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Cool star flux spectra for population studies in galaxies*

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Abstract. Five solar-composition cool giant stars have been observed with the IUE low resolution mode. The UV energy distributions were merged with visual spectrophotometry from the literature and compared with predictions from two new grids of model atmospheres. Atmospheric parameters were derived consistent with the literature data by matching observations and models in the optical region. Significant discrepancies between data and model predictions found in the IUE ultraviolet region are illustrated and briefly discussed.

Key words: stars: giant – stars: fundamental parameters – stars: atmosphere ultraviolet: stars – galaxies: stellar content

1. Introduction

In order to construct a comprehensive grid of stellar flux distributions for the evolutionary synthesis of stellar systems, we need to combine observed and theoretical flux data over a wide wavelength range (1200–10 000 Å) for stars and stellar models representing the different stellar populations. The observations and calculations can be used in a complementary manner, provided that they are shown to match over the full wavelength range and for a significant range of parameters ($T_{\rm eff}$, $\log g$, [M/H]) common to both observed and theoretical spectra.

This work has been done successfully for stars with $T_{\rm eff} > 5500$ K by Malagnini et al. (1986) and Cacciari et al. (1987) using visual scans and IUE data as well as the massive grid of model atmosphere flux spectra published by Kurucz (1979). We have started extending the work to cooler stars with $4000\ {\rm K} < T_{\rm eff} < 6000$ K, using both archival as well as new observed flux spectra and a grid of newly computed theoretical spectra by Buser & Kurucz (1985, 1988, 1992). While the initial results for metal-poor stars are very promising, it is necessary to tie them in with an absolute calibration provided by solar-abundance reference stars that have both high-accuracy optical spectrophotometry and high-accuracy spectroscopic determinations of their astrophysical parameters. We have identified, for the most critical temperature interval, a sample of 5 giant stars that satisfy these requirements, and for which we obtained IUE fluxes (LC 040, 25 August 1989).

The complete flux distribution from the UV to the visual has been obtained for each star by complementing the IUE observations with the spectrophotometric data from Breger (1976).

In Sect. 2 we present the observations and the spectral energy distributions. Sect. 3 briefly describes the main characteristics of the above-mentioned theoretical grid, and of a new set of atmosphere models from Kurucz (1991). Final results and conclusions are given in Sect. 4.

2. Observations

The observed stars constitute a sample of late type giants with excellent determinations of $T_{\rm eff}$, $\log g$, and with (approximately) solar metal abundances (Lambert & Ries 1981; Kjaergaard et al. 1982), for which visual absolute energy distributions are available in the literature.

We obtained IUE LWP low dispersion, large aperture observations whose characteristics are reported in Table 1, together with the basic stellar data (photometric quantities are from Nicolet 1978).

In Figs. 1a–e we present the absolute flux distributions in the IUE range 2000–3300 Å. The presence of spurious scattered light shortward of 2550 Å is evident. Since at these wavelengths, the signal-to-noise ratio is in any case very poor, we shall retain only data above this wavelength limit for the analysis. We want to stress the presence of emission in the Mg II resonance lines for the two coolest, low gravity, stars HD 131873 and HD 164058.

The spectrophotometric scans reported in Breger Catalogue (Breger 1976) have been denormalized, using the visual magnitudes reported in Table 1, and the resulting fluxes have been connected to the ultraviolet ones. Few inconsistent visual data for HD 27371 have been removed after checking the original source quoted by Breger (Oke & Conti 1966). In all the cases the resulting energy distributions start at 2550 Å, and extend up to 6050 Å (last data point in the original source of visual data, referred to as "SCH" in Breger Catalog), except for HD 27371, whose data reach the near infrared at 10 800 Å. As far as the upper limit of photometric accuracy is concerned, Breger reports ±0.020 mag and ±0.015 mag, shortward and longward of the Balmer discontinuity, respectively. An estimate of ±0.10 mag can be safely assumed for the IUE range.

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* Based on observations by the International Ultraviolet Explorer, collected at Villafranca Satellite Tracking Station of the European Space Agency.

Table 1. Program stars

HD	HR	Sp. Type	IUE image no.	Exp. time (s)	V	$E(B-V)$
27371	1346	K0III	LWP 16210	20	3.65	0.00
131873	5563	K4III	LWP 16205	15	2.08	0.09
133208	5602	G8III	LWP 16208	15	3.53	0.02
164058	6705	K5III	LWP 16204	50	2.23	0.02
168723	6869	K0III-IV	LWP 16207	20	3.26	0.00

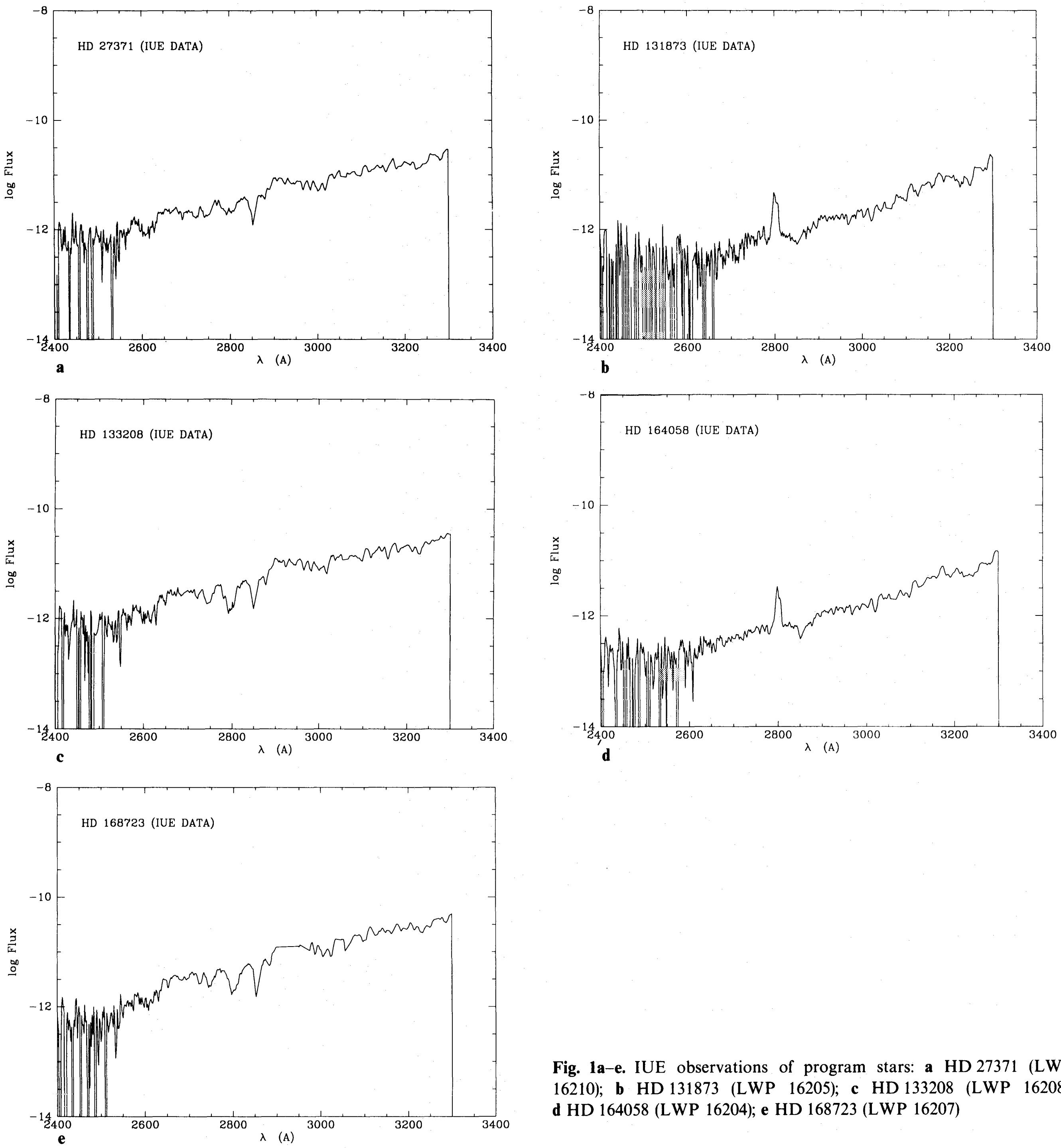

Fig. 1a–e. IUE observations of program stars: **a** HD 27371 (LWP 16210); **b** HD 131873 (LWP 16205); **c** HD 133208 (LWP 16208); **d** HD 164058 (LWP 16204); **e** HD 168723 (LWP 16207)

For the three stars which have reported color excesses $E(B-V)>0$, the flux distributions were dereddened by using the reddening law proposed by Nandy et al. (1975).

3. Model spectra

The observed data will be compared with two new grids of theoretical flux spectra computed from model atmospheres and described in the following sub-sections.

3.1. Buser & Kurucz (BK) spectra from Gustafsson et al. (GBEN) models

Buser & Kurucz (1985, 1988, 1992) have computed new flux distributions from a grid of flux constant, line-blanketed LTE model atmospheres for F-K giants published by Gustafsson et al. (1975: henceforth GBEN) and by Bell et al. (1976). This grid covers the temperatures between 3750 and 6000 K, the surface gravities $0.75 \leq \log g \leq 3.00$, and the metallicities $-3.0 \leq [\mathrm{M/H}] \leq 0.0$, and its properties in terms of synthetic spectra and colors were described by Bell & Gustafsson (1978) and discussed by Gustafsson & Bell (1979) and Bell & Gustafsson (1989).

These models have been widely used in both spectroscopic and photometric analyses of field and cluster stars, but Buser and Kurucz' principal motivation for recomputing their flux distributions was the lack of adequate atomic opacity employed in the original spectrum calculations. While Gustafsson & Bell's group have been using about 50000 atomic lines and a number of molecular lines "many times greater" (Gustafsson & Bell 1979), Buser and Kurucz have neglected molecular lines but used the nearly one million atomic lines compiled by Kurucz & Peytremann (1975). The effect of this difference in opacity source input is significant: as was shown in Buser & Kurucz (1985, 1988, 1992), their more realistic account of atomic line blanketing eliminates the largest fraction of the so-called "ultraviolet discrepancy", which badly plagues the flux distributions and synthetic colors computed for the same models by Bell & Gustafsson (1978) and by VandenBerg & Bell (1985). Furthermore, since the Kurucz & Peytremann line list is more than tenfold larger than the list used by Bell and Gustafsson, and since the bulk of these additional (and strong!) metallic lines appear in the blue-violet-ultraviolet range, we expect the additional blocking in flux constant, line-blanketed models to be balanced by corresponding flux increases at longer wavelengths. Indeed, Buser & Kurucz (1992) have shown that their synthetic BVRI colors provide fits to the spectroscopic calibrations of the color-effective-temperature relations which are as good as, or even better than, those published by Bell and Gustafsson (1978, 1989). Thus, the BK spectra should also provide similarly reliable temperature determinations from visual or near-infrared colors, despite the fact that they were calculated neglecting molecular opacities – which introduces a significant error at these wavelengths only at temperatures decreasing below 4000 K.

All the new flux distributions computed by Buser and Kurucz are available for the same set of 342 wavelength points as was used with the published Kurucz (1979) models; most of these wavelengths cover the range between 229 Å and about 2 μm, with spacings between 25 and 100 Å.

3.2. New Kurucz (NK) models and spectra

A set of solar-abundance models spanning the temperature range 3500–8750 K at steps of 250 K and log g 1.5–5.0 at steps of 0.5 dex has been kindly provided by R.L. Kurucz (1991). They have been computed with a new model atmosphere program, new line opacities, and additional continuous opacities with respect to those of the 1979 grid, using now a line list of over 58 million atomic and molecular lines. The wavelength range spans from 506 Å to 1600000 Å for a total of 1141 wavelength points, and the resolution in the ultraviolet is on the order of 10 Å.

4. Results and conclusions

The automatic fitting procedure developed by Malagnini & Morossi (1983) has been applied to the dereddened spectral energy distributions of the program stars by using both theoretical grids described in Sect. 3. Different weights have been used to take into account the accuracies shortward and longward of 3660 Å; the initial UV wavelength was fixed to 2550 Å to avoid data polluted by scattered light. Solar chemical composition has been assumed for all the stars, while effective temperature, T_{eff}, surface gravity, log g, and apparent angular diameter, ϕ, have been used as free parameters for the fit.

The same kind of analysis performed in Cacciari et al. (1987) showed several inconsistencies between observations and model predictions in the IUE region. Moreover, the rms errors of the fit were much higher than expected from the observational uncertainties, thus making the results of the fit including the UV data unreliable.

On the other hand, fits performed using only visual data resulted in a very good agreement between theoretical and observed energy distributions. The only exception refers to one wavelength point, namely 4167 Å, where the residual from fitting the BK spectra is always too high, most probably because CN opacity was ignored in the calculations. In order to avoid a bad effect on the overall fit, zero weight was given to that wavelength point. On the other hand, CN opacities are included in the NK models and spectra, which well reproduce the 4167 Å feature.

In Table 2 we present T_{eff}, log g and ϕ (marcsec), along with the root mean square error of the fit (mag) resulting from the visual data (the BK results refer to fits performed ignoring the 4167 Å data point). Since visual scans cover only continuum or pseudo-continuum regions, they are not suitable for deriving accurate surface gravities (Malagnini & Morossi 1992). Therefore, the fit was performed without interpolating the log g values given in the original grids. Comparison with Table 3 shows that results obtained from either grid are consistent with the spectroscopic data reported in the literature, even though the temperatures derived from the BK spectra are systematically cooler than those based on the more recent NK models. In the UV region, we compare the observations with the theoretical predictions resulting from the above model spectra (Table 2), i.e. those that have best-fitting spectra in the visual. The characteristics of the above-mentioned UV discrepancies appear to be rather different for our two groups of stars having temperatures around 5000 K and 4000 K, respectively. We shall discuss these two groups separately now.

4.1. $T_{eff}=5000$ K, $\log g=2.0-3.0$

Both grids of spectra give comparable rms errors of the fits, and provide estimates of T_{eff} and apparent angular diameters with uncertainties on the order of 4% and 10%, respectively. While in the optical region the residuals are always within the quoted

Table 2. Fit results

HD	NK grid				BK grid			
	T_{eff}	log g	ϕ	rms	T_{eff}	log g	ϕ	rms
27371	4930	2.50	2.46	0.04	4850	3.00	2.63	0.03
131873	4160	1.50	9.92	0.09	4090	1.50	10.64	0.06
133208	5140	2.00	2.36	0.05	4850	2.25	2.87	0.05
164058	4000	1.50	9.94	0.10	3970	1.50	10.15	0.07
168723	5110	3.00	2.61	0.05	4850	3.00	3.16	0.05

Table 3. Parameters from literature

HD	T_{eff}	log g	[Fe/H]	ϕ	Ref.
27371	4942	—	—	—	7
	5050	2.58	—	—	4
	5050	2.95	0.00	—	12
	4940	2.50	0.18	—	3
	4950	3.20	0.22	—	3
	5080	2.90	—	—	3
	4930	2.60	0.16	—	2
	—	—	—	2.84	5
	—	—	—	3.20	15
	—	—	—	3.10	15
	4966	—	—	2.36	14
131873	4020	2.40	—	—	3
	4220	—	—	8.90	11
	—	—	—	14.00	15
	—	—	—	16.40	15
	—	—	—	8.10	15
	—	—	—	10.70	15
	4050	1.60	−0.14	—	2
133208	4950	1.60	—	—	3
	4989	—	—	2.47	7
	4929	2.30	0.04	2.61	2
	—	—	—	2.39	15
	—	—	—	2.37	15
	—	—	—	3.10	15
	—	—	—	3.40	15
	5008	—	—	2.44	14
164058	3938	—	—	10.24	7
	3940	—	—	10.20	9
	4300	—	—	8.70	11
	3981	—	—	10.13	8
	3957	—	—	10.20	10
	3955	1.55	−0.23	10.45	2
	—	—	—	10.20	13
	4308	1.60	0.33	—	6
	—	—	—	14.00	15
	—	—	—	10.90	15
	—	—	—	18.00	15
	—	—	—	9.90	15
	—	—	—	7.90	15
	3986	—	—	10.00	14
168723	4930	3.23	−0.10	—	1
	4970	3.20	−0.23	—	3
	5090	3.20	−0.16	—	3
	4940	2.91	—	—	4
	4949	2.90	−0.08	2.98	2
	4893	3.10	−0.31	—	6
	—	—	—	4.60	15
	—	—	—	3.40	15

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observational uncertainties, Figs. 2 and 3 clearly show that in the UV, they are quite often higher than expected from the IUE photometric errors.

In order to check these results, we compared the observations also with predictions from models having plausible parameters different from those given in Table 2 but within the ranges covered by the literature data of Table 3. However, we were unable to improve our results of Table 2, because in most cases that we tried, either local or systematic discrepancies existing between the model spectra and the observations kept growing beyond acceptable limits.

4.2. $T_{eff}=4000$ K, $\log g=1.5$

For the two stars of this group, the most obvious – and unexpected – message of Figs. 4 and 5 is the dramatic failure of the NK spectra to correctly reproduce the observed UV flux distributions shortward of 3000 or 3200 Å, while the BK spectra approximate well the observed slopes over the full wavelength

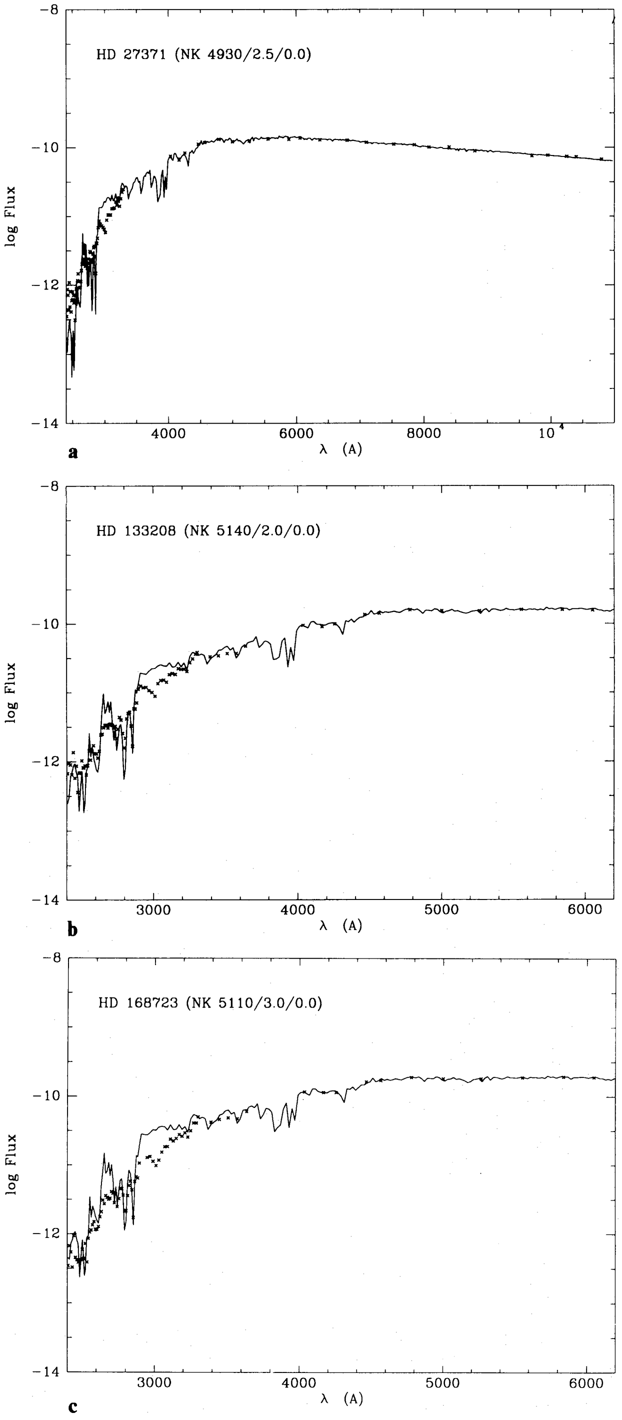

Fig. 2a–c. Observed and computed (NK) energy distributions: **a** HD 27371; **b** HD 133208; **c** HD 168723

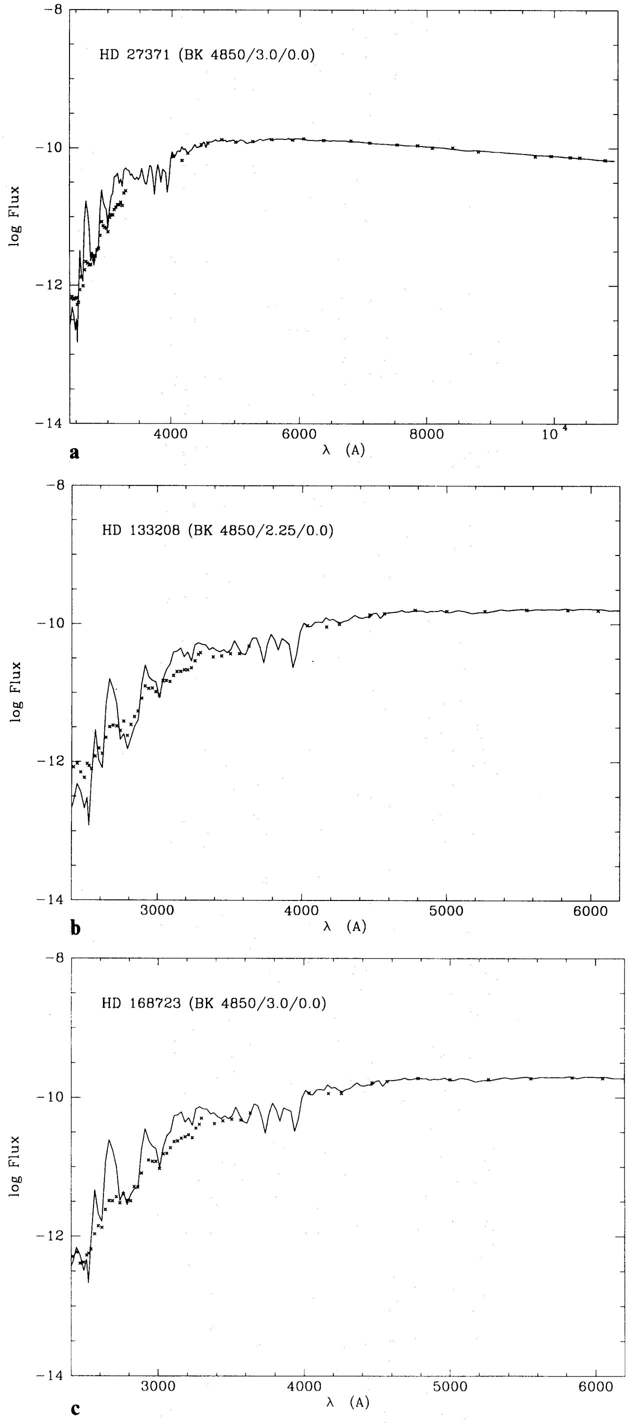

Fig. 3a–c. Observed and computed (BK) energy distributions: **a** HD 27371; **b** HD 133208; **c** HD 168723

range. Accordingly, the rms errors and the uncertainties in the parameter estimates derived from the NK spectra are significantly larger than those obtained from the BK spectra (although in either case the residuals of the visual fits are within the observational uncertainties). In particular, the statistical error on the NK-derived apparent angular diameters is on the order of 20%! Again, we have tried alternative solutions for parameter values ranging within the literature data of Table 3; but as for the hotter stars discussed above, the systematic UV discrepancies between the NK models and the observations could neither be eliminated nor even decreased.

The origin of this mismatch is not yet fully understood. However, calculations performed for the NK model with $T_{\rm eff}=4000$ K and log $g=1.5$ but using the old (Kurucz & Peytremann) instead of the new multi-million line list provide a UV spectrum which essentially matches the corresponding BK spectrum. On the other hand, if the GBEN model for the same effective temperature (4000 K) and surface gravity (1.5) is used

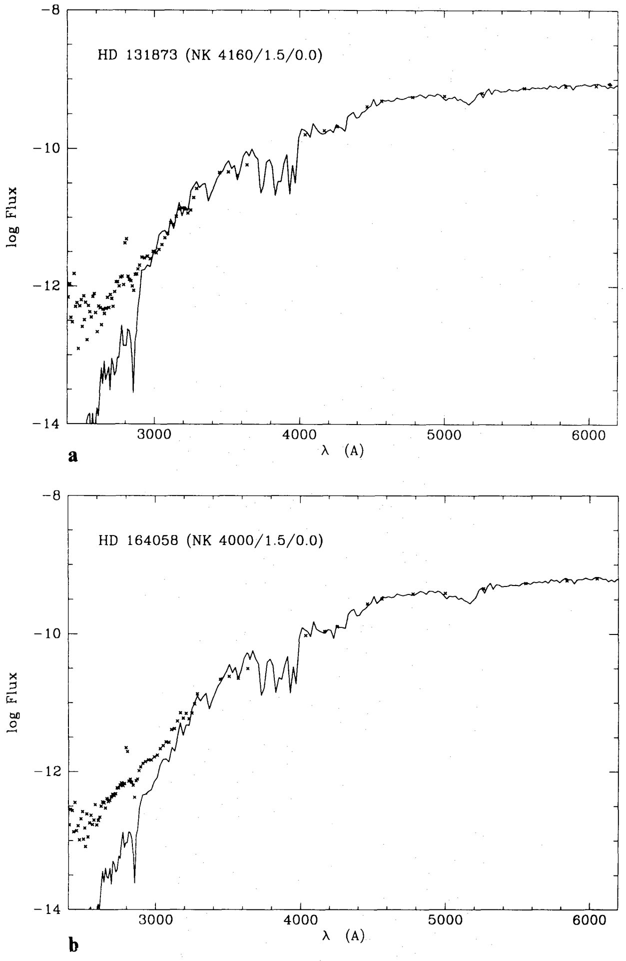

Fig. 4a and b. Observed and computed (NK) energy distributions: **a** HD 131873; **b** HD 164058

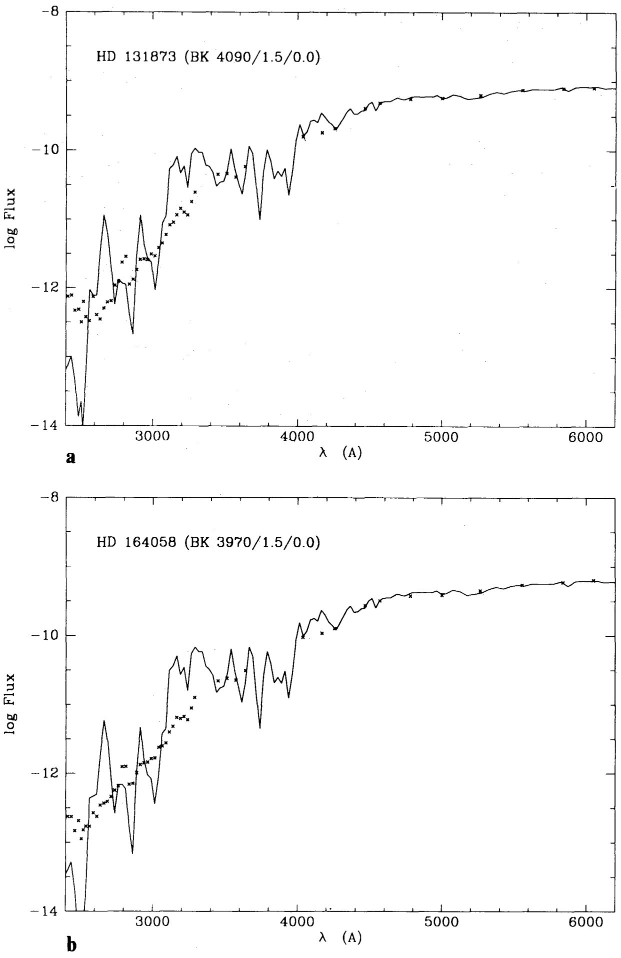

Fig. 5a and b. Observed and computed (BK) energy distributions: **a** HD 131873; **b** HD 164058

along with Kurucz' new multi-million line list, the resulting flux distribution deviates from the observations in very much the same way as does the NK spectrum in Fig. 4b (the flux underestimate for the GBEN model spectrum is actually slightly larger than for the NK spectrum). Thus, the different ultraviolet flux distributions predicted by the NK and the BK spectra shown in Figs. 4 and 5, respectively, seem to be due to the different line lists employed rather than due to differences in the temperature structures between the NK and the GBEN models. Unless these models happen to have similarly wrong temperature structures, the large systematic discrepancies in Fig. 4 between observations and NK model spectra strongly suggest that the opacities in Kurucz' new line list might be overestimated.

We conclude that, while the Buser and Kurucz spectra do not provide faithful representations of most features in the stellar observed ultraviolet, they do provide fairly accurate fluxes for, and flux gradients between, broad-band measures of the stellar flux distributions. On the other hand, the new Kurucz models give, in general, more accurate descriptions of observed spectral features, but the systematic UV discrepancies found above between theory and observations of cool giants at 4000 K indicate that, at this stage, it is clearly premature to conclude that the new generation of model flux distributions has successfully superseded all the earlier calculations.

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