eff}$(fund) for either Hα or Hβ. The discrepancy around 8000 K noted by GKS99 is not evident. Even the two anomalous Hα points just hotter than 8000 K for V624 Her can be brought into agreement if the IRFM $T_{\rm eff}$ is used (see Sect. 2). The MLT_noOV results are in broad agreement with those for CM, but with the α = 0.5 models giving better agreement around 8000 K relative to α = 1.25 and CM models. Contrary to GKS99, who reported that F-type stars might require models with $\alpha \geq$ 1.25 (see their Fig. 9), we find that the binary systems do not support this. Overall, α = 0.5 models are preferred to those with higher values. The MLT_OV models are generally more discrepant, yielding too high values of $T_{\rm eff}$ (and even

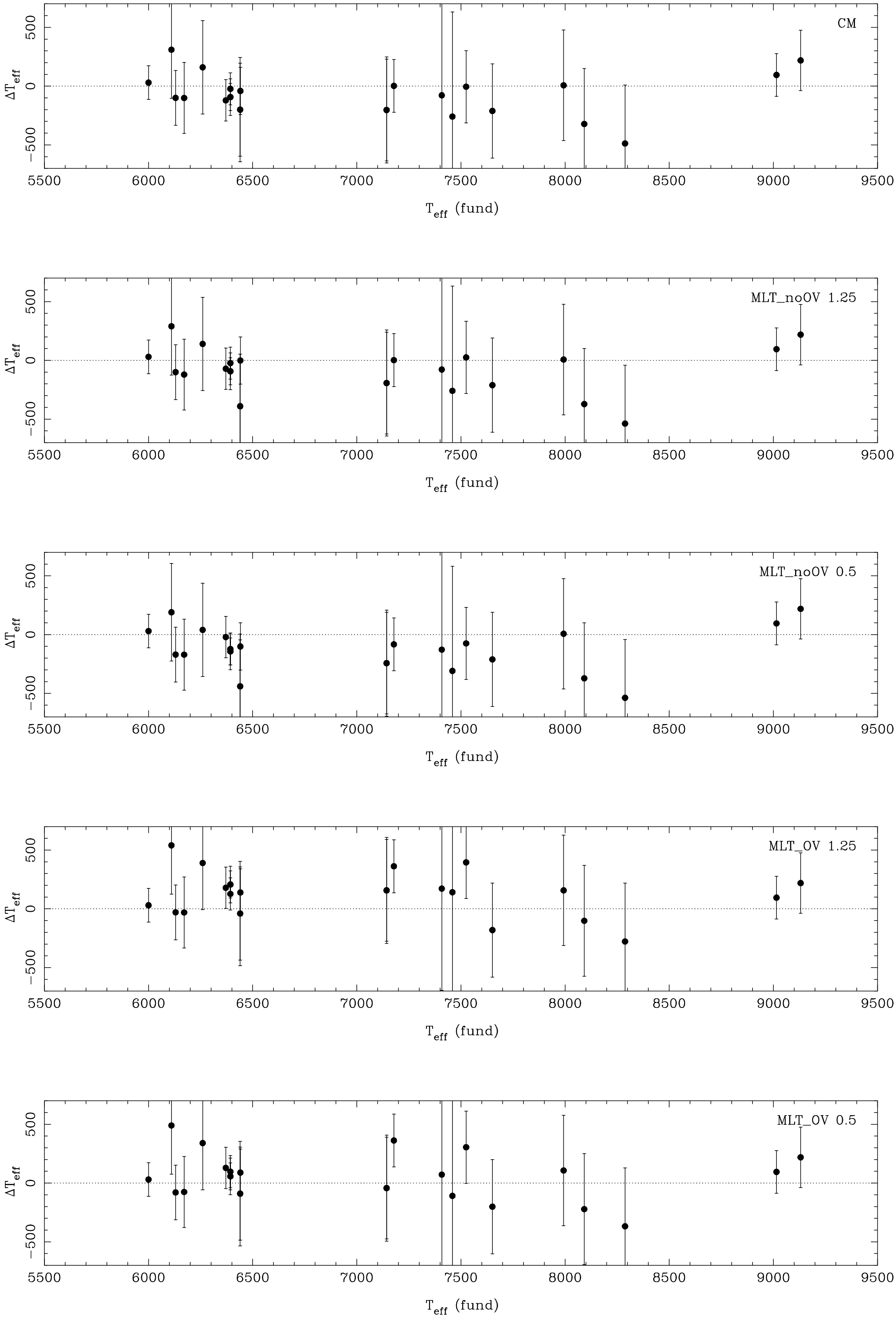

Fig. 1. Comparison between $T_{\rm eff}$ calculated from Balmer line profiles Hα to those derived from fundamental methods for the five convection models. $\Delta T_{\rm eff} = T_{\rm eff}$(Balmer) − $T_{\rm eff}$(fund) is plotted against $T_{\rm eff}$(fund).

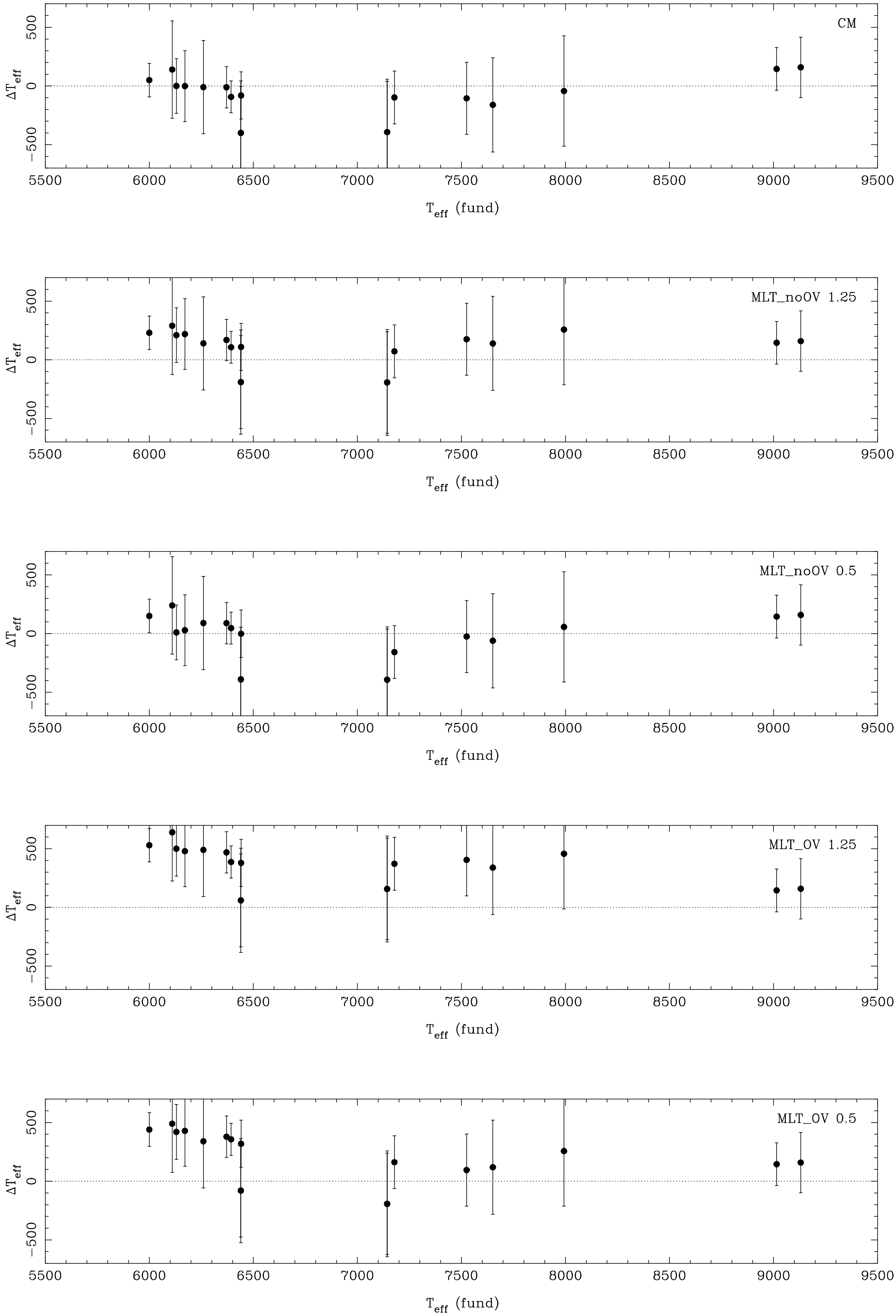

Fig. 2. Same as Fig. 1, but for Hβ.

Table 4. $T_{\rm eff}$ obtained from Balmer line profiles for binary systems with known values of $\log g$.

			CM			MLT_noOV 0.5		MLT_noOV 1.25		MLT_OV 0.5		MLT_OV 1.25	
Star		$T_{\rm eff}$ (fund)	Hα	Hβ	*uvby*	Hα	Hβ	Hα	Hβ	Hα	Hβ	Hα	Hβ
12 Per	A	6371 ± 176	6250	6360		6350	6460	6300	6540	6500	6750	6550	6840
	B	6000 ± 143	6030	6050		6030	6150	6030	6230	6030	6440	6030	6530
CD Tau	A	6110 ± 415	6420	6250	6276	6300	6350	6400	6400	6600	6600	6650	6750
	B	6260 ± 397	6420	6250	6311	6300	6350	6400	6400	6600	6600	6650	6750
UX Men	A	6171 ± 302	6070	6170	6131	6000	6200	6050	6390	6095	6600	6140	6650
	B	6130 ± 233	6030	6130	6094	5960	6140	6030	6340	6050	6550	6100	6630
β Aur	A	9131 ± 257	9350	9290	9586	9350	9290	9350	9290	9350	9290	9350	9290
	B	9015 ± 182	9110	9160	9438	9110	9160	9110	9160	9110	9160	9110	9160
WW Aur	A	7993 ± 470	8000	7950		8000	8050	8000	8250	8100	8250	8150	8450
	B	7651 ± 401	7440	7490		7440	7590	7440	7790	7450	7770	7470	7990
RS Cha	A	7525 ± 307	7520	7420	7739	7450	7500	7550	7700	7830	7620	7920	7930
	B	7178 ± 225	7180	7080	7375	7095	7020	7180	7250	7540	7340	7540	7550
RZ Cha	A	6440 ± 444	6240	6040	6278	6000	6050	6050	6250	6350	6360	6400	6500
	B	6440 ± 396	6240	6040	6357	6000	6050	6050	6250	6350	6360	6400	6500
γ Vir	A	7143 ± 451	6940	6750	6906	6900	6750	6950	6950	7100	6950	7300	7300
	B	7143 ± 433	6940	6750	6906	6900	6750	6950	6950	7100	6950	7300	7300
V624 Her	A	8288 ± 476	7800			7750		7750		7920		8010	
	B	8092 ± 450	7770			7720		7720		7870		7990	
V1143 Cyg	A	6441 ± 201	6400	6360	6467	6340	6440	6440	6550	6530	6760	6580	6820
	B	6393 ± 136	6370	6300	6467	6270	6440	6370	6500	6490	6750	6520	6780
MY Cyg	A	7459 ± 891	7200		7079	7150		7200		7350		7600	
	B	7408 ± 865	7330		7223	7280		7330		7480		7580	
δ Equ	A	6393 ± 156	6300		6203	6250		6300		6450		6600	
	B	6393 ± 115	6300		6203	6250		6300		6450		6600	

larger ones for Hβ, if $\alpha = 1.25$ is used rather than 0.5), as found previously by GKS99. Note also the systematic difference between Hα and Hβ for $\alpha = 1.25$ MLT_noOV models, which is even more pronounced for the MLT_OV models.

4.1. The apparent A-star anomaly

The use of stars with fundamental values of both $T_{\rm eff}$ and $\log g$ has failed to support the apparent anomaly around 8000 K found by GKS99, in which Balmer profiles gave progressively lower values of $T_{\rm eff}$ compared to fundamental values. However, there are too few stars within the $T_{\rm eff}$ range 8000–9000 K to fully explore this region. In addition, GKS99 found that four fundamental $T_{\rm eff}$ stars showed the anomaly: HR 4534, HR 6556, HR 7557, and HR 8728. In order to be sure that there is no anomaly in the Balmer line profiles, we need to explain why these stars might appear anomalous. We have also included HR 2421 which is just hotter than 9000 K, but find that this is in agreement with its fundamental and IRFM $T_{\rm eff}$.

Table 5 summarizes the values of $T_{\rm eff}$ obtained from CM models and *uvby* photometry, the IRFM and by fitting to Hα and Hβ profiles. We have allowed both $T_{\rm eff}$ and $\log g$ to vary in order to obtain the best least-squares fit (see Figs. 3 and 4). Values of $\log g$ are also given as obtained from *uvby* photometry, as well as those adopted by GKS99.

The rapidly rotating star HR 7557 has recently been studied by van Belle et al. (2001) using interferometry. Their analysis revealed the oblateness of the star and gave revised angular diameter values and a new determination of fundamental $T_{\rm eff} = 7680 \pm 90$ K. This is significantly cooler than the previous determination, but in accord with that inferred from the IRFM. As such, the $T_{\rm eff}$ from Hα and Hβ are no longer significantly discrepant. In fact the new $T_{\rm eff}$ is in agreement with that given in Gray (1992) for a A7V star. It is certainly possible that revision to the other fundamental stars could occur once new interferometric measurements are obtained, especially HR 6556 which has a similar $v \sin i$ and might be expected to exhibit significant oblateness. Thus, the anomalies for HR 6556 and HR 7557 can be explained in terms of their *rapid rotation*. However, the earlier angular diameter measurements are not necessarily the source of any discrepancy, since the new Vega (HR 7001) value obtained by Ciardi et al. (2001) is in excellent agreement with that of Hanbury Brown et al. (1974).

The two other stars, HR 4534 and HR 8728, have lower $v \sin i$ values, but are the two most discrepant stars in the GKS99 sample. Unless the fundamental values are truly wrong there must be some other reason for the discrepancy. The IRFM values both point to a slightly cooler $T_{\rm eff}$, but even then the discrepancy is ~300 K. However, in this temperature region the Balmer lines are near their maximum strength and sensitive to $\log g$. It is certainly possible that a small error in adopted $\log g$ could lead to a large error in $T_{\rm eff}$ obtained from Balmer profiles. In fact, using the values of $\log g$ obtained from *uvby* photometry requires $T_{\rm eff} \simeq 7900$ K in order to fit the observed Hα profiles for both stars and $T_{\rm eff} \simeq 8100$ K to fit the Hβ profile of HR 4534. In addition, the Balmer profiles change little with relatively large changes in $T_{\rm eff}$. Thus, we conclude that the two stars are not discrepant, due to the low sensitivity of Balmer lines with respect to changes in $T_{\rm eff}$ and both sensitivity to, and the uncertainty in, the surface gravity for these stars.

In general, for stars hotter than 8000 K the sensitivity to $\log g$ prevents us from using Balmer line profiles to obtain

Table 5. Early A-stars with fundamental values of $T_{\rm eff}$, but not $\log g$.

HR	star	$v \sin i$	$T_{\rm eff}$	$\log g$	CM *uvby*		$T_{\rm eff}$	Hα		Hβ	
		(km s^{-2})	Fund	GKS99	$T_{\rm eff}$	$\log g$	IRFM	$T_{\rm eff}$	$\log g$	$T_{\rm eff}$	$\log g$
2421	γ Gem	45	9220 ± 330	3.5	9250 ± 460	3.56 ± 0.30	9040 ± 86	9220 ± 300	3.40 ± 0.2	9060 ± 250	3.52 ± 0.2
4534	β Leo	122	8870 ± 350	4.1	8770 ± 300	4.32 ± 0.11	8660 ± 60	8370 ± 400	3.77±0.2	8450 ± 350	4.07 ± 0.2
6556	α Oph	240	7960 ± 330	3.8	7940 ± 210	3.80 ± 0.17	7883 ± 63	7510 ± 100	3.69 ± 0.3	7580 ± 150	3.42 ± 0.6
7557	α Aql	245	7990 ± 210	4.2	7840 ± 200	4.18 ± 0.17	7588 ± 73	7420 ± 100	4.17 ± 0.3	7450 ± 150	4.38 ± 0.6
8728	α PsA	85	8760 ± 310	4.2	8890 ± 320	4.30 ± 0.10	8622 ± 86	8340 ± 400	3.87 ± 0.2		

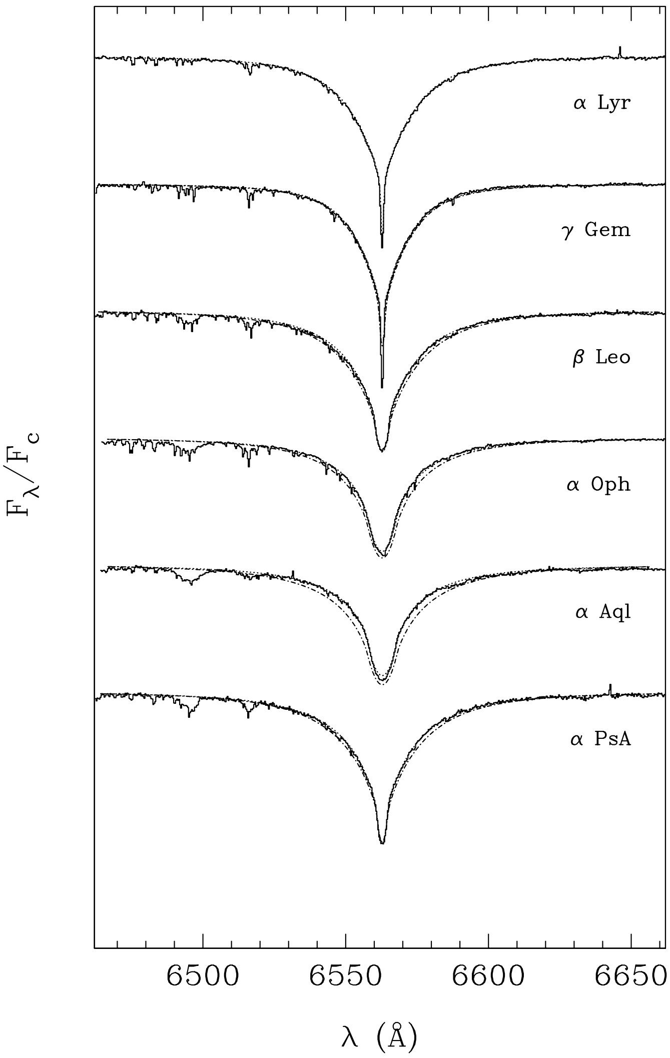

Fig. 3. Hα profiles of A stars. The continuous line is the observed profile, while the dotted line is the synthetic profile for best fitting parameters given in Table 5. The dash-dot line is that for profiles calculated for the fundamental parameters. The profiles for Vega are given for reference.

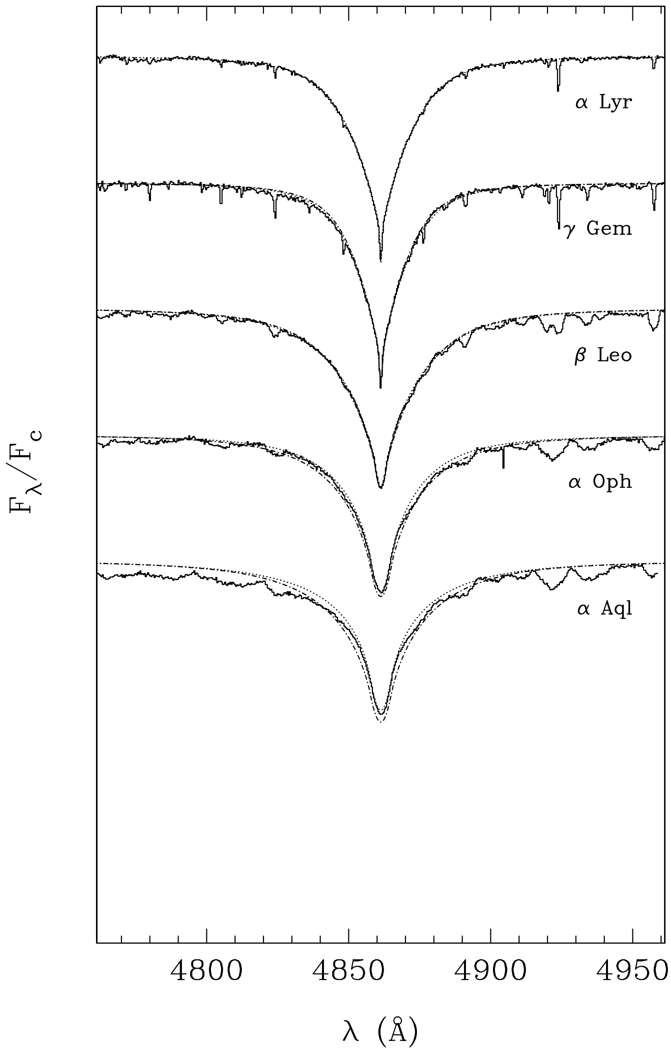

Fig. 4. Same as Fig. 3, but for Hβ profiles.

values of $T_{\rm eff}$ to the accuracy required for the present task, unless we have accurate fundamental values of $\log g$. However, until we do have stars with accurate fundamental $\log g$ values, we cannot be totally sure that there is not a problem with the model predictions in this $T_{\rm eff}$ region.

5. Conclusion

The availability of the Hipparcos parallax measurements has enabled the list of stars with fundamental values of both $T_{\rm eff}$ and $\log g$ to be considerably extended, from the 4 originally given by Smalley & Dworetsky (1995), to the 15 presented here. Even when the available optical flux measurements are limited to only UBV magnitudes, the quality of the final $T_{\rm eff}$ values is good. In some cases, it is the uncertainty of the Hipparcos parallax measurements that limits the accuracy of the $T_{\rm eff}$ obtained. The stars with IRFM values are mostly in very good agreement with the fundamental values, showing that the two methods are self-consistent and reliable. Since there are more systems with $T_{\rm eff}$ values from the IRFM (e.g. Blackwell & Lynas-Gray 1994; Alonso et al. 1995), this method can be used to obtain 'near-fundamental' values, provided we avoid binary systems with markedly dissimilar components (Smalley 1993).

Balmer line profiles have been fitted to the fundamental binary systems. To within the errors of the fundamental $T_{\rm eff}$ values, neither the Hα or Hβ profiles exhibit any significant discrepancies for the CM and MLT_noOV models. As in previous work, the MLT_OV models are found to be discrepant. Moreover, there are no systematic trends, such as offsets, between results from Hα and Hβ as long as α in MLT models is chosen small enough (e.g. 0.5). The discrepancies exhibited by the fundamental $T_{\rm eff}$ stars in GKS99 can be explained by rapid rotation in two cases and by the fact that the Balmer profiles become sensitive to $\log g$ and less sensitive to $T_{\rm eff}$ in the other two cases. However, for the time being the lack of any stars with fundamental values of both $T_{\rm eff}$ and $\log g$ in this region precludes the conclusion that there is not a problem with the models in the $T_{\rm eff}$ range 8000 ~ 9000 K.

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