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ASTRONOMY AND ASTROPHYSICS

The missing UV opacity and the colours of solar-type stars

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Summary. A simple method is proposed to take into account the "missing UV opacity" in solar-type stars. It is shown that the mere inclusion of that UV opacity through a very simple formula is sufficient to bring the theoretical colours in agreement with observed ones for stars of different metal abundances and belonging to the spectral range from mid-F to late-G. Synthetic colours computed in the Geneva and UBV systems reproduce the various observed relations satisfactorily. The relations based on these colours allow reliable estimates of effective temperatures, surface gravities and metal abundances of stars. In addition, solar colours are obtained and three more solar twin candidates are proposed.

Key words: solar-type stars – stellar atmospheres – photometry

I. Introduction

Multicolour photometry is widely used to determine the physical parameters of stars, such as effective temperature or surface gravity, as well as the overall chemical composition. To infer physical properties of stars from colours, two main ways are available. First, one can rely on empirical relations (see, e.g. Crawford, 1975), but such relations are valid only over the limited range covered by the calibrating stars. To extrapolate to other ranges (e.g., to the very metal-poor stars), one must often rely on the second method, which uses theoretical colours. But the latter colours must at least satisfy one constraint: they should agree with the empirical ones throughout their common range of validity. This constraint is not satisfied for the solar-type stars, at least when a blue or violet colour is included (see Relyea and Kurucz, 1978; Gustafsson and Bell, 1979; North and Hauck, 1979, and Sect. IV below).

The aim of this paper is to provide synthetic colours which are in good agreement with the observed ones for solar-type stars of different metallicities, in order to allow safer inter- or extrapolation. Our main hypothesis is that the discrepancy between theoretical and observed colours is due to a source of opacity present in the stars but not included in the models and acting mainly at wavelengths shorter than 5000 Å (the so-called "missing UV opacity", see, e.g., Michard, 1950, 1953).

II. Assumptions and method

In order to obtain a simple formula for that extra UV opacity, we make the following assumptions:

(a) it is due to a veil of weak metal lines (Holweger, 1970);

(b) it has a weak wavelength dependence, so that it acts more or less like a continuous opacity;

(c) its temperature, electron pressure and abundance dependences can be represented by a mean line, chosen to be a Fe I line of 3 eV excitation potential (Holweger, 1970);

(d) the relative abundances of the metals are solar: for each metal M, [M/H] = [Fe/H], where

$$[\mathrm{M/H}] = \log(N_{\mathrm{M}}/N_{\mathrm{H}})_* - \log(N_{\mathrm{M}}/N_{\mathrm{H}})_\odot .$$

The following additional assumptions are valid for solar-type stars:

(e) Fe, the "typical metal", is mainly ionized, so that

$$N_{\mathrm{Fe\,I}} \ll N_{\mathrm{Fe\,II}} \simeq N_{\mathrm{Fe}}$$

(f) the continuous opacity is dominated by the bound-free absorption of H^- in the spectral region considered (3000 Å to 5000 Å).

The preceding assumptions should be appropriate for dwarfs and subgiants belonging roughly to the spectral range F5 to G5. For hotter or more luminous stars, assumption (f) breaks down, while for cooler stars, assumption (e) is no more valid. However, extrapolation towards hotter main sequence stars should be rather safe since the correction becomes very weak and a small error does not matter very much. On the contrary, for cooler stars (e.g., red giants), where the extra opacity becomes very important, assumption (e) leads to a strong overestimate of the correction and should be relaxed before the treatment can be extended to this important group of stars.

From assumption (c), the extra UV opacity κ_{add} is proportional to the number N_i of Fe I atoms in the level of excitation potential $\chi(=3\,\mathrm{eV})$. We can then write:

$$\kappa_{\mathrm{add}} \propto \frac{N_i}{N_{\mathrm{Fe\,I}}} \times \frac{N_{\mathrm{Fe\,I}}}{N_{\mathrm{Fe\,II}}} \times \frac{N_{\mathrm{Fe\,II}}}{N_{\mathrm{Fe}}} \times \frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}} \times N_{\mathrm{H}} . \tag{1}$$

The first and second factors are given by the Boltzmann and Saha equations, the third one is supposed equal to 1 (assumption (e)) and the fourth one is the iron abundance A.

Therefore, Eq. (1) becomes:

$$\kappa_{\mathrm{add}} \propto P_e \theta^{5/2} 10^{\theta(I_{\mathrm{Fe\,I}} - \chi)} A N_{\mathrm{H}} \tag{2}$$

where P_e is the electron pressure, I is the ionization potential and $\theta = 5040/T$.

Similarly, the continuous (H^-) opacity can be written (Gray, 1976):

$$\kappa_{\mathrm{cont}} \propto P_e \theta^{5/2} 10^{\theta I_{\mathrm{H}^-}} N_{\mathrm{H}} . \tag{3}$$

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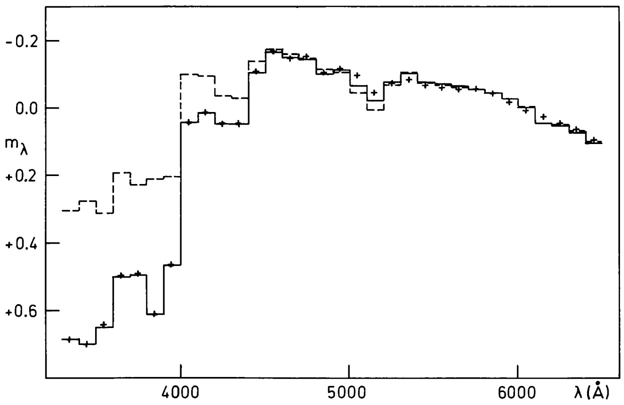

Fig. 1. The solar flux measurements of Neckel (crosses) compared to the fluxes computed with the unmodified solar model (dashed line) and with the modified solar model (continuous line) – Magnitude units are used

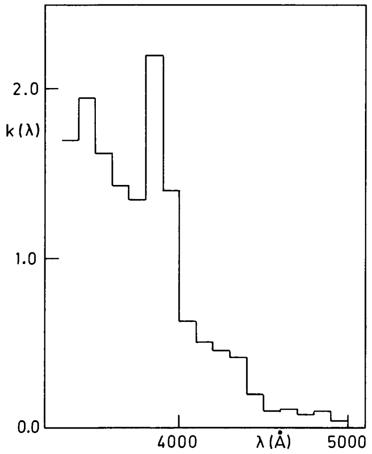

Fig. 2. The coefficient $k(\lambda)$ determined from a fit of the solar model flux to the observed one

Combining Eqs. (2) and (3), we can write:

$$\kappa_{\mathrm{add}}(\lambda, T, P_e, A) = k(\lambda)\frac{A}{A_\odot}10^{(\theta-1)(I_{\mathrm{FeI}}-\chi-I_{\mathrm{H}^-})}\kappa_{\mathrm{cont}}(\lambda, T, P_e), \quad (4)$$

where $k(\lambda)$ is a wavelength-dependent factor, representing the strength and density of the lines contributing to the veil ($k(\lambda)\sim 1$, thanks to the -1 in the exponent). $k(\lambda)$ is determined empirically by forcing the flux computed with the model (5770, 4.44, 0) (i.e., a model with $T_{\mathrm{eff}}=5770$ K, $\log g = 4.44$ and [Fe/H] = 0) to match the observed solar flux.

These models are computed with a version of the model atmosphere programme kindly provided by Gustafsson (Gustafsson et al., 1975; Bell et al., 1976) whereas the solar flux was determined by Neckel (1981) on the basis of the Labs and Neckel (1968) centre of disk measurements and of centre-to-limb variations measured at Kitt Peak in May 1981.

The determination of $k(\lambda)$ is made as follows. We devide the spectral region from 3300 Å to 5000 Å in bands having 100 Å bandwidth (corresponding to the ODF bands of the models, see Gustafsson et al., 1975). In each band, the coefficient $k(\lambda)$ is approximated by a constant k_i and adjusted until the mean model ODF flux matches the observed one (within 1%). We extrapolate below 3300 Å since we have no flux measurement there (Neckel, 1981) and we put $k_i=0$ for wavelengths greater than 5000 Å.

In Figs. 1 and 2 we show the observed and computed solar fluxes, together with the adjusted values of $k(\lambda)$.

Note that the solar flux, without the correction to the opacity of Eq. (4), and represented by the dashed line in Fig. 1, is not identical to the flux computed by Gustafsson et al. (1979), which is based on detailed synthetic spectra.

The peak of $k(\lambda)$ around 3900 Å seems to indicate some contribution from the CN *uv*-band. However, since this molecular band is included in the model opacities, it should not contribute to the missing opacity if the molecular parameters, as well as the CN solar abundance, are correct. Anyhow, no definite conclusion should be based on ODF spectra since the numerical (quadrature) uncertainties can significantly affect the $k(\lambda)$ determination. The detailed interpretation of the nature of the missing *uv* opacity would require the computation of synthetic spectra.

III. Computation of the colours

Since the model fluxes are computed with a 100 Å resolution we are restricted to broad-band colours. We chose to compute colours in the UBV and Geneva systems. The transmission curves are from Rufener and Maeder (1971, Hayes' calibration) for the Geneva system, while those of the UBV system are from Matthews and Sandage (1963, one air mass, see Gustafsson and Bell, 1979, for the choice of the transmission curves).

In order to fix the zero point of the colours, we need at least one "standard" star with reliable physical parameters and colours. Since we want to base our work on a temperature zero point independent of previous stellar colours and to avoid uncertainties in the colours of the sun, we selected a set of standard stars from the work of Gehren (1981), where the effective temperatures are determined by a fit of hydrogen line profiles. Moreover, we only retained the stars for which the surface gravity and abundance are known through high dispersion studies. The set of standards has been completed by adding the solar analog 16 Cyg B (HD 186427), with the following parameters: $T_{\mathrm{eff}}=5730$ K, $\log g=4.5$, [Fe/H] = 0 (see Hardorp, 1980; Perrin and Spite, 1981; Neckel and Labs, 1981).

We thus have a set of 8 standards for UBV and 6 standards for the Geneva system. The zero points are determined in order to minimize the difference between the computed and observed colours (with a greater weight for 16 Cyg B).

The list of standards, as well as the colour residuals, are given in Table 1. As an illustration of the internal agreement note that the mean residual in $(B-V)$ or (B_2-V_1) corresponds to a 70 K uncertainty in effective temperature, that is less than the quoted uncertainty in Gehren (1981), all other quantities supposed to be known exactly.

IV. Results and discussion

The synthetic colours were computed for a grid of models with the following parameters: $T_{\mathrm{eff}}=5500$, 6000, 6500 K; $\log g=3.0$, 3.75, 4.5 and [Fe/H] = 0, −1, −2. In addition, other models were computed to extend the grid (see Table 2). Convection was treated by the standard mixing length theory, with a ratio of mixing length to pressure scale height equal to 2.

The synthetic colours are shown in Table 2, normalized as described in the preceding section.

Table 1. Standard stars

HD number	T_{eff}	log g	[Fe/H]	Colour residuals (observed-computed)							
				UBV		*Geneva*					
				$U-B$	$B-V$	U	V	B_1	B_2	V_1	G
102870	6170	4.25	+0.20	+0.006	−0.005	−0.004	+0.027	−0.009	−0.002	+0.017	+0.029
109358	6000	4.50	+0.07	−0.046	−0.001	−0.063	+0.001	−0.012	+0.006	−0.002	−0.003
124570	6280	4.15	+0.13	+0.017	+0.003						
141004	6080	4.20	+0.05	+0.022	+0.039						
142373	5950	4.25	−0.40	+0.036	+0.004	+0.024	−0.032	+0.006	−0.014	−0.031	−0.042
186427	5730	4.50	0.00	−0.001	−0.001	0.000	−0.008	+0.003	+0.002	−0.002	−0.003
187691	6180	4.40	+0.14		+0.004	+0.022	+0.005	−0.005	−0.011	−0.005	−0.002
207978	6320	4.20	−0.51	−0.029	−0.039	+0.026	+0.039	+0.010	+0.007	+0.030	+0.035

Table 2. Synthetic colours

Models			UBV colours		Geneva colours					
Teff	log g	[Fe/H]	U-B	B-V	U	V	B_1	B_2	V_1	G
5250	4.50	0	0.608	0.847	1.789	-0.111	1.238	1.189	0.653	0.879
5500	3.00	0	0.505	0.753	1.735	0.003	1.174	1.238	0.761	1.031
5500	3.75	0	0.425	0.746	1.634	0.017	1.165	1.243	0.774	1.042
5500	4.50	0	0.357	0.739	1.555	0.032	1.158	1.247	0.789	1.051
5770	4.44	0	0.177	0.646	1.400	0.155	1.094	1.296	0.906	1.200
6000	3.00	0	0.250	0.574	1.572	0.248	1.058	1.327	0.995	1.314
6000	3.75	0	0.150	0.577	1.428	0.246	1.056	1.328	0.993	1.310
6000	4.50	0	0.066	0.580	1.310	0.244	1.053	1.329	0.991	1.305
6500	3.00	0	0.174	0.437	1.580	0.426	0.991	1.385	1.165	1.523
6500	3.75	0	0.059	0.452	1.398	0.409	0.993	1.382	1.148	1.504
6500	4.50	0	-0.046	0.463	1.242	0.396	0.994	1.379	1.136	1.487
7000	4.50	0	-0.057	0.370	1.269	0.511	0.962	1.410	1.245	1.628
5250	4.50	-1	-0.010	0.684	1.234	0.139	1.047	1.326	0.895	1.160
5500	3.00	-1	0.012	0.615	1.305	0.219	1.014	1.355	0.969	1.277
5500	3.75	-1	-0.054	0.618	1.211	0.217	1.014	1.355	0.967	1.271
5500	4.50	-1	-0.093	0.621	1.161	0.216	1.014	1.353	0.967	1.263
6000	3.00	-1	-0.029	0.482	1.326	0.387	0.966	1.402	1.129	1.476
6000	3.75	-1	-0.123	0.494	1.183	0.374	0.967	1.399	1.116	1.459
6000	4.50	-1	-0.187	0.505	1.090	0.361	0.969	1.396	1.104	1.442
6500	3.00	-1	0.010	0.371	1.431	0.522	0.936	1.434	1.256	1.637
6500	3.75	-1	-0.107	0.391	1.246	0.498	0.939	1.429	1.234	1.609
6500	4.50	-1	-0.208	0.408	1.095	0.480	0.941	1.426	1.216	1.586
5250	4.50	-2	-0.085	0.660	1.185	0.178	1.001	1.366	0.931	1.221
5500	3.00	-2	-0.095	0.559	1.218	0.301	0.971	1.396	1.048	1.370
5500	3.75	-2	-0.146	0.573	1.139	0.284	0.974	1.392	1.032	1.350
5500	4.50	-2	-0.164	0.591	1.107	0.264	0.978	1.388	1.012	1.324
6000	3.00	-2	-0.122	0.441	1.238	0.447	0.935	1.433	1.187	1.542
6000	3.75	-2	-0.217	0.457	1.093	0.429	0.938	1.429	1.169	1.520
6000	4.50	-2	-0.273	0.474	1.007	0.408	0.942	1.425	1.149	1.495
6500	3.00	-2	-0.077	0.345	1.340	0.561	0.914	1.457	1.294	1.679
6500	3.75	-2	-0.195	0.367	1.152	0.535	0.918	1.452	1.270	1.648
6500	4.50	-2	-0.293	0.386	1.005	0.513	0.921	1.448	1.249	1.622

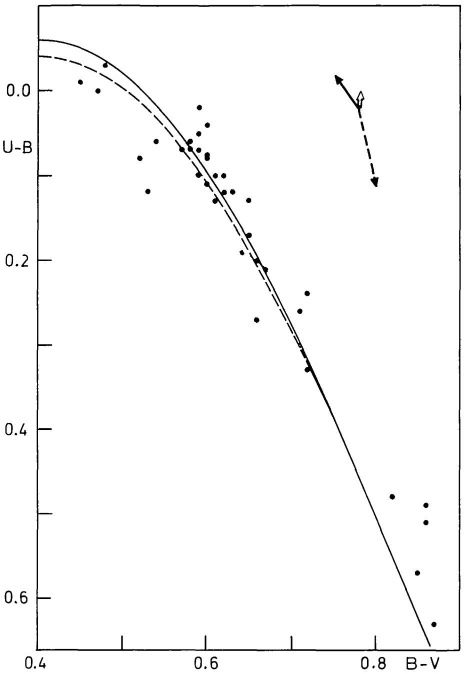

Fig. 3. ($U-B$, $B-V$) diagram for luminosity class V stars with nearly solar abundance. The continuous curve refers to the models with $\log g = 4.5$ and the dashed curve to the models with $\log g$ from Eq. (8)

a) Two-colour diagrams

A good way to test the validity of the synthetic colours is to compare predicted two-colour diagrams with observed ones for well represented groups of stars.

In order to have as homogeneous a group as possible, and to avoid bias, we selected from the catalogue of Cayrel de Strobel et al. (1980) the luminosity class V single stars with $-0.2 < [Fe/H] < +0.2$ in the temperature range $5250\,K < T_{eff} < 7000\,K$.

The corresponding points are plotted in some representative two-colour diagrams, along with the theoretical curves computed from the models with $\log g = 4.5$ and solar abundance (Figs. 3 to 5).

The *UBV* colours are from Nicolet (1978) and the Geneva colours from Rufener (1976).

In each of these figures, the small arrows indicate roughly the predicted effect of a change of
+100 K in T_{eff} (black arrow)
+0.2 in $\log g$ (white arrow)
+0.2 in [Fe/H] (dashed arrow)

These effects are computed for the (6000, 4.5, 0) model. Some of the two-colour diagrams display the following multicolour indices (Golay, 1980):

$$d = (U - B_1) - 1.430(B_1 - B_2) \quad (5)$$

$$\Delta = (U - B_2) - 0.832(B_2 - G) \quad (6)$$

$$g = (B_1 - B_2) - 1.357(V_1 - G) \,. \quad (7)$$

Figure 3 shows the ($U-B$, $B-V$) diagram. The continuous curve corresponds to the predicted $[Fe/H] = 0$, $\log g = 4.5$ sequence, while the dashed curve corresponds to the sequence with $[Fe/H] = 0$ and the values of surface gravity appropriate for the main sequence stars (Gray, 1975):

$$\log g = 4.17 + 0.38(B - V) \,. \quad (8)$$

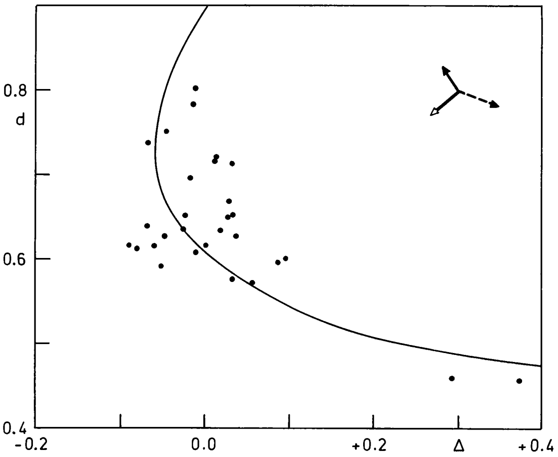

Fig. 4. (d, Δ) diagram for luminosity class V stars with nearly solar abundance

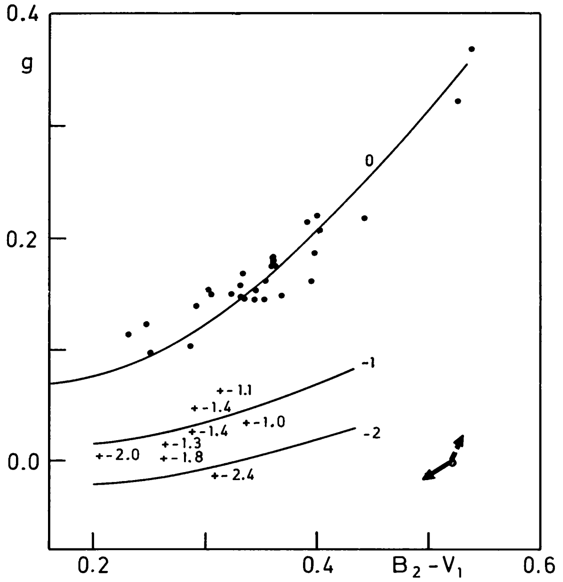

Fig. 5. (g, B_2-V_1) diagram for solar-type stars of different metallicities. The points correspond to stars with $-0.2<[Fe/H]<+0.2$. The crosses represent stars with $[Fe/H]<-1$, as indicated at the right. The curves correspond to the models with $\log g=4.5$ and [Fe/H] as indicated

In Fig. 5 are also added some metal-poor stars ($[Fe/H]<-1$), and the corresponding computed curves.

b) Solar colours

The solar colours are obtained as a byproduct of our analysis (see Table 2). In particular, we obtain $(B-V)_\odot=0.646$, just between the two groups of values found in the literature (0.62 to 0.67, see Hayes, 1979; Hardorp, 1980).

We have also computed the solar $(B-V)$ according to the calibration given by Hayes (1975), using the "Vilnius response function" and the observed solar flux (Neckel, 1981). We obtain a value of $(B-V)_\odot=0.65$.

The good agreement of the two values supports the adopted zero point (Sect. III). Therefore, their accuracy rests almost exclusively on the accuracy of the solar flux measurements.

Table 3. $T_{\rm eff}(B-V)$ relation for dwarfs of solar metallicity

$\frac{\partial(B-V)}{\partial\theta_{\rm eff}}$	Source
1.96	Our models, $[Fe/H]=0$, $\log g=4.5$
1.57	Kurucz's models (1979), $[Fe/H]=0$, $\log g=4.5$
2.18	Gehren (1981), stars with $-0.1<[Fe/H]<+0.1$
1.80	Böhm-Vitense (1981)

Table 4. $T_{\rm eff}(B-V)$ relation for dwarfs of different metallicities, computed with the $\log g=4.5$ models

$B-V$	$T_{\rm eff}$		
	$[Fe/H]=0$	$[Fe/H]=-1$	$[Fe/H]=-2$
0.40	6820	6550	6410
0.45	6560	6270	6120
0.50	6330	6020	5880
0.55	6120	5800	5660
0.60	5930	5590	5470
0.65	5760	5380	5280
0.70	5610		
0.75	5470		

In addition, we have searched in the Rufener (1976) catalogue the stars with colours as close as possible to those of the solar model (Table 2). Among those solar analog candidates, three stars bright enough for spectroscopic analysis do not seem to have received much attention. These stars are HD 111513, 112753, and 159222.

c) $T_{\rm eff}(B-V)$ relation for dwarfs

In Table 3 we compare the values of $\partial(B-V)/\partial\theta_{\rm eff}$ obtained from different grids of models with the value computed by a r.m.s. fit of Gehren's temperatures (1981), based on hydrogen line profiles and with the value given by Böhm-Vitense (1981). The value computed from our grid is in better agreement with empirical values than the other ones, giving further support to our analysis.

In Table 4 are shown the predicted $T_{\rm eff}(B-V)$ relations for dwarfs of different metallicities. Clearly, a single relation is not valid for all stars, so it is necessary to take into account the chemical composition of a star when deriving its effective temperature via a $(B-V)$ or similar colour, unless errors up to 500 K can be accepted.

As an example, for a main sequence star with $T_{\rm eff}\sim 6000$ K, an error of only 0.2 in [Fe/H] will lead to an error of more than 100 K in $T_{\rm eff}$ if it is derived through a $(B-V)$ colour. Therefore, it is better to derive the effective temperature through an infrared colour whenever possible (see Peterson and Carney, 1979 for relations between $T_{\rm eff}$ and $(R-I)$ or $(V-K)$ indices).

d) $(U-B)$ excess and metal abundance

Carney (1979) has given an empirical calibration of $\delta(U-B)_{0.6}$ $(=(U-B)_{\rm star}-(U-B)_{\rm ref}$ at constant $(B-V)=0.6)$ in terms of [Fe/H]. The comparison between his value and different theoretical values is given in Table 5. Again, the comparison strongly supports our computations.

Table 5. Abundance dependence of the $(U-B)$ excess. The theoretical values are approximated by:

$$\frac{\partial(U-B)_{0.6}}{\partial[\mathrm{Fe/H}]} \simeq (U-B)_{[\mathrm{Fe/H}]=0} - (U-B)_{[\mathrm{Fe/H}]=-1}$$

at $(B-V) = 0.6$

$\frac{\partial(U-B)_{0.6}}{\partial[\mathrm{Fe/H}]}$	Source
0.210	Our models, $\log g = 4.5$
0.135	Kurucz (1979), $\log g = 4.5$
0.209	Carney (1979)

Table 6. Physical parameters of some stars

	Spectroscopic parameters			Photometric parameters		
HD number	T_{eff}	log g	[Fe/H]	T_{eff}	log g	[Fe/H]
10307	5930	4.38	+0.12	5860	4.46	-0.01
19373	5910	4.1	+0.09	5990	4.36	+0.10
19445	5790	4.0	-1.86	6100	4.66	-1.44
34411	5890	4.17	+0.19	5850	4.31	-0.02
86728	5900	4.26	+0.16	5730	4.25	+0.04
106516	5930	4.20	-0.49	6360	4.70	-0.31
114710	6010	4.47	+0.16	6070	4.54	+0.10
140283	5670	3.69	-2.32	5720	3.66	-2.05
142373	5880	4.12	-0.37	5820	4.04	-0.46

e) Determination of physical parameters

In the preceding subsections the ability of the new synthetic colours to reproduce various observed relations has been demonstrated. Here we show how they can be used to obtain estimates of the physical parameters of stars. As an example, we show in Table 6 the predicted parameters for some stars which have been previously analysed several times by means of high dispersion spectroscopy (Cayrel de Strobel et al., 1980).

The spectroscopic parameters are simply means of the different catalogue values, excluding some old or low quality data (refs. 11 and 244 of Cayrel de Strobel et al., 1980). Note that these spectroscopic values are not necessarily "best values", due to the inhomogeneous quality of the analyses.

The photometric parameters are determined in order that the colours of the model match as closely as possible the stellar colours. The procedure is iterative and makes use of the following Geneva colour indices:
(B_2-V_1) and (V_1-G) for $T_{\rm eff}$, d and Δ for $\log g$, g and m_2 for [Fe/H]. These parameters are computed by interpolation in the grid of colours.

V. Concluding remarks

The aim of this paper was not to elucidate the nature of the missing UV opacity, but mainly to provide a tool for deriving reliable physical parameters of stars via multicolour photometry.

Thus, we have shown that the mere inclusion of that opacity via a very simple formula is sufficient to bring the colours of the models in agreement with observation for stars belonging to more than one spectral class (mid-F to late-G). We recall that all the free parameters $k(\lambda_i)$ were deduced entirely from the comparison of the solar model flux with the observed one, so that there remained no free parameter to adjust when comparing the observed and computed stellar colours. We believe that this agreement is in favour of the missing UV opacity hypothesis. The presence of a veil of weak metal lines, or of some opacity source behaving more or less in the same way, is the most natural explanation of the disagreement between observed and theoretical stellar fluxes. Other explanations (e.g. wrong treatment of convection) seem unable to explain all the observed relations.

On the other hand, the final solution of the problem will not be reached before we are able to take all the opacity sources into account, including the numerous very weak lines. But this will only be possible after a tremendous spectroscopic work, since the inclusion of all the *known* lines does not solve the problem completely (Dragon and Mutschlecner, 1980). Therefore we have to rely on rather empirical corrections for many years yet, and this is one of the justifications of our work.

Finally, a slightly more detailed description of the extra UV opacity (relaxing some of the hypotheses of Sect. II) should allow to extend the treatment to other classes of stars.

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