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The role of convection on the $uvby$ colours of A, F, and G stars*

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Abstract. We discuss the effects of convection on the theoretical $uvby$ colours of A, F, and G stars. The standard mixing-length theory ATLAS9 models of Kurucz (1993), with and without approximate overshooting, are compared to models using the turbulent convection theory proposed by Canuto & Mazzitelli (1991, 1992) and implemented by Kupka (1996a).

Comparison with fundamental T_{eff} and $\log g$ stars reveals that the Canuto & Mazzitelli models give results that are generally superior to standard mixing-length theory (MLT) without convective overshooting. MLT models with overshooting are found to be clearly discrepant. This is supported by comparisons of non-fundamental stars, with T_{eff} obtained from the Infrared Flux Method and $\log g$ from stellar evolutionary models for open cluster stars. The Canuto & Mazzitelli theory gives values of $(b-y)_0$ and c_0 that are in best overall agreement with observations.

Investigations of the m_0 index reveal that all of the treatments of convection presented here give values that are significantly discrepant for models with $T_{\text{eff}} < 6000$ K. It is unclear as to whether this is due to problems with the treatment of convection, missing opacity, or some other reason. None of the models give totally satisfactory m_0 indices for hotter stars, but the Canuto & Mazzitelli models are in closest overall agreement above 7000 K.

Grids of $uvby$ colours, based on the CM treatment of convection, are presented. These grids represent an improvement over the colours obtained from models using the mixing-length theory. The agreement with fundamental stars enables the colours to be used directly without the need for semi-empirical adjustments that were necessary with the earlier colour grids.

Key words: convection – stars: atmospheres – stars: general – stars: fundamental parameters

1. Introduction

The gross properties of a star, such as broad-band colours and flux distributions are significantly influenced by the microscopic effects of convection in stars later than mid A-type. Consequently, our treatment of convection in stellar atmosphere models can significantly alter our interpretation of observed phenomena. The Kurucz (1979a) ATLAS6 model atmospheres have generally had considerable success in the interpretation of stellar fluxes and spectra of O, B, A, F, and G stars. However, small systematic errors were found in the colours calculated for late-A and F stars. Relyea & Kurucz (1978) discussed several possible reasons for discrepancies between theoretical and observational Strömgren (1963, 1966) $uvby$ colours, including the effects of missing opacity and convection.

Model atmosphere fluxes enable us to calculate $uvby$ colours by using suitable filter passbands. Details of this procedure can be found in Relyea & Kurucz (1978). In all three cases of models considered here, the colours have been calculated with the routines used by Kurucz (1993). All the model grids have been normalized to agree for Vega (α Lyr), the usual procedure in normalizing theoretical colours. The normalization was the same as that given in Kurucz (1993), with Vega represented by an ATLAS9 model with T_{eff} = 9550 K, $\log g$ = 3.95, [M/H] = -0.5 and a microturbulence of 2 km s^{-1} (Castelli & Kurucz 1994). In this way, the grids used here all agree at one point. This does not in any way bias the convection study, since the atmosphere of Vega can be considered as totally radiative and thus unaffected by changes in the treatments of convection. Though the Schwarzschild stability criterion predicts an instability of the atmospheric stratification against convection within a small layer (where the ionization of hydrogen takes place), all convection models investigated in this paper give convective fluxes for Vega which are several orders of magnitudes less than the usual deviations from flux constancy obtained for "converged" ATLAS model atmospheres. Consequently, an entirely radiative ATLAS model atmosphere of Vega cannot be distinguished from its convective counterparts in terms of observed fluxes and colours. Thus, our normalization to Vega allows us to compare only the differences due to treatment of convection.

In this paper we present a discussion of the effects of different treatments of convection on the $uvby$ colours. The effects of mixing-length theory, with and without approximate overshooting, on $b-y$ and c_0 were discussed in detail by Castelli et al. (1997). In this paper we concentrate on the comparison be-

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* Table 5 is only available at the CDS via anonymous ftp 130.79.128.5 or via http://cdsweb.u-strasbg.fr/Abstract.html

tween mixing-length theory and the turbulent convection theory of Canuto & Mazzitelli (1991, 1992).

2. The treatment of convection

2.1. Synthetic colours from convective model atmospheres

The Kurucz (1979a) model calculations represented a landmark in the study of stellar atmospheres. These included the opacity for approximately 900 000 atomic lines and provided realistic emergent flux distributions, spectra and colours of O, B, A, F, and G stars. Since molecular line opacity was not included, systematic errors began to appear in models and fluxes for $T_{\rm eff} \lesssim 6000$ K (Relyea & Kurucz 1978). Nevertheless, they have been enormously successful and widely used.

Relyea & Kurucz (1978) presented theoretical $uvby$ colours based on the Kurucz (1979a) model fluxes. They discussed the accuracy of these colours and compared them to the observed colours of the stars in the Hauck & Mermilliod (1975) catalogue. The colours were found to agree well with the observations, except for late-A and early-F stars. Theoretical c_0 colours were in error around 7500 K, and m_0 colours were discrepant for $(b-y)_0 > 0.050$, first too small and then too large. The colours were not expected to agree for $T_{\rm eff} < 6000$ K due to the lack of molecular opacity.

Possible reasons for the discrepancies between 8500 K and 6000 K were discussed by Relyea & Kurucz (1978). They concluded that the probable sources of error included improper representation of opacities and improper treatment of convection. They stated that convection may account for part or even all the discrepancy between the models and the observations. The choice of mixing length, $[l/H]$ = 2, might be physically suspect and lead to grossly overestimated convective flux. They showed that changing convective flux can easily induce large changes in the colours (see their Fig. 12).

In light of the work of Relyea & Kurucz (1978), several attempts have been made to improve the accuracy of the model colours by modifying the treatment of convection. It has to be remembered that the reason for the discrepancies may not be totally due to convection; missing opacity (atomic and molecular) could well be as important. In fact, improvements to opacity has been an ongoing project by Kurucz (1991a). Others have taken the model $uvby$ colours and adjusted them until they agreed better with colours of stars with known $T_{\rm eff}$ and $\log g$ (e.g. Philip & Relyea 1979; Moon & Dworetsky 1985; see also Smalley 1996). While this approach does give good agreement with fundamental or standard stars, it masks any physical problems with the models.

Kurucz (1979b) introduced an improvement to the treatment of convection, compared to that used in Kurucz (1979a), by considering the different amount of energy loss by the "convective elements" during their life time in an optically thin medium as compared to an optically thick one where the diffusion approximation to radiative transfer is assumed. Lester et al. (1982) discussed the modifications proposed by Deupree (1979) and Deupree & Varner (1980) to include "horizontally averaged opacity" and a "variable mixing length". The model $uvby$ colours could be brought closer to the observed colours, but not enough to entirely remove the discrepancies found by Relyea & Kurucz (1978). For ATLAS9 as published by Kurucz (1993) further modifications were included, the "horizontally averaged opacity" and "approximate overshooting". The original formulation of the "approximate overshooting" lead to several discontinuities in the colour indices obtained from the models (e.g. North et al. 1994). Castelli (1996) presented a discussion on convection in ATLAS and re-defined the "approximate overshooting" so as to remove the discontinuities. A detailed description of mixing-length convection and the modifications used in ATLAS is given by Castelli et al. (1997).

Recently, a model of turbulent convection has been proposed (Canuto & Mazzitelli 1991, 1992; Canuto 1996b) to overcome one of the most basic short-comings of MLT, the "one-eddy approximation". Within this approximation it is assumed that one eddy which has a given size as a function of the local mixing length (and which is usually called "bubble" or "convective element") is responsible for all the transportation of energy due to convection. Because of the one-eddy approximation the MLT systematically overestimates the flux for inefficient convection and underestimates it in the efficient case (Canuto 1996b). The new theory suggested first in Canuto & Mazzitelli (1991) adopts a turbulence model which accounts for eddies of various sizes (scales) that interact with each other.

If we take the quantity S, the product of Rayleigh and Prandtl number, as a measure of convective efficiency, the new model, known as the CM model, predicts ten times more flux than MLT for the case of efficient convection and only one tenth of MLT's values in the inefficient case. As in an incompressibility model the pressure becomes a function of the velocity field itself, it is no longer an independent variable and one can no longer construct a unit of length of the type $\sim P/(g\rho)$. The only remaining length is the geometrical distance to the nearest stable layer, $l = z$. This choice also leads to a great degree of generality which was recently confirmed by Stothers & Chin (1997). No free parameter α_z (analogue to MLT's parameter α) was necessary to perform their $T_{\rm eff}$-luminosity calibrations of the red giant branch for stars with masses ranging from 1–20 $M_\odot$. In this sense, the CM model has no adjustable free parameters, unlike MLT which can be "adjusted" to fit observations. Despite the loss of a fit parameter the CM model has had considerable success in explaining observations (see Stothers & Chin 1995; and Canuto 1996b for references). However, the model is still a local concept that has been adapted for one dimensional geometry. Thus, the CM model cannot describe the phenomenon of overshooting or the influence of large scale structures on the integral of the radiation field over the stellar disk. This can be done by "large eddy simulations", which are, however, on a different level of numerical complexity and up to now have not included the same sophistication in their treatment of radiative transfer as classical model atmospheres (e.g. Nordlund & Dravins, 1990; Freytag, 1996).

2.2. New grids based on the CM model

In 1995 the CM convection model was implemented in the ATLAS9 code (Kupka 1996a). The model was tested by F. Kupka with various other prescriptions of a local length. As part of the same project the "approximate overshooting" was applied to the CM model, and a correction for convection in optically thin media was investigated. After applying the model atmosphere code with various treatments of convection to several regions throughout the whole lower and central part of the HR diagram, it was decided to use the CM model in its original form for model grid computations, because the differences found were either small or lacked a convincing physical motivation that could be corroborated by experimental tests. More details on these experiments and on the implementation itself will be discussed in Kupka & Canuto (1997). A brief description of results for A and F type stars has already been given by Kupka (1996b). More extensive discussions of the properties of models in various regions of the HR diagram will be presented in Kupka & Canuto (1997), thus only a few remarks will be given here.

In the upper part of a stellar atmosphere (with $\tau_{\rm ross} < 0.001$) the radiative time scale (see Canuto 1996b) is necessarily very short as (most of) the observed radiation leaves the star in this region which must hence be an efficient means of energy transportation. Well below these layers, at $\tau_{\rm Ross} \approx 1$, the ionization of hydrogen takes place and decreases the efficiency of radiative transfer. Where the radiative time scale becomes comparable to that of buoyancy, energy can be transported by means of convection instead of radiation. In the observable atmosphere layers of A, F, and G stars we only encounter the case of inefficient convection. As the CM model predicts *less* convective flux than MLT for an inefficient convective region, the temperature gradient has to be closer to the purely radiative gradient in the top layers of the convection zone for a larger range of τ.

If we map the HR diagram onto a $T_{\rm eff} - \log g$ plane, we may distinguish between four regions of different atmospheric conditions for convection. For main sequence stars and a $T_{\rm eff}$ well above 10 000 K the $T - \tau$ relation is entirely radiative. For the early A-type stars there is a region around the zone of hydrogen ionization that is convectively unstable according to the Schwarzschild criterion, but convective transport remains so inefficient that the resulting temperature gradient cannot be distinguished from the radiative one. In the case of the MLT, minor deviations from the radiative gradient can be observed beginning around $T_{\rm eff} \approx 8500$ K for $\log g = 4$. This convection zone is still entirely contained in the stellar atmosphere. For $T_{\rm eff} < 7500$ K the convection zone finally extends below the atmosphere (normal, solar like convection as opposed to "plume convection" for higher $T_{\rm eff}$; see Kurucz 1996). Examples and illustrations for the MLT case can be found in Kurucz (1996), as well as in Castelli et al. (1997). For lower surface gravity these transitions occur at lower $T_{\rm eff}$. For the case of the CM model the last two transition regions occur for $T_{\rm eff}$ about 1000 K less than in the MLT case, but otherwise they have very similar properties (see below). On the other hand, the extent of the overall *convectively unstable* region of the HR diagram remains unchanged when changing from MLT to the CM model.

Continuous manual interaction during the computation of large grids of models is rather tedious, but software tools may reduce the necessary amount of work. To facilitate the determination of $T_{\rm eff}$ and $\log g$ from photometric observations, a suite of empirical calibrations was assembled by Rogers (1995). In addition to this toolbox, he provided another set of tools which unifies the access to and application of software for the computation of model grids, synthetic fluxes, and synthetic colour indices. This was achieved by adapting those parts of the Abundance Analysis Procedure (AAP) tool (see Gelbmann et al. 1997), which allow *interactive* computation of single ATLAS9 model atmospheres, for background computation of a grid of models. *Automatic* convergence to a prescribed value of flux constancy (typically less than 3% for the deepest layers) and a zero flux derivative with depth (typically less than 10% for the uppermost layers) is achieved by comparing the output information of ATLAS9 with the criteria just mentioned. The relatively large maximum error for the flux was used in the transition region from "normal" convection to "plume like" convection where the models tend to switch between a radiative and a convective solution for the bottom layer. Only a small neighbourhood of layers at the bottom is contaminated by this effect. Nevertheless, "long-time persistent errors" are created that may slow down convergence considerably. Similar holds for the flux derivative error of the top layer which also affects only a few nearby layers. However, the latter phenomenon is *not* related to convection. As both the very top and bottom layers mainly affect their local regions and as they either do not contribute to the observable flux (deepest layers with $\tau_{\rm ross} > 10$) or cannot affect it any more (at $\tau_{\rm ross} < 10^{-6}$), this is a rather safe choice for general model atmosphere grid computations. If the criteria are not fulfilled after a maximum of 200 iterations (which might happen in the transition region from "plume" to "normal" convection if a simple grey model atmosphere is taken as a starting point for the temperature iterations), a notification is generated for the user and the model has to be converged interactively (as an alternative to still more iterations, a different starting model might be chosen or the temperature correction may be changed manually or a different algorithm could be used, if available).

Grids of CM $uvby$ colours were calculated to include the whole range from $T_{\rm eff}$ 5500 K to 8500 K (spaced by 250 K) and $\log g$ from 2.0 to 5.0 (spaced by 0.25) for solar scaled metallicities ranging from -1.0 to 1.0 (spaced 0.5). A microturbulence of 2 km s^{-1} was used for all grid models. For $T_{\rm eff} > 8500$ K the models are either totally radiative or have essentially radiative temperature gradients (similar to the case of Vega). Already for a $T_{\rm eff}$ = 8500 K and $\log g$ = 4.0, the temperature differences are less than 20 K for all layers, with resulting differences in colour indices which are an order of magnitude smaller than the typical errors assigned to synthetic colours as a function of physical parameters or vice versa (see Sect. 3). Hence, they can be smoothly completed by the original Kurucz (1993b) models. Fig. 1 shows the CM $[(b-y)_0, c_0]$ and $[(b-y)_0, m_0]$ grids for solar-composition models. The actual numerical values are

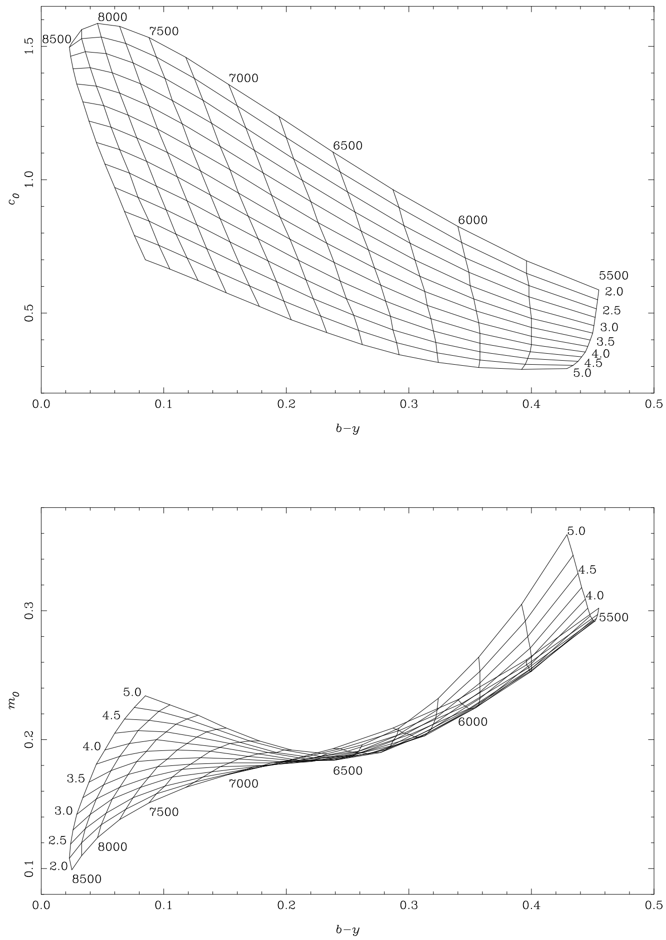

Fig. 1. The $[(b-y)_0, c_0]$ and $[(b-y)_0, m_0]$ grids for solar-composition CM models

given in Table 1. The full grids for solar and other metallicities ([−1.0], [−0.5], [0.0], [+0.5], [+1.0]) are available from the authors or by anonymous ftp at the Centre de Données de Strasbourg (CDS), following the instructions given in A&A 280, E1-E2 (1993).

In this paper we compare how the different treatments of convection affect the *uvby* colours for models with $T_{\rm eff} \leq$ 8500 K. We discuss the colours calculated from three grids of solar-composition Kurucz (1993) ATLAS9 models:

1. Standard ATLAS9 models using mixing-length theory with approximate convective overshooting, as modified by Castelli (1996). These models, called COLK95 by Castelli et al. (1997), will be referred to as the MLT OV models in this paper (grids provided by F. Castelli).
2. Standard ATLAS9 models using mixing-length theory, but without convective overshooting. These will be referred to as MLT noOV models.
3. Modified ATLAS9 models using the Canuto & Mazzitelli (1991, 1992) model of turbulent convection. These will be referred to as the CM models.

All the model grids were calculated identically, except for the treatment of convection. For a detailed description of MLT in ATLAS9 and a comparison between MLT OV and MLT noOV models refer to Castelli et al. (1997). In this paper we are primarily concerned with a comparison between MLT and CM treatments of convection.

3. Comparison with fundamental stars

The ultimate test of any model colours is to compare them to the colours of stars whose atmospheric parameters have been determined by direct, model-independent, methods. Unfortunately, such fundamental stars are relatively few in number, mainly due to the difficulty in obtaining the necessary observations. The current best list was discussed by Smalley & Dworetsky (1995). They reviewed the list of stars with fundamental values of $T_{\rm eff}$ and those with fundamental values of $\log g$. Of all those available, only three (α CMa, α CMi, α Vir) have fundamental values of *both* $T_{\rm eff}$ and $\log g$. They extended this by using 4 eclipsing binary systems, but the lower quality of the currently available spectrophotometry and uncertainties in distances, meant that these stars have much lower quality fundamental $T_{\rm eff}$ values compared to those in Code et al. (1976).

Fundamental stars were used by Smalley & Dworetsky (1995) to investigate the accuracy of the Kurucz (1991b) models. Clear inadequacies were found, which warranted further investigations. In this paper we use the same fundamental stars to compare the various treatments of convection and their effects on calculated *uvby* colours. Fundamental stars represent the only *truly* model-independent tests of the theoretical colours.

Throughout this paper, the observed *uvby* colours were obtained from Hauck & Mermilliod (1990). These were dereddened, if necessary, using UVBYBETA (Moon 1985). This de-reddening process is based on the standard empirical relationships determined by Crawford (1975, 1979), which have been widely used with great success. For all the grids discussed here, any given pair of $(b-y)_0$, c_0 colours corresponds to a unique pair of $T_{\rm eff}$, $\log g$ values. The procedure is to locate the grid point ($T_{\rm eff}$, $\log g$) closest to the observed $(b-y)_0$, c_0 colours. Then, parabolic interpolation is made within the grid in both the $T_{\rm eff}$ and $\log g$ directions to obtain the $T_{\rm eff}$ and $\log g$ that corresponds to the $(b-y)_0$, c_0 colours. Once $T_{\rm eff}$ and $\log g$ have been obtained, either parameter can be compared to a fundamental (this section) or non-fundamental (Sect. 4) value. Hence, $T_{\rm eff}$ and $\log g$ can be compared independently.

In order to assign an error on the $T_{\rm eff}$ and $\log g$ obtained from the grids, we used those appropriate to the *uvby* colours. The typical error on *uvby* colours is ±0.015 (see Relyea & Kurucz 1978). This value was propagated through the grid fitting process in order to obtain the error estimates for $T_{\rm eff}$ and $\log g$ from grids. The errors on the fundamental values were taken from Smalley & Dworetsky (1995), except for those improved by recent HIPPARCOS results (see below). These are the actual uncertainties due to observational errors. In comparing the grids with the fundamental values we assign a total error (ob-

Table 1. The CM $uvby$ colours for solar metallicity models, normalized as described in Sect. 1.

$T_{\rm eff}$	log g	$(b-y)_0$	m_0	c_0	$T_{\rm eff}$	log g	$(b-y)_0$	m_0	c_0	$T_{\rm eff}$	log g	$(b-y)_0$	m_0	c_0
5500	2.00	0.455	0.306	0.587	6500	3.25	0.267	0.193	0.737	7500	4.50	0.162	0.202	0.682
5500	2.25	0.454	0.301	0.550	6500	3.50	0.272	0.194	0.669	7500	4.75	0.170	0.203	0.602
5500	2.50	0.453	0.298	0.516	6500	3.75	0.277	0.194	0.605	7500	5.00	0.178	0.203	0.525
5500	2.75	0.452	0.296	0.484	6500	4.00	0.281	0.196	0.545	7750	2.00	0.064	0.138	1.575
5500	3.00	0.451	0.296	0.453	6500	4.25	0.285	0.199	0.488	7750	2.25	0.069	0.146	1.511
5500	3.25	0.450	0.297	0.425	6500	4.50	0.287	0.203	0.437	7750	2.50	0.075	0.155	1.438
5500	3.50	0.448	0.300	0.399	6500	4.75	0.290	0.207	0.389	7750	2.75	0.081	0.167	1.360
5500	3.75	0.446	0.306	0.375	6500	5.00	0.292	0.213	0.344	7750	3.00	0.088	0.175	1.277
5500	4.00	0.444	0.313	0.354	6750	2.00	0.194	0.186	1.237	7750	3.25	0.095	0.183	1.190
5500	4.25	0.441	0.322	0.336	6750	2.25	0.200	0.187	1.158	7750	3.50	0.103	0.189	1.102
5500	4.50	0.438	0.333	0.319	6750	2.50	0.206	0.187	1.078	7750	3.75	0.111	0.196	1.011
5500	4.75	0.434	0.347	0.304	6750	2.75	0.213	0.187	0.998	7750	4.00	0.119	0.201	0.921
5500	5.00	0.429	0.363	0.292	6750	3.00	0.220	0.187	0.918	7750	4.25	0.127	0.206	0.831
5750	2.00	0.396	0.266	0.696	6750	3.25	0.226	0.188	0.839	7750	4.50	0.135	0.210	0.742
5750	2.25	0.396	0.262	0.649	6750	3.50	0.233	0.188	0.762	7750	4.75	0.143	0.212	0.657
5750	2.50	0.398	0.260	0.603	6750	3.75	0.239	0.188	0.690	7750	5.00	0.151	0.213	0.576
5750	2.75	0.398	0.258	0.561	6750	4.00	0.244	0.189	0.620	8000	2.00	0.046	0.124	1.586
5750	3.00	0.399	0.257	0.519	6750	4.25	0.249	0.191	0.554	8000	2.25	0.049	0.134	1.535
5750	3.25	0.400	0.257	0.480	6750	4.50	0.255	0.192	0.492	8000	2.50	0.053	0.143	1.473
5750	3.50	0.400	0.259	0.446	6750	4.75	0.259	0.195	0.435	8000	2.75	0.058	0.154	1.401
5750	3.75	0.400	0.263	0.413	6750	5.00	0.262	0.200	0.382	8000	3.00	0.064	0.167	1.325
5750	4.00	0.400	0.268	0.382	7000	2.00	0.153	0.177	1.357	8000	3.25	0.071	0.177	1.242
5750	4.25	0.399	0.275	0.355	7000	2.25	0.160	0.179	1.277	8000	3.50	0.078	0.187	1.157
5750	4.50	0.397	0.284	0.330	7000	2.50	0.167	0.181	1.194	8000	3.75	0.086	0.195	1.069
5750	4.75	0.395	0.296	0.308	7000	2.75	0.174	0.183	1.110	8000	4.00	0.094	0.204	0.976
5750	5.00	0.392	0.309	0.289	7000	3.00	0.181	0.184	1.026	8000	4.25	0.102	0.210	0.887
6000	2.00	0.340	0.235	0.825	7000	3.25	0.188	0.186	0.942	8000	4.50	0.110	0.216	0.796
6000	2.25	0.343	0.232	0.765	7000	3.50	0.195	0.187	0.859	8000	4.75	0.119	0.220	0.707
6000	2.50	0.346	0.230	0.707	7000	3.75	0.203	0.188	0.777	8000	5.00	0.128	0.223	0.622
6000	2.75	0.349	0.228	0.653	7000	4.00	0.210	0.188	0.698	8250	2.00	0.033	0.110	1.563
6000	3.00	0.350	0.228	0.603	7000	4.25	0.216	0.189	0.625	8250	2.25	0.033	0.120	1.529
6000	3.25	0.353	0.228	0.553	7000	4.50	0.222	0.190	0.554	8250	2.50	0.036	0.131	1.480
6000	3.50	0.355	0.229	0.508	7000	4.75	0.228	0.191	0.489	8250	2.75	0.040	0.142	1.420
6000	3.75	0.357	0.231	0.464	7000	5.00	0.233	0.193	0.427	8250	3.00	0.045	0.154	1.351
6000	4.00	0.358	0.236	0.424	7250	2.00	0.118	0.167	1.459	8250	3.25	0.051	0.169	1.278
6000	4.25	0.358	0.241	0.387	7250	2.25	0.125	0.171	1.380	8250	3.50	0.057	0.180	1.197
6000	4.50	0.358	0.248	0.355	7250	2.50	0.132	0.175	1.298	8250	3.75	0.064	0.191	1.113
6000	4.75	0.358	0.257	0.324	7250	2.75	0.139	0.179	1.212	8250	4.00	0.072	0.201	1.025
6000	5.00	0.357	0.268	0.296	7250	3.00	0.146	0.183	1.125	8250	4.25	0.079	0.211	0.934
6250	2.00	0.287	0.213	0.963	7250	3.25	0.154	0.186	1.038	8250	4.50	0.088	0.219	0.845
6250	2.25	0.292	0.211	0.896	7250	3.50	0.161	0.189	0.950	8250	4.75	0.096	0.226	0.754
6250	2.50	0.296	0.209	0.828	7250	3.75	0.169	0.191	0.863	8250	5.00	0.105	0.231	0.665
6250	2.75	0.301	0.208	0.762	7250	4.00	0.177	0.193	0.779	8500	2.00	0.025	0.099	1.513
6250	3.00	0.305	0.206	0.699	7250	4.25	0.185	0.194	0.696	8500	2.25	0.023	0.108	1.497
6250	3.25	0.309	0.206	0.638	7250	4.50	0.192	0.194	0.618	8500	2.50	0.024	0.119	1.463
6250	3.50	0.313	0.207	0.581	7250	4.75	0.198	0.196	0.545	8500	2.75	0.026	0.130	1.416
6250	3.75	0.315	0.209	0.529	7250	5.00	0.204	0.196	0.475	8500	3.00	0.029	0.142	1.359
6250	4.00	0.318	0.212	0.479	7500	2.00	0.088	0.151	1.533	8500	3.25	0.034	0.159	1.292
6250	4.25	0.320	0.216	0.433	7500	2.25	0.094	0.162	1.460	8500	3.50	0.039	0.171	1.220
6250	4.50	0.322	0.221	0.390	7500	2.50	0.101	0.168	1.380	8500	3.75	0.045	0.185	1.140
6250	4.75	0.323	0.227	0.351	7500	2.75	0.107	0.175	1.297	8500	4.00	0.052	0.196	1.059
6250	5.00	0.324	0.236	0.315	7500	3.00	0.115	0.181	1.210	8500	4.25	0.060	0.209	0.971
6500	2.00	0.238	0.197	1.104	7500	3.25	0.122	0.185	1.122	8500	4.50	0.068	0.220	0.881
6500	2.25	0.244	0.197	1.029	7500	3.50	0.130	0.190	1.033	8500	4.75	0.076	0.229	0.791
6500	2.50	0.250	0.195	0.954	7500	3.75	0.138	0.195	0.943	8500	5.00	0.085	0.238	0.700
6500	2.75	0.256	0.194	0.879	7500	4.00	0.146	0.198	0.854					
6500	3.00	0.261	0.194	0.808	7500	4.25	0.154	0.201	0.767					

Table 2. Comparison of fundamental and grid values of $T_{\rm eff}$. $\Delta T_{\rm eff} = T_{\rm eff}({\rm grid}) - T_{\rm eff}({\rm fund})$, with the error obtained from the sum of the variances on the fundamental and grid values.

	Fundamental			CM			MLT noOV			MLT OV		
HD	$T_{\rm eff}$	$(b-y)_0$	c_0	$T_{\rm eff}$	log g	$\Delta T_{\rm eff}$	$T_{\rm eff}$	log g	$\Delta T_{\rm eff}$	$T_{\rm eff}$	log g	$\Delta T_{\rm eff}$
16739	6610±420	0.345	0.396	6084±103	4.28	−526±432	6147±114	4.16	−463±435	6287±113	4.04	−323±435
61421	6560±130	0.272	0.532	6578±129	4.15	18±183	6691±145	4.13	131±195	6830±142	3.96	270±193
110379	7280±450	0.176	0.710	7329±168	4.28	49±480	7514±192	4.30	234±489	7600±171	4.08	320±481
159561	7960±330	0.093	1.039	7943±213	3.80	−17±393	8049±180	3.81	89±376	8037±189	3.75	77±380
187642	7990±210	0.116	0.876	7836±203	4.18	−154±292	8027±196	4.21	37±287	8017±194	4.09	27±286
202275	6270±150	0.327	0.411	6207±111	4.33	−63±187	6277±124	4.22	7±195	6422±119	4.11	152±191

tained from the sum of the variances of the grid and fundamental values) to their difference.

In the comparisons that follow, in this and the next section, we use three statistical measures to compare the three grids:

1. A weighted mean of the differences between the grid and fundamental values, in order to determine which grid is in closest overall agreement with the fundamental values.
2. A weighted root mean square of the differences, given by rms $= \sqrt{\frac{\sum w_i(\Delta x_i)^2}{\sum w_i}}$, where w_i are the weights as given by the square of the reciprocal of the errors, and Δx_i are the differences between grid and fundamental values.
3. The reduced chi-square χ^2_ν and its associated probability, $P(\chi^2_\nu)$, as a measure of the goodness of agreement between the grid and fundamental values.

These three measures, together with a visual inspection, enable us to fully compare the three grids, in order to determine which gives the best overall agreement.

3.1. Effective temperature

The observed $uvby$ colours of the fundamental stars were used to obtain values of $T_{\rm eff}$ and $\log g$ from the 3 grids: CM, MLT noOV and MLT OV. The values of $T_{\rm eff}$ obtained for the 3 grids were then compared to the fundamental $T_{\rm eff}$ values (Table 2). Three of these fundamental stars are binary systems (HD 16739, HD 110379, HD 202275), whose $T_{\rm eff}$ values are dependant on the adopted distances. As noted above, the $T_{\rm eff}$ of these stars have been adjusted to take into account the significantly improved parallax measurements from HIPPARCOS. The $T_{\rm eff}$ of HD 110379 is now over 500 K hotter than that obtained by Smalley & Dworetsky (1995). A full discussion on the revisions and extensions to the list fundamental stars is given in Smalley (1997). Note that HD 16739 appears to have a discrepant fundamental $T_{\rm eff}$ value. Referring to Smalley & Dworetsky (1995) we see that the value was obtained without using any ultraviolet fluxes. Hence, we conclude that the fundamental $T_{\rm eff}$ for HD 16739 is certainly too high. In fact, Smalley & Dworetsky (1995) obtained $T_{\rm eff}$ = 6100 K from spectrophotometry and $T_{\rm eff}$ = 6200 K from the Hβ profile. A temperature close to these values would remove the large discrepancy for all 3 grids. Therefore, HD 16739 will be excluded from the following discussion.

The results of the comparison of the various model colours with those of the fundamental stars are shown in Fig. 2, as a function of $\Delta T_{\rm eff} = T_{\rm eff}({\rm grid}) - T_{\rm eff}({\rm fund})$ against $T_{\rm eff}$(fund). The CM model is in very good agreement with the fundamental values, with a weighted mean difference of -36 ± 111 K and a weighted rms difference of 71 K. The χ^2_ν = 0.102 which gives a 98% probability that the model fits to the fundamental points. The MLT noOV model has a weighted mean difference of 75 $\pm$ 115 K and a weighted rms difference of 100 K. This agreement is not as good as that for the CM model, but still acceptable to within the error bars. Indeed, the χ^2_ν = 0.190 implies a 94% probability of a good fit, which is very good, but not quite as good as the CM model. The MLT OV model, however, has a weighted mean of 175 $\pm$ 113 K and a weighted rms difference of 199 K, which is clearly not in good agreement with the fundamental values. In addition, the χ^2_ν = 0.770, which gives only a 54% probability of a good fit. This shows that the MLT OV model is not very satisfactory.

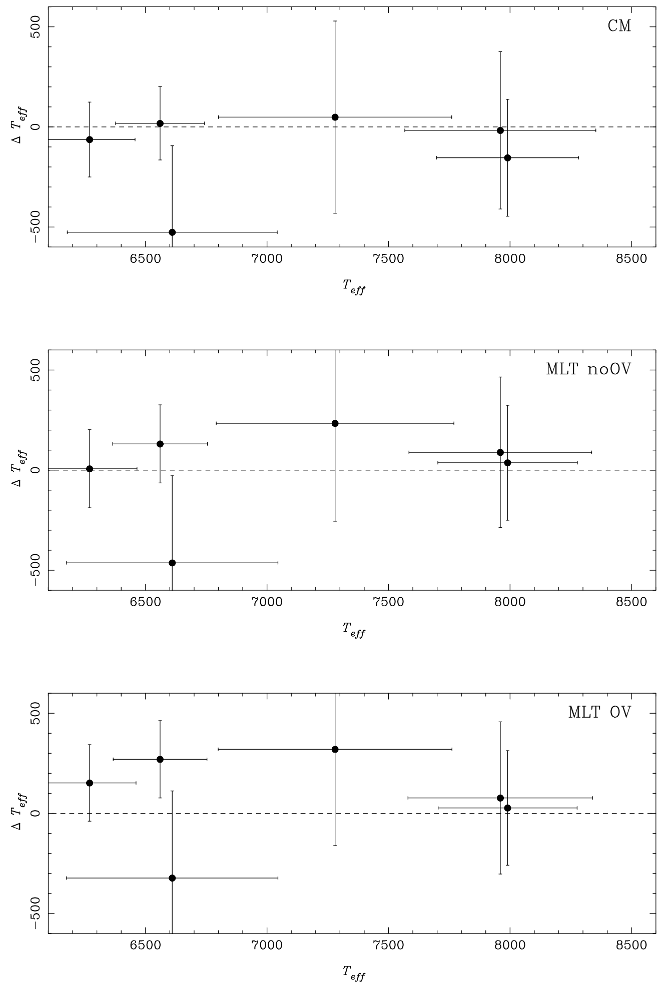

Fig. 2. Comparison of difference between grid and fundamental $T_{\rm eff}$ for the 3 grids: CM, MLT noOV and MLT OV. $\Delta T_{\rm eff} = T_{\rm eff}({\rm grid}) - T_{\rm eff}({\rm fund})$. The CM results are in the best overall agreement with the fundamental stars.

Procyon (HD 61421, α CMi) is the fundamental star with the most tightly constrained value of $T_{\rm eff}$. As such, this star ought to be a stringent test of the different grids. Inspection of Table 2 shows that the CM grid is in excellent agreement with the fundamental $T_{\rm eff}$ value. The MLT noOV models are somewhat discrepant, but still just within the error bars. The MLT OV models are clearly discrepant and well outside the error bars. Hence, from this comparison alone, we expect that the CM models should be the more realistic.

Overall, the CM models are in best agreement with the fundamental stars. The MLT noOV models are in less agreement, but still agree to within the error bars. The MLT OV models, however, are clearly discrepant.

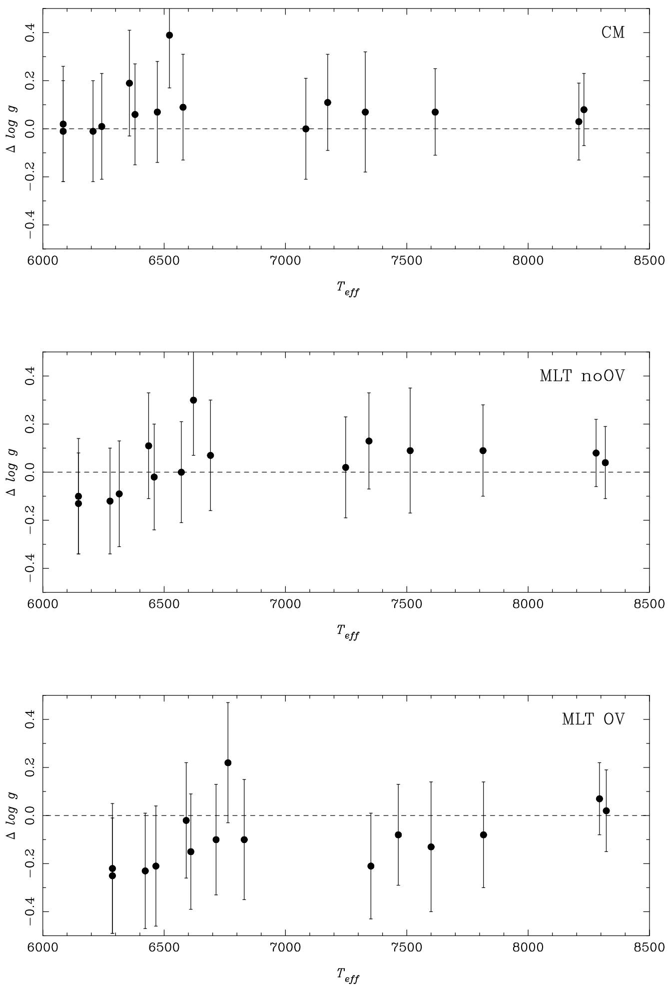

Fig. 3. Comparison of difference between grid and fundamental $\log g$ for the 3 grids: CM, MLT noOV and MLT OV. $\Delta\log g = \log g(\text{grid}) - \log g(\text{fund})$. Both the CM and MLT noOV models are in good agreement, with very little of any trend with T_{eff}. Note that the MLT OV models predicts surface gravities which are systematically too low, in particular for stars with lower temperatures.

3.2. Surface gravity

Fundamental $\log g$ values are a fairly stringent test of the grids, since they are more numerous and generally less uncertain than fundamental T_{eff} values. However, if we include the uncertainties in the values of $\log g$ obtained from the grids due to uncertainties in $uvby$ colours, the test becomes less stringent (Table 3). Nevertheless, the observed $uvby$ colours were used to obtain values of $\log g$ for the 3 model grids, which were then compared to the fundamental values. Note that HD 90242 has widely discrepant $\log g$ values. The exact reason for this anomaly is not known, but could be due to problems with the $uvby$ photometry, since all the grids give values of $\log g > 4.5$. Therefore, HD 90242 will be excluded from the following discussion.

The results of the comparison of the $\log g$ obtained from the various models with the fundamental values are shown in Fig. 3, as a function of $\Delta\log g = \log g(\text{grid}) - \log g(\text{fund})$ against T_{eff} (obtained from the appropriate grid). With the exception of HD 90242 (see above), the CM model values of $\log g$ agree with the fundamental values to within the error bars. The weighted mean difference is $\Delta\log g = 0.06 \pm 0.05$, and indicates that the CM models may, on average, very slightly overestimate $\log g$. The weighted rms difference of 0.075 shows that the points are clustered very tightly around the fundamental value. There is no evidence that the difference varies systematically with T_{eff}. The MLT noOV models give results that are similar to the CM models. The weighted mean difference of $\Delta\log g = 0.02 \pm 0.05$, which is in better formal agreement than the CM models, but there is slightly more scatter (weighted rms difference = 0.085). This larger scatter is primarily due to a discrepancy which appears to be developing at the cool end. Both the CM and MLT noOV models are in agreement with the fundamental stars to within the error bars and have χ^2_ν values that give a probability in excess of 99.9% for a good fit! The same cannot be said of the MLT OV models which have a weighted mean difference of $\Delta\log g = -0.09 \pm 0.06$ and weighted rms difference of 0.141. In this case $\chi^2_\nu = 0.445$, which gives a 95% probability for a good fit. Certainly the MLT OV points just agree to within the error bars, but the agreement is nowhere near as good as those for the CM and MLT noOV models. In addition, there is a distinct trend of decreasing $\Delta\log g$ with decreasing T_{eff}. The MLT OV models underestimate $\log g$ for cooler stars.

To conclude, there is very little difference between the results from the CM and MLT noOV models. The CM models give slightly better results, since there is slightly less scatter and no evidence of any systematic trends in $\Delta\log g$ with T_{eff}. The MLT noOV models give a hint of a discrepancy in the coolest fundamental stars. The MLT OV models are somewhat discrepant and underestimate $\log g$ for the cooler stars.

4. Comparison with non-fundamental stars

The relatively few fundamental stars means that non-fundamental stars are often used when testing model grids (e.g. Künzli et al. 1997; Castelli et al. 1997). Non-fundamental stars offer an alternative to the truly fundamental stars discussed above. However, there is always a very real danger of hidden model-dependent systematic errors that could bias any results. Hence, non-fundamental stars must be chosen carefully and the possible sources of bias identified.

4.1. Effective temperature

The Infrared Flux Method (IRFM) developed by Blackwell & Shallis (1977) allows for the simultaneous determination of T_{eff} and angular diameter. The method requires a measurement of the total integrated flux from the star and an observation of infrared flux. Model atmospheres are only required to determine the stellar surface infrared flux, but this is relatively insensitive to the actual choice of model atmospheres (Blackwell et al. 1979, 1980). Hence, the IRFM has a clear advantage over other model-dependent methods (e.g. spectrophotometric flux fitting), in that

Table 3. Comparison of fundamental and grid values of $\log g$. $\Delta \log g = \log g(\mathrm{grid}) - \log g(\mathrm{fund})$, with the error obtained from the sum of the variances on the fundamental and grid values.

	Fundamental			CM			MLT noOV			MLT OV		
HD	$\log g$	$(b-y)_0$	c_0	T_{eff}	$\log g$	$\Delta \log g$	T_{eff}	$\log g$	$\Delta \log g$	T_{eff}	$\log g$	$\Delta \log g$
16739	4.26±0.12	0.345	0.396	6084	4.28±0.21	0.02±0.24	6147	4.16±0.21	−0.10±0.24	6287	4.04±0.24	−0.22±0.27
34335	4.12±0.04	0.320	0.454	6243	4.13±0.22	0.01±0.22	6315	4.03±0.22	−0.09±0.22	6466	3.91±0.25	−0.21±0.25
37513	4.29±0.01	0.345	0.396	6084	4.28±0.21	−0.01±0.21	6147	4.16±0.21	−0.13±0.21	6287	4.04±0.24	−0.25±0.24
46052	4.17±0.02	0.081	0.944	8209	4.20±0.16	0.03±0.16	8318	4.21±0.15	0.04±0.15	8322	4.19±0.17	0.02±0.17
61421	4.06±0.06	0.272	0.532	6578	4.15±0.21	0.09±0.22	6691	4.13±0.22	0.07±0.23	6830	3.96±0.24	−0.10±0.25
62863	4.27±0.01	0.198	0.634	7174	4.38±0.20	0.11±0.20	7344	4.40±0.20	0.13±0.20	7465	4.19±0.21	−0.08±0.21
75747	4.00±0.02	0.135	0.863	7617	4.07±0.18	0.07±0.18	7814	4.09±0.19	0.09±0.19	7816	3.92±0.22	−0.08±0.22
90242	4.34±0.10	0.287	0.397	6522	4.73±0.20	0.39±0.22	6621	4.64±0.21	0.30±0.23	6763	4.56±0.23	0.22±0.25
93486	3.91±0.01	0.303	0.486	6357	4.10±0.22	0.19±0.22	6436	4.02±0.22	0.11±0.22	6591	3.89±0.24	−0.02±0.24
110379	4.21±0.17	0.176	0.710	7329	4.28±0.19	0.07±0.25	7514	4.30±0.20	0.09±0.26	7600	4.08±0.21	−0.13±0.27
123423	4.11±0.01	0.301	0.477	6380	4.17±0.21	0.06±0.21	6459	4.09±0.22	−0.02±0.22	6610	3.96±0.24	−0.15±0.24
161321	3.93±0.01	0.074	1.018	8230	4.01±0.15	0.08±0.15	8280	4.01±0.14	0.08±0.14	8294	4.00±0.15	0.07±0.15
185912	4.33±0.02	0.290	0.450	6472	4.40±0.21	0.07±0.21	6571	4.33±0.21	0.00±0.21	6714	4.23±0.23	−0.10±0.23
193637	4.01±0.02	0.199	0.723	7084	4.01±0.21	0.00±0.21	7248	4.03±0.21	0.02±0.21	7352	3.80±0.22	−0.21±0.22
202275	4.34±0.02	0.327	0.411	6207	4.33±0.21	−0.01±0.21	6277	4.22±0.22	−0.12±0.22	6422	4.11±0.24	−0.23±0.24

the T_{eff} obtained can be regarded as semi-fundamental. In fact, it is the closest model-dependent method to a true fundamental T_{eff} determination.

Blackwell & Lynas-Gray (1994) presented a list of stars with T_{eff} determined from the IRFM. They used standard ATLAS9 models for the stellar infrared fluxes, but as stated above the effect of the choice of model should not be significant. Indeed, Blackwell & Lynas-Gray (1994) found very good agreement with the angular diameters obtained from interferometry. They stated that the values of T_{eff} should be accurate to 2%. This equates to ±130 K at 6500 K, which is of the same order of accuracy as the fundamental T_{eff} of Procyon. Thus, the IRFM values should be of sufficient quality to be useful in the comparison of the different *uvby* grids.

Table 4 shows the IRFM stars considered here. The list is based on Table 9 of Künzli et al. (1997), which is primarily from Blackwell & Lynas-Gray (1994). Because the IRFM can be very sensitive to the presence of a binary companion (Smalley 1993b), we have excluded those stars noted as spectroscopic binaries by Blackwell & Lynas-Gray (1994).

Fig. 4 shows a comparison between the IRFM T_{eff} values and those obtained from *uvby* for the 3 grids. Since the IRFM stars do not have formal error estimates we have adopted a typical uncertainty of ±200 K, in order to calculate χ^2_ν values. The CM models give values of T_{eff} that agree very well with those given by the IRFM, with mean difference of ΔT_{eff} = 29 ± 105 and an rms difference of 109 K. The three hottest stars, however, appear to indicate that the CM models give higher values of T_{eff} than the IRFM. Possibly, this is due to the IRFM underestimating the T_{eff} of these stars, since the fundamental stars are in good agreement (cf. Fig. 2). This would be consistent with underestimating the contribution from unobserved ultraviolet flux. Nevertheless, the agreement for the cooler stars supports that found from the fundamental stars, with χ^2_ν = 0.312, giving a greater than 99.9% probabilty for a fit to within the ±200 K error bars adopted above. The MLT noOV models are generally somewhat discrepant, with the T_{eff} obtained from the *uvby* colours being, on average, slightly hotter (mean difference of ΔT_{eff} = 109 ± 118 and rms = 160 K). In addition, there appears to be a distinct slope that develops for stars with $T_{\mathrm{eff}} <$ 7000 K. This sort of slope was noted by Künzli et al. (1997) who used colour indices from the Geneva photometric system for their study. In addition, Castelli et al. (1997) found that the differences in T_{eff} from colours and the IRFM are of different sizes either side of T_{eff} = 6250 K (see their Table 5). Only for the coolest stars does the MLT noOV models begin to agree with the IRFM values, but the overall χ^2_ν = 0.671, gives only a 87% probability for agreement with the IRFM points over the whole T_{eff} range. The MLT OV models are clearly discrepant, with *all* the stars hotter than the corresponding IRFM T_{eff} (mean difference of ΔT_{eff} = 228 ± 95 and an rms of 247 K). Indeed, the χ^2_ν = 1.598 gives only a 4% probability for a fit!

Overall, the results from the IRFM agree with that found using the smaller sample of fundamental stars. The CM grid has the greatest success in recovering the T_{eff} obtained from *both* fundamental and non-fundamental methods.

4.2. Surface gravity

Open cluster stars can be used as surface gravity standards. Stellar evolutionary models enable the $\log g$ of cluster members to be determined by fitting isochrones to the cluster photometry. These are not truly fundamental values of $\log g$, since they rely on the stellar evolutionary models. However, the values of $\log g$ are not directly dependent on the model-atmospheres considered here. Stellar interior calculations do, however, involve the use of convection theory and changes in the treatment of convection may influence the results of the evolutionary calculations (e.g. Stothers & Chin 1995; Canuto 1996a; Canuto et al. 1996). Nevertheless, we shall use the cluster surface gravity values to test the values obtained from the *uvby* colours for the 3 model grids. The Hyades have a metallicity of [M/H] = +0.125 (Boesgaard 1989). Linear interpolation in metallicity was used to obtain colours appropriate to the Hyades.

Fig. 5 shows a comparison between the $\log g$ obtained from the *uvby* colours and that given by evolutionary models for the Hyades (Künzli et al. 1997, Table 10). The actual numerical values are given in Table 5, which is available electronically from the CDS. Since the $\log g$ stars do not have formal error estimates we have adopted a typical uncertainty of ±0.20 dex in

Table 4. The $T_{\rm eff}$ obtained from the IRFM compared to the values obtained from the 3 grids. $\Delta T_{\rm eff} = T_{\rm eff}(\rm grid) - T_{\rm eff}(\rm IRFM)$.

	IRFM				CM			MLT noOV			MLT OV		
HR	$T_{\rm eff}$	$\log g$	$(b-y)_0$	c_0	$T_{\rm eff}$	$\log g$	$\Delta T_{\rm eff}$	$T_{\rm eff}$	$\log g$	$\Delta T_{\rm eff}$	$T_{\rm eff}$	$\log g$	$\Delta T_{\rm eff}$
269	7959	3.82	0.067	1.056	8284	3.93	325	8312	3.92	353	8328	3.92	369
343	7949	3.91	0.087	0.997	8069	3.98	120	8161	3.99	212	8170	3.96	221
937	6042	4.50	0.375	0.376	5895	4.22	−147	5944	4.08	−98	6071	3.92	29
996	5732	4.45	0.406	0.302	5674	4.80	−58	5734	4.57	2	5832	4.42	100
1101	5977	3.98	0.354	0.372	6026	4.39	49	6088	4.25	111	6222	4.13	245
1676	6909	3.14	0.176	0.935	7117	3.40	208	7293	3.43	384	7305	3.21	396
1729	5947	4.17	0.386	0.363	5828	4.26	−119	5875	4.10	−72	5995	3.94	48
2852	6974	4.11	0.214	0.613	7029	4.32	55	7189	4.33	215	7320	4.13	346
2930	6531	3.34	0.260	0.659	6600	3.67	69	6705	3.64	174	6857	3.43	326
5072	5488	3.75	0.428	0.348	5488	4.31	0	5480	4.06	−8	5725	3.77	237
5107	8287	4.00	0.062	1.007	8417	4.12	130	8448	4.12	161	8461	4.12	174
5185	6389	4.40	0.305	0.435	6362	4.36	−27	6449	4.28	60	6592	4.17	203
5338	6175	4.00	0.333	0.443	6156	4.08	−19	6221	3.98	46	6369	3.84	194
5404	6230	4.28	0.312	0.414	6316	4.43	86	6401	4.33	171	6540	4.23	310
5447	6763	4.40	0.253	0.488	6771	4.54	8	6889	4.50	126	7037	4.38	274
5570	7026	3.75	0.206	0.708	7030	4.00	4	7188	4.02	162	7313	3.81	287
5634	6617	4.50	0.285	0.449	6511	4.45	−106	6615	4.39	−2	6758	4.28	141
5933	6320	4.00	0.319	0.401	6269	4.45	−51	6345	4.34	25	6485	4.24	165
6623	5521	4.47	0.418	0.404	5651	3.68	130	5689	3.55	168	5805	3.32	284
7061	6380	4.00	0.296	0.481	6418	4.19	38	6498	4.11	118	6650	3.99	270
7469	6713	4.40	0.256	0.505	6731	4.43	18	6847	4.39	134	6997	4.26	284
8665	6225	4.10	0.324	0.406	6231	4.38	6	6303	4.27	78	6446	4.17	221
8905	6050	3.61	0.359	0.455	5990	3.79	−60	6036	3.68	−14	6176	3.50	126

order to calculate χ^2_ν values. All three models exhibit the same general pattern in that there is a distinct change in behaviour of the differences below $T_{\rm eff} \sim 7000$ K. Above 7000 K the differences are essentially independent of $T_{\rm eff}$. But, below 7000 K the trend in difference is non-linear, with a "bump" around 6500 K. This was discussed by Künzli et al. (1997) who showed that the observed Hyades main sequence clearly has a sudden change in slope when compared to model atmosphere colours. Evolutionary models are unable to account for the implied sudden change in $\log g$. They concluded that something is missing in the atmosphere models what certainly requires further investigation, since the fundamental $\log g$ stars *do not* exhibit the same behaviour (cf. Fig. 3).

The above problems not withstanding, the CM and MLT noOV models both agree reasonably well with the Hyades $\log g$ values. The vast majority of the points are within 0.20 dex of the Hyades value, which is of the order of the typical error due to the uncertainties in the *uvby* colours alone. The CM models have a mean difference of $\Delta\log g = -0.04 \pm 0.14$ and an rms of 0.14 dex, while the MLT noOV models give $\Delta\log g = -0.10 \pm 0.12$ and an rms of 0.16 dex. Generally, the CM models give slightly better agreement with the Hyades $\log g$ than the MLT noOV models. However, the difference between the two is not significant, since both have χ^2_ν values that give a greater than 99% probability for agreement. Interestingly, both models give values of $\log g$ which are slightly *less* than the Hyades values for the hotter stars, which is the opposite to that found using the fundamental stars (Fig. 3). This may indicate that the evolutionary calculations are not producing the correct $\log g$ values for the Hyades. Note in particular, that a decrease of $\log g$ obtained from the evolutionary calculations for hotter stars would increase $\Delta\log g$ in the same $T_{\rm eff}$ region and, hence, reduce the size of the "bump" around 6500 K. The MLT OV models are, yet again, somewhat discrepant, with a mean difference of $\Delta\log g = -0.23 \pm 0.14$ and an rms of 0.27 dex. Both the difference and rms are greater than the adopted typical error of $\pm$0.20 dex, which indicates very poor agreement. In fact, $\chi^2_\nu = 1.800$, which gives a less than 0.1% probability for agreement! The MLT OV models systematically underestimate the Hyades $\log g$ values.

Overall, the results from the Hyades $\log g$ values agree with that found using the fundamental $\log g$ stars, but with much more scatter and uncertainty. The model-dependent nature of the Hyades $\log g$ values means that they should not be used as the primary test of $\log g$ obtained from model grids; stars with fundamental $\log g$ values should always be preferred. Nevertheless, the CM grid has the greatest success in recovering the $\log g$ obtained from both fundamental and non-fundamental methods, with the MLT noOV models a very close second.

5. Solar colours

While, the $T_{\rm eff}$ and $\log g$ of the Sun are very well known, the *uvby* colours for the Sun are not. Published values of $(b-y)_\odot$ range from $(b-y)_\odot = 0.406 \pm 0.004$ (Edvardsson et al. 1993) to $(b-y)_\odot = 0.414 \pm 0.003$ (Gray 1992). An extensive literature search revealed no values of c_0 and m_0 for the Sun. Therefore, we cannot use the same procedures to obtain grid $T_{\rm eff}$ and $\log g$ values as used above. Hence, models with $T_{\rm eff} = 5777$ K and $\log g = 4.44$ were used to calculate values of $(b-y)$ for the three sets of grids; CM gives $(b-y)_\odot = 0.393 \pm 0.006$, MLT noOV gives $(b-y)_\odot = 0.400 \pm 0.006$, and MLT OV gives $(b-y)_\odot = 0.414 \pm 0.006$.

The CM solar model is not in agreement with the observed colours. It appears that the solar colours are in better agreement with those obtained using the MLT noOV or MLT OV models. In fact, the MLT OV models appear to give the best agreement with the observed colours. However, Fig. 2 does not appear to support this, unless the discrepancy starts to manifest itself at $T_{\rm eff} < 6000$ K. The fundamental stars go as cool as 6290 K, but the non-fundamental stars go down to 5500 K. From the results shown in Fig. 4, it might appear that CM and MLT noOV solar

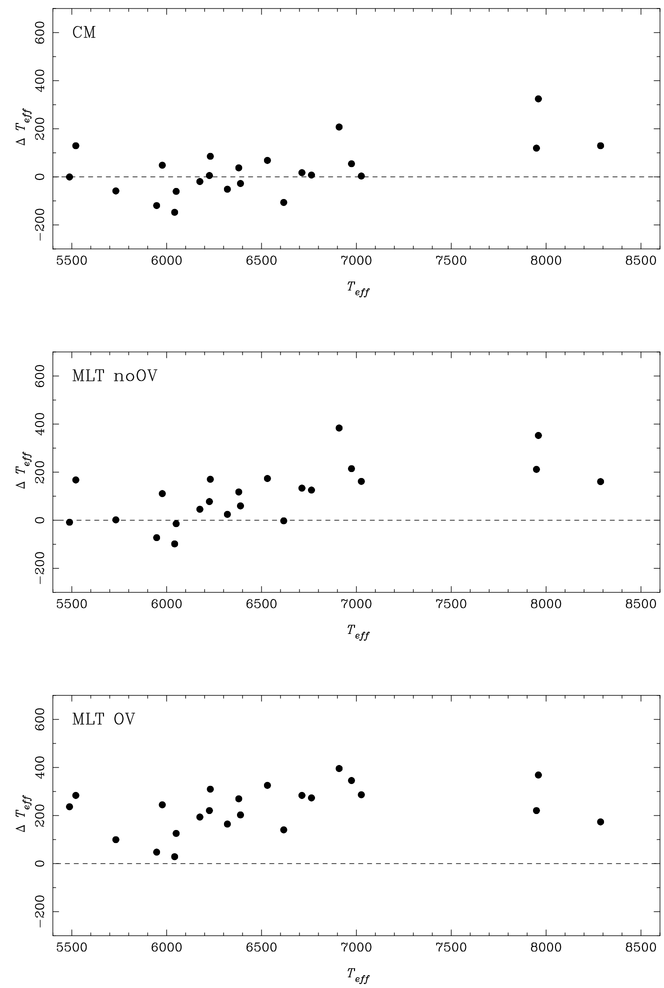

Fig. 4. Comparison of difference between grid and IRFM $T_{\rm eff}$ values for the 3 grids: CM, MLT noOV and MLT OV. $\Delta T_{\rm eff}$ = $T_{\rm eff}$(grid) − $T_{\rm eff}$(IRFM). The CM models give the best overall agreement with the IRFM.

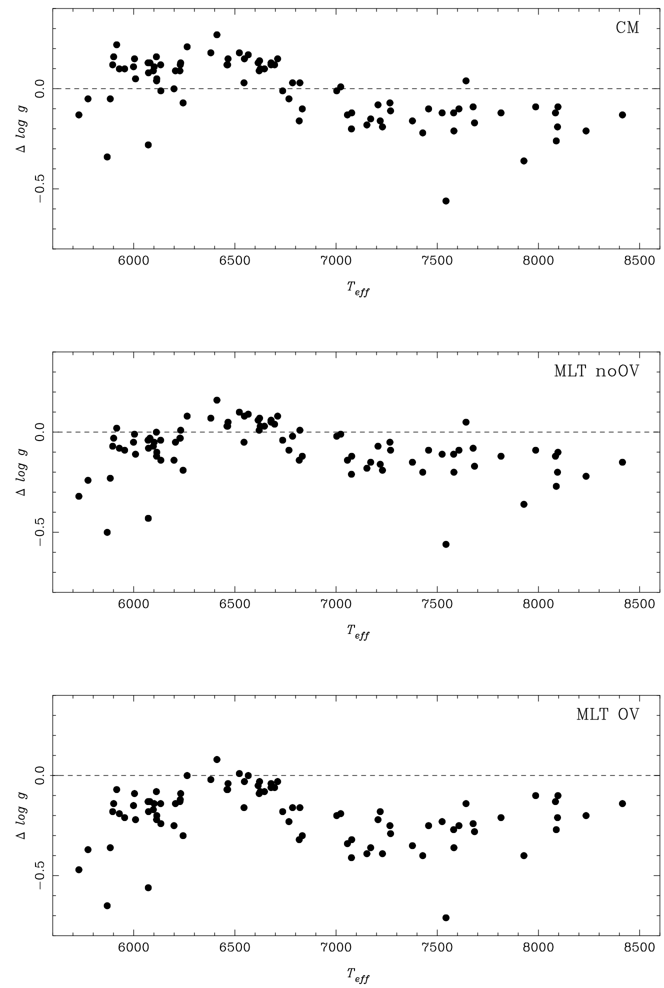

Fig. 5. Comparison of difference between grid and evolutionary model $\log g$ values of Hyades stars for the 3 grids: CM, MLT noOV and MLT OV as a function of $T_{\rm eff}$. $\Delta\log g$ = $\log g$(grid) − $\log g$(Hyades). Both, the CM and MLT noOV grids are in reasonable agreement.

models should be reliable, while the MLT OV should not. The opposite is indicated by the solar colours! This conclusion was found by Castelli et al. (1997), who, however, stated that the uncertainties in the solar colours preclude any definite conclusion.

6. Metallicity effects

The colours of late-A and F stars can be significantly affected by the effects of metallicity, due to the vast amount of metal lines. Unfortunately, there are no such objects as fundamental metallicity stars; all abundance determinations are model dependent. The Strömgren *uvby* system has a metallicity index (m_0) which can be used to estimate the overall metal abundance ([M/H]) of late-A, F and early-G stars (Strömgren 1966). Several good empirical relationships are available (Smalley 1993a and references therein).

One of the major discrepancies found by Relyea & Kurucz (1978) was in the m_0 index, calculated from the Kurucz (1979a) model fluxes. The m_0 index for A and F stars disagreed with the observed values. Fig. 6 shows how well the various solar-composition grids compare with the main-sequence m_0 values listed in Philip & Egret (1980). It is clear that none of the models agrees completely with the main-sequence m_0 values, and *all* are discrepant for late-type stars. Large differences are caused by the different treatments of convection. Hence, the m_0 appears to be a sensitive indicator of convection in cool stars. Interestingly, for cool models, the Relyea & Kurucz (1978) m_0 values are coincident with the MLT OV line, even though the newer MLT OV models contain much improved line opacity. This may indicate that the problem is more fundamental, and not due to the effects of line opacity alone. In addition, m_0 is sensitive to the adopted value of microturbulence (Strömgren 1966; Kurucz 1991b). All the models discussed here were calculated with a microturbulence of 2 km s^{-1}, but lowering its value reduces

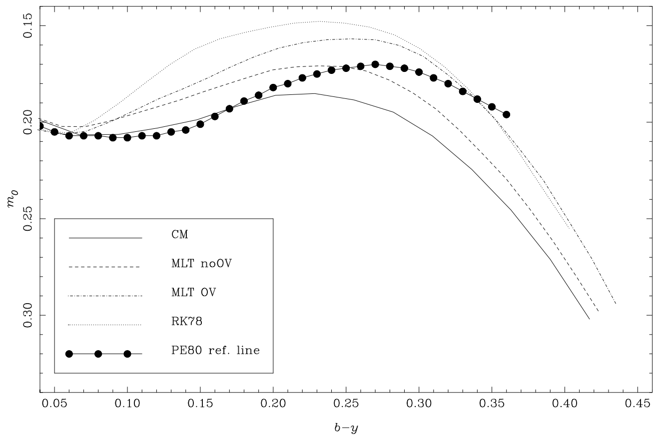

Fig. 6. The observational main-sequence m_0 reference line (Philip & Egret 1980) and the position of the m_0 main sequence as predicted by the three grids. The original Relyea & Kurucz (1978) m_0 main-sequence line is given for reference. Clearly, none of the models can reproduce fully the observed m_0 main sequence and the m_0 index appears to be highly sensitive to treatment of convection.

the discrepancy for the coolest models. Microturbulence is a free parameter in the models, but is probably closely related to the small-scale part of the photospheric convective flow pattern (Holweger & Stürenburg 1993; see also Cowley 1996). Clearly, further investigations into the cause of this discrepancy need to be performed.

7. Conclusion and future work

A discussion of the effects of the treatment of convection on the theoretical $uvby$ colours of A, F, and G stars has been presented. The standard mixing-length theory ATLAS9 models of Kurucz (1993), with and without approximate overshooting, were compared to models using the turbulent convection theory proposed by Canuto & Mazzitelli (1991, 1992).

Comparison with fundamental $T_{\rm eff}$ and $\log g$ stars reveals that the CM models yield results that are generally superior to standard mixing-length theory without convective overshooting (MLT noOV). Models with overshooting (MLT OV) are found to be clearly discrepant. This is supported by comparisons to non-fundamental stars with $T_{\rm eff}$ obtained from the Infrared Flux Method and $\log g$ from stellar evolutionary models for open cluster stars.

Investigations of the m_0 index have revealed that all three treatments of convection produce values that are significantly discrepant for models with $T_{\rm eff} < 6000$ K. It is unclear as to whether this is due to problems with the treatment of convection, missing atomic or molecular opacity, or due to some other reason. None of the models give totally satisfactory m_0 indices for hotter stars, but the CM models are in good agreement above 7000 K.

Several models with a local treatment of convection had been implemented and tested before the colour grids discussed here were computed (among them the CM model and the CGM model of Canuto et al. 1996). They revealed rather small differences in observed fluxes and colours for early G stars. If the discrepancies between observations and model predictions for the m_0 index of stars with $T_{\rm eff} < 6000$ K are indeed mainly induced by convection, only a fully non-local model of convection can be expected to provide a sufficiently large quantitative jump to bring both into better agreement. A non-local model based on a one-point Reynolds stress closure was already derived in Canuto (1993) who also gives many references on earlier work on this field. An improved version of this model has recently passed a severe test provided by helioseismology which requires the size of the under-shooting below the solar convection zone to be $< 0.05\ H_p$ (see Basu 1997; Basu & Antia 1997).

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