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ASTRONOMY AND ASTROPHYSICS

Intrinsic UV colours of OB stars

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Abstract. The intrinsic energy distributions in spectra of young, hot OB stars, based on the photometric UV measurements in the ANS satellite bands, are presented. The colour indices, free of interstellar reddening, are derived from the two-colour diagrams with the application of the special check of the correctness of intrinsic $B-V$ indices (the ironing-out of the 2200 Å extinction band in the mean unreddened spectra of given spectral types and luminosity classes). The obtained flux distributions are compared to those based on the TD – 1 UV spectra. The agreement is very satisfactory. The present results, based on much bigger samples of every Sp/L than any other, previously determined UV colours, may be very useful both when determining stellar atmospheric parameters and extinction laws. Intrinsic continuous spectra of Be stars are proved to be identical with those of normal B stars.

Key words: stars: colors of – stars: early-type

1. Introduction

The intrinsic parameters of young and hot OB stars are still not known with a satisfactory accuracy, comparable to the precision of actually recorded spectra (with the aid of solid state detectors). Such stars are bright enough for being observed at very long distances and, moreover, known as the Galaxy spiral tracers, i.e. related to the spiral structures filled with interstellar matter. This is why only a few of them are observed without any reddening. This reddening may be either of interstellar or of circumstellar origin as very young objects, such as OB stars, may be still immersed in some remnants of their parent clouds. We must not, in practice, distinguish between different sources of extinction as no method of separating inter- and circumstellar reddening effects exists. It makes the determination of intrinsic parameters of OB stars, especially flux distributions in their continua, a very complicated task.

Ground-based observations of OB stars cover only the spectral range very far from the Planck maxima of their continua. Such flux distribution "tales" do not allow a precise determinations of spectral types assuming the latter is a simple function of effective temperature. Often spectral types derived from IUE spectra do not agree with MK spectral types. It is not clear whether such discrepancies are simply due to some errors in the classification or follow some real effect creating doubts about the identity of two stars of the same Sp/L MK class. This fact makes the determination of intrinsic parameters related to certain Sp/L very important. It requires to determine average spectra of stars belonging to every MK class, especially in the range of extraterrestrial ultraviolet – very close to the maxima of the flux distributions. They should allow to find precise relations between Sp/L classes and effective temperatures and atmospheric pressures as well as some finer physical parameters of their atmospheres.

There are a couple of papers dealing with the intrinsic UV colour indices of OB stars: Wesselius et al. (1980), Wu et al. (1980) and Gałęcki et al. (1983). There are differences between the determinations presented in these papers (Table 1). They are probably due to different methods applied by the authors. It seems thus to be of importance to rediscuss the intrinsic colours based on the ANS photometry (Wesselius et al. 1982) to improve their accuracy which plays an important role when determining both stellar atmospheric parameters and the extinction law toward many stars. The ANS photometric system was defined such that the most striking spectral feature of the extinction law, the 2200 Å bump, is very well represented, and its intensity can be determined quite accurately. Its measurements form still the only deep-sky photometric survey in the range of extraterrestrial ultraviolet which makes it still a very attractive source of information concerning distant stars and interstellar clouds. The IUE spectra concern in some cases even fainter objects, but this sample is too scarce to allow statistical investigations.

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Table 1. Comparison of published intrinsic colours

	1550–1800				1800–2200				2200–2500				2500–3300			
Sp/L	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
O9 I	–	−0.15	−0.16	–	–	−0.26	−0.24	–	–	−0.58	−0.56	–	–	−1.07	−1.05	–
O9 III	–	–	−0.21	–	–	–	−0.31	–	–	–	−0.55	–	–	–	−1.12	–
O9 V	−0.27	−0.25	−0.21	–	−0.45	−0.40	−0.31	–	−0.50	−0.51	−0.55	–	−1.05	−1.12	−1.12	–
B1 I	–	−0.12	−0.12	–	–	−0.27	−0.10	–	–	−0.29	−0.44	–	–	−0.83	−0.95	–
B1 III	–	−0.24	−0.21	−0.19	–	−0.40	−0.31	−0.42	–	−0.44	−0.50	−0.30	–	−0.96	−1.02	−0.88
B1 V	−0.26	−0.24	−0.21	−0.19	−0.42	−0.37	−0.31	−0.38	−0.47	−0.49	−0.50	−0.39	−0.98	−0.99	−1.02	−0.89
B2 I	–	−0.13	−0.18	−0.13	–	−0.26	−0.14	−0.40	–	−0.24	−0.38	−0.15	–	−0.77	−0.96	−0.79
B2 III	–	−0.20	−0.24	−0.19	–	−0.31	−0.24	−0.48	–	−0.41	−0.54	−0.29	–	−0.86	−0.90	−0.78
B2 V	−0.25	−0.25	−0.24	−0.24	−0.38	−0.36	−0.24	−0.37	−0.43	−0.44	−0.54	−0.42	−0.87	−0.88	−0.90	−0.81
B3 I	–	−0.12	−0.06	−0.14	–	−0.29	−0.06	−0.18	–	−0.20	−0.29	−0.16	–	−0.63	−0.56	−0.58
B3 III	–	−0.21	−0.23	−0.20	–	−0.32	−0.22	−0.36	–	−0.41	−0.50	−0.30	–	−0.70	−0.84	−0.67
B3 V	−0.25	−0.27	−0.23	−0.25	−0.35	−0.34	−0.22	−0.36	−0.39	−0.43	−0.50	−0.41	−0.73	−0.76	−0.84	−0.73
B5 I	–	−0.12	−0.06	−0.06	–	−0.31	−0.13	−0.23	–	−0.17	−0.27	−0.20	–	−0.36	−0.34	−0.29
B5 III	–	−0.19	−0.23	−0.19	–	−0.31	−0.25	−0.29	–	−0.33	−0.44	−0.37	–	−0.54	−0.66	−0.55
B5 V	−0.24	−0.24	−0.23	−0.23	−0.33	−0.35	−0.25	−0.34	−0.37	−0.35	−0.44	−0.37	−0.59	−0.61	−0.66	−0.60
B8 I	–	−0.18	−0.04	−0.04	–	−0.50	−0.30	−0.49	–	−0.07	−0.08	−0.07	–	−0.31	−0.14	−0.11
B8 III	–	−0.17	−0.15	–	–	−0.26	−0.24	–	–	−0.34	−0.35	–	–	−0.35	−0.40	–
B8 V	−0.17	−0.16	−0.15	–	−0.30	−0.26	−0.24	–	−0.33	−0.33	−0.35	–	−0.40	−0.39	−0.40	–

References: 1. Wesselius et al. (1980), 2. Wu et al. (1980), 3. Gałęcki et al. (1983), 4. this paper.

2. Data reduction and analysis

The existing intrinsic UV colours presented in the papers of Wesselius et al. (1980) and Wu et al. (1980) are based on a few slightly reddened stars each. Moreover because, as mentioned above, it is rather difficult to find a completely unreddened OB star, the authors dereddened their targets using an average reddening law. Such a procedure as shown recently by Papaj, Wegner and Krełowski (1990, hereinafter PWK) is very uncertain as slightly reddened stars are usually obscured by clouds characterized by extinction laws highly discrepant from any "mean law". This makes it difficult to attach any realistic errors to these intrinsic colours. Moreover the published intrinsic $B-V$ indices differ also from one determination to another (see the discussion of PWK). This fact creates large uncertainties among small colour excesses and thus contributes substantially to the final uncertainties of intrinsic colours.

Gałęcki et al. (1983) tried to include more stars in their determination of intrinsic colours. Producing two-colour diagrams for samples containing stars of the same Sp/L they based their colours on average relations between $B-V$ and indices involving the ANS bands. These results are uncertain as the choice of sources of MK classes and intrinsic $B-V$ indices were rather arbitrary. Let's emphasize also that a two-colour relation involving 15–18 colours suffers great uncertainties (see their Fig. 1). It is thus of importance to rediscuss also these colours.

The method applied in this paper is also based on two-colour diagrams but it is a modified version, invented by Krełowski et al. (1986) and improved recently by PWK in their investigations of ultraviolet spectra. The method contains the following steps:

1. Careful selection of samples of the same Sp/L– spectral classifications taken from different sources (Hoffleit & Jaschek 1982; Blanco et al. 1970; Kennedy & Buscombe 1974; Buscombe 1977, 1980, 1981, 1984) are to be compared and evaluated.
2. Production of two-colour diagrams for these samples in the form $(\lambda-V)$ versus $(B-V)$.
3. Calculation of mean relations between the colours involved.
4. Calculation of intrinsic $(\lambda-V)$ colours by inserting the intrinsic $(B-V)$ indices in these relations.
5. Small correction to these intrinsic colours based on the assumption that the 2200 Å extinction bump does not appear neither in absorption nor in emission, in the resultant intrinsic spectra.

The above-mentioned two-colour relations are always linear and thus the mean relations between the colour indices may be written as

$$\lambda-V=a(B-V)+b \tag{1}$$

where a and b are the slope and intercept of the mean relation respectively. When the intrinsic value of $B-V$ is substituted into this formula the left-hand side should equal the intrinsic $(\lambda-V)$ colour

$$(\lambda-V)_0=a(B-V)_0+b \tag{2}$$

which allows to calculate ultraviolet intrinsic colours when intrinsic $B-V$ indices are known. The precision of the latter determines the precision of the UV colours together with the quality of a two-colour relation. By subtracting Eq. (2) from Eq. (1) we obtain

$$(\lambda-V)-(\lambda-V)_0=a\ [(B-V)_0] \tag{3}$$

which may be rewritten as

$$E_{\lambda-V}=a E_{B-V} \tag{4}$$

thus the slope of a two-colour relation determines the average normalized extinction curve for any sample of a given Sp/L class:

$$\frac{E_{\lambda-V}}{E_{B-V}}=a \tag{5}$$

This procedure may be used to determine extinction curves only if we may assume that the extinction law is the same towards all the stars under consideration as, for example, in certain OB associations (Krełowski & Strobel 1987). Another application of the method outlined above is the comparison of long distance average extinction curves, where the probability of every kind of cloud along a line of sight is very similar and thus the extinction law (averaged over all intervening clouds) does not differ from one sightline to another. The method is, however, useless when determining individual extinction curves. In the latter case the above described intrinsic colours are to be applied. However, as shown by PWK the intrinsic values of $B-V$ may be improved making the assumption that the extinction bump should be absent in the "mean intrinsic" spectra. This fact allowed PWK to propose the new set of intrinsic UV colours, slightly different from the older determinations. Their paper does not concern supergiants as such stars are very scarce in the sample of TD – 1 spectra. The ANS samples of supergiants are large enough, but we must make a choice: which intrinsic $B-V$ indices are the best?

Two examples of such two-colour diagrams are shown in Fig. 1. The good correlation is evident; also the relations can be satisfactorily described by a linear fit. The relations are much more convincing than those of Gałęcki et al. (1983), especially for the far-UV.

The additional question which is to be answered is whether intrinsic spectra of Be stars differ from those of "normal" B stars. The former objects are believed to be closely related to some diffuse matter in the form of, for example, disks. This matter causes probably an extinction different from that in diffuse interstellar clouds (Sitko et al. 1981; Schild 1983; Papaj et al. 1991). It is thus of

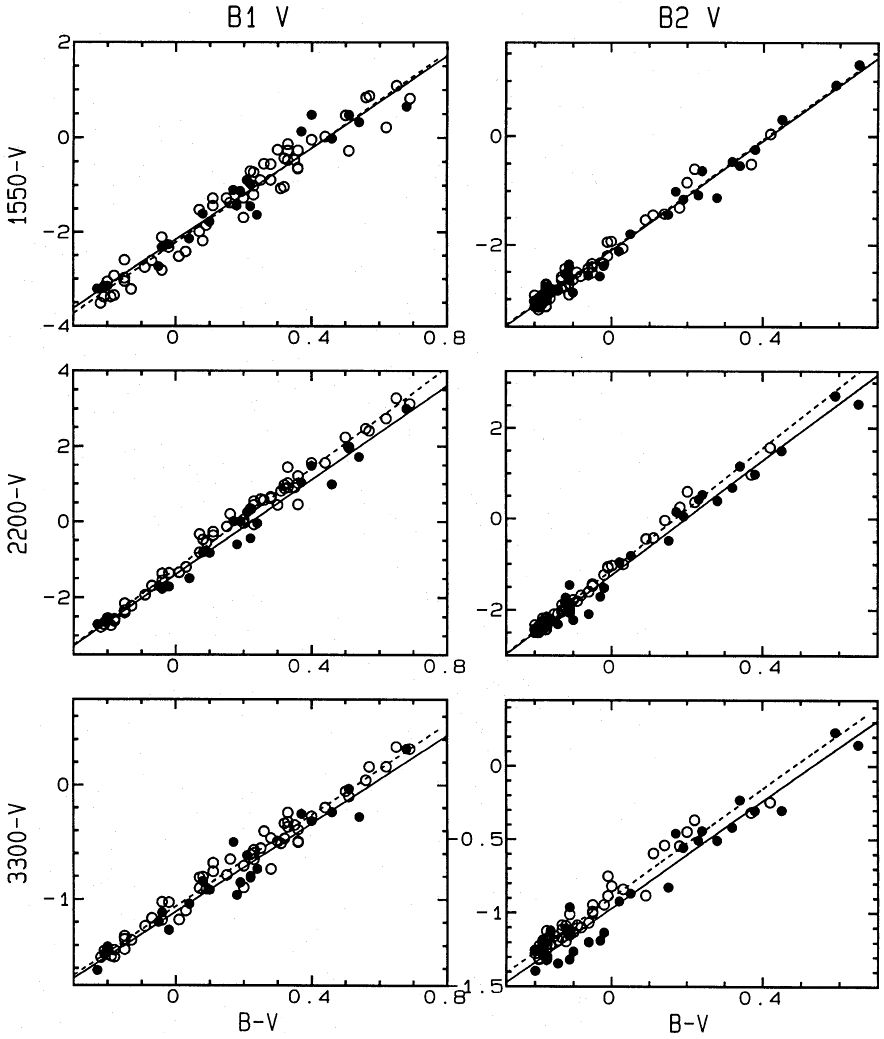

Fig. 1. Examples of two-colour relations. In these two samples "normal" B stars are plotted as open circles Be stars as dots. Mean relations: normal stars – broken line, Be stars – solid line. Note the coincidences of the mean relations for $B-V$ colour indices close to intrinsic values

importance to decide whether intrinsic spectra of such stars are the same as those of B stars, only being affected by a "peculiar" extinction. Figure 1 presents two-colour diagrams for normal and Be stars. The scatter of points representing Be stars is greater, sometimes the mean relation derived from such points is also different, especially in the 2200 Å band (due to the lack of this band in Be extinction curves) but in the vicinity of the intrinsic $B-V$ indices the relations typically intersect or are identical. Thus we conclude that there is no difference between intrinsic flux distributions of normal B and Be stars – the only problem is the correct dereddening of the stars obscured by circumstellar shells. If an incorrect (e.g. "mean galactic") extinction curve is applied the "dereddened" spectrum may contain "foreign" features, like the 2200 Å bump in emission or a wrong spectral gradient. We conclude anyway, based on a very simple analysis of photometric data (Fig. 1) that the same standard intensity distributions apply to normal as well as Be stars.

3. Results

The intrinsic $\lambda - V$ colour indices determined for the ANS samples of OB stars allow to plot quasi-continua of the spectra of our "artificial standards". It is reasonable to assume that such "spectra" should not contain any extrema in the 2200 Å band which are likely due to an incorrect dereddening. For dwarfs and giants we have used the intrinsic $(B-V)$ colours proposed by PWK. For supergiants we applied the "ironing out" of the 2200 Å feature. Thus the set of intrinsic UV colours of supergiants is less certain than that of dwarfs or giants as the "ironing-out" procedure is less reliable when dealing only with five photometric bands instead of spectra.

The sets of quasi-continua derived for main sequence stars, giants and supergiants are presented in Fig. 2. We have derived intrinsic colours for all samples that had a large enough range in reddening values to allow a reliable least squares fit. Only for these samples the "spectra", normalized to the V band are depicted in Fig. 2.

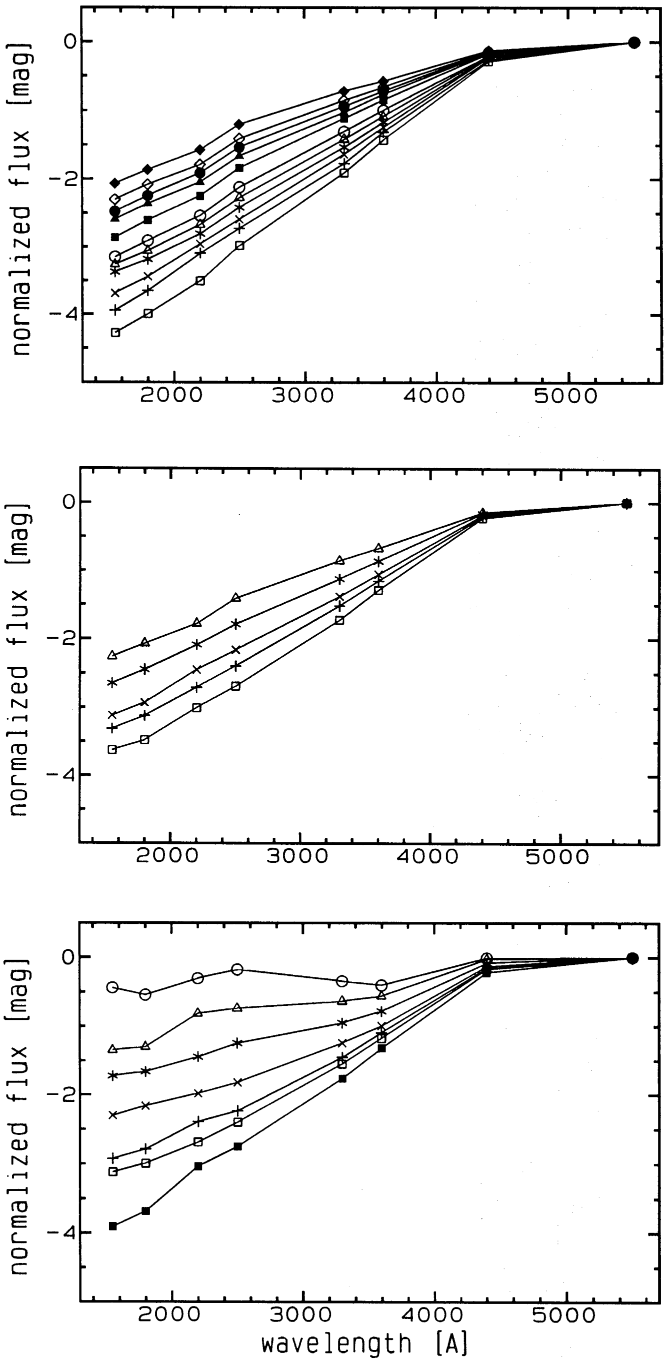

Fig. 2. The unreddened quasicontinua of early-type stars normalized to the V band: the frames from top to bottom contain dwarfs, giants and supergiants respectively. The dwarfs are plotted as follows: full diamonds – B 7, open diamonds – B 6, dots – B 5, full triangles – B 4, full squares – B 3, open circles – B 2, open triangles – B 1.5, asterisks – B 1, × signs – B 0.5, plus signs – O 9.5, open squares – O 7. The giants: triangles – B 5, asterisks – B 3, × signs – B 2, plus signs – B 1, open squares – B 0. The supergiants: open circles – B 9, triangles – B 8, asterisks – B 5, × signs – B 3, plus signs – B 2, open squares – B 1.5, full squares – B 0

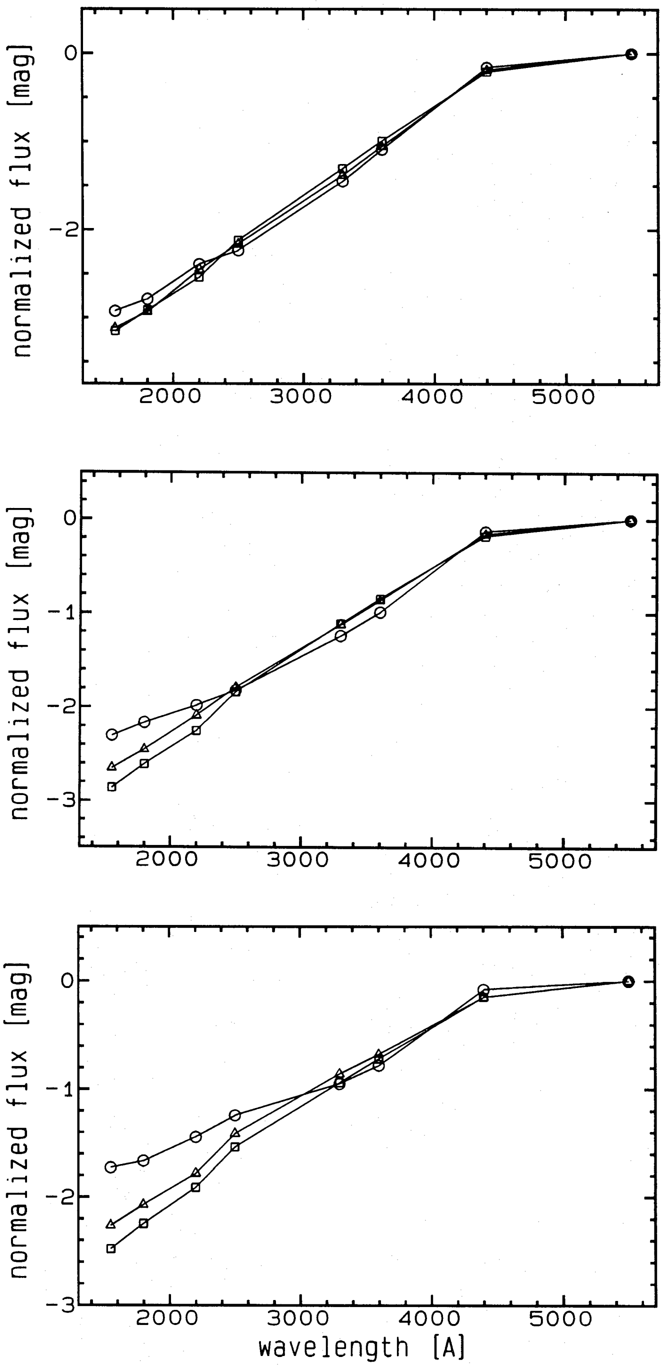

Fig. 3. The unreddened quasicontinua of dwarfs (squares), giants (triangles) and supergiants (open circles) compared for the same spectral types. From top to bottom: B 2, B 3 and B 5

Table 2. Intrinsic colours and effective temperatures attributed to early-type stars

Sp/L	T_{eff}	$B-V$	$U-B$	σ	$33-V$	σ	$25-V$	σ	$22-V$	σ	$18-V$	σ	$15-V$	σ
O7 V	28700	−0.29	−1.14	0.01	−1.91	0.03	−2.98	0.06	−3.51	0.10	−3.99	0.07	−4.28	0.08
O9 V	27200	−0.28	−1.07	–	−1.84	–	−2.81	–	−3.23	–	−3.72	–	−4.09	–
O9.5 V	25700	−0.27	−1.04	0.02	−1.77	0.03	−2.73	0.04	−3.10	0.08	−3.65	0.08	−3.94	0.12
B0 V	24500	−0.26	−1.02	–	−1.71	–	−2.66	–	−3.02	–	−3.49	–	−3.79	–
B0.5 V	22000	−0.24	−1.00	0.01	−1.64	0.02	−2.59	0.04	−2.96	0.07	−3.44	0.07	−3.69	0.10
B1 V	20900	−0.23	−0.94	0.01	−1.53	0.01	−2.42	0.02	−2.81	0.04	−3.19	0.03	−3.38	0.05
B1.5 V	19800	−0.22	−0.86	0.01	−1.42	0.02	−2.28	0.03	−2.67	0.04	−3.06	0.05	−3.26	0.07
B2 V	18700	−0.21	−0.79	0.01	−1.31	0.02	−2.12	0.02	−2.54	0.03	−2.91	0.03	−3.15	0.03
B2.5 V	17200	-0.19_5	−0.73	–	−1.22	–	−1.99	–	−2.43	–	−2.80	–	−2.97	–
B3 V	15800	−0.18	−0.67	0.02	−1.11	0.02	−1.84	0.02	−2.25	0.02	−2.61	0.03	−2.86	0.03
B4 V	14500	−0.16	−0.60	0.03	−1.03	0.04	−1.66	0.07	−2.05	0.09	−2.37	0.10	−2.60	0.12
B5 V	13900	−0.15	−0.57	0.03	−0.94	0.03	−1.54	0.05	−1.91	0.06	−2.25	0.05	−2.48	0.06
B6 V	13400	−0.14	−0.52	0.02	−0.85	0.02	−1.41	0.04	−1.79	0.05	−2.08	0.04	−2.31	0.05
B7 V	13000	−0.13	−0.45	0.03	−0.72	0.04	−1.20	0.07	−1.58	0.09	−1.86	0.09	−2.07	0.09
B0 III	20900	−0.23	−1.06	0.01	−1.73	0.03	−2.69	0.03	−3.01	0.06	−3.48	0.06	−3.63	0.09
B0.5 III	19800	−0.22	−1.01	–	−1.64	–	−2.57	–	−2.88	–	−3.34	–	−3.51	–
B1 III	18700	−0.21	−0.94	0.01	−1.52	0.03	−2.40	0.04	−2.71	0.06	−3.12	0.09	−3.31	0.10
B1.5 III	17700	−0.20	−0.91	–	−1.45	–	−2.28	–	−2.58	–	−3.02	–	−3.21	–
B2 III	16800	−0.19	−0.87	0.01	−1.38	0.02	−2.16	0.03	−2.45	0.04	−2.93	0.04	−3.12	0.06
B2.5 III	15800	−0.18	−0.79	–	−1.24	–	−1.96	–	−2.25	–	−2.66	–	−2.86	–
B3 III	14500	−0.16	−0.71	0.02	−1.12	0.02	−1.79	0.03	−2.09	0.03	−2.45	0.04	−2.65	0.06
B4 III	14000	−0.15	−0.61	–	−0.97	–	−1.55	–	−1.87	–	−2.21	–	−2.41	–
B5 III	13900	−0.15	−0.52	0.04	−0.86	0.05	−1.41	0.09	−1.78	0.08	−2.07	0.10	−2.26	0.12
B0 I	21200	−0.22	−1.10	0.02	−1.76	0.04	−2.75	0.06	−3.04	0.10	−3.69	0.09	−3.91	0.13
B0.5 I	19100	−0.20	−1.07	–	−1.72	–	−2.69	–	−3.03	–	−3.55	–	−3.70	–
B1 I	18200	−0.19	−1.03	–	−1.65	–	−2.57	–	−2.88	–	−3.32	–	−3.44	–
B1.5 I	16500	−0.17	−1.00	0.04	−1.55	0.07	−2.40	0.10	−2.69	0.15	−2.99	0.10	−3.12	0.15
B2 I	15700	−0.16	−0.93	0.03	−1.45	0.06	−2.24	0.08	−2.39	0.07	−2.79	0.17	−2.92	0.20
B2.5 I	14500	−0.14	−0.90	–	−1.34	–	−2.02	–	−2.18	–	−2.44	–	−2.58	–
B3 I	14000	−0.13	−0.86	0.04	−1.24	0.05	−1.82	0.09	−1.98	0.10	−2.16	0.16	−2.30	0.18
B4 I	13000	-0.10_5	−0.77	–	−1.07	–	−1.48	–	−1.64	–	−1.83	–	−1.93	–
B5 I	11900	−0.08	−0.70	0.02	−0.95	0.04	−1.24	0.05	−1.44	0.05	−1.67	0.06	−1.73	0.08
B6 I	11200	−0.06	−0.65	–	−0.87	–	−1.08	–	−1.32	–	−1.63	–	−1.67	–
B7 I	10700	−0.04	−0.60	–	−0.78	–	−0.95	–	−1.14	–	−1.58	–	−1.63	–
B8 I	10400	−0.03	−0.53	0.04	−0.63	0.06	−0.74	0.10	−0.81	0.15	−1.30	0.14	−1.35	0.21
B9 I	9900	−0.01	−0.39	0.04	−0.34	0.05	−0.18	0.05	−0.30	0.09	−0.54	0.07	−0.44	0.11

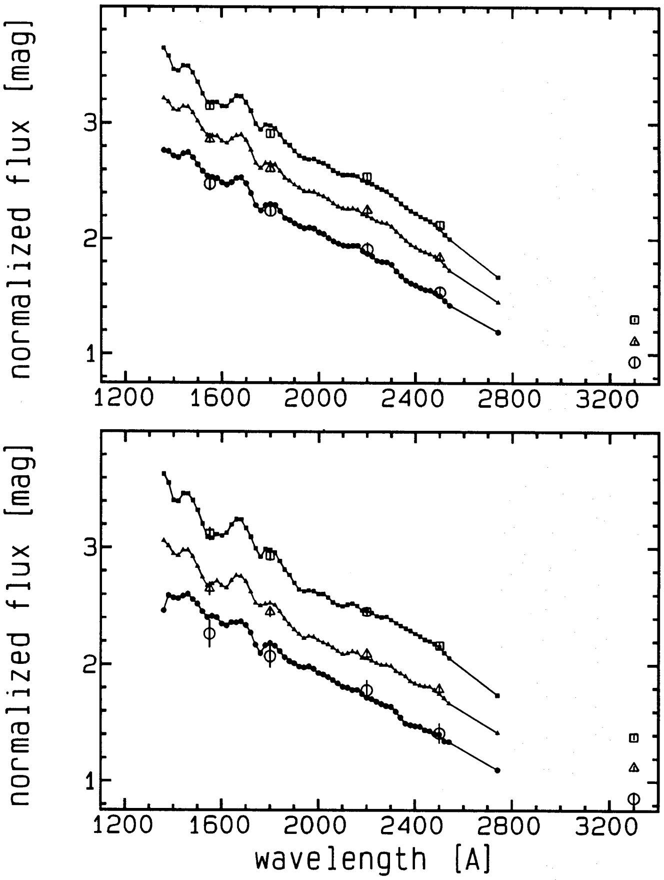

Fig. 4. The comparison of intrinsic UV continua taken from PWK with the results of the present paper. *Upper frame:* squares – B2V, triangles – B3V, open circles – B5V. Lower frame: squares – B2III, triangles – B3III, open circles – B5III

The finally applied intrinsic $B-V$ colours are usually not very much discrepant from those of the Schmidt-Kaler (1982) compilation. They have been chosen as mentioned above to make the "spectra" featureless, especially no maximum or minimum should appear in the 2200 Å band. The entries of Table 2 show the calculated intrinsic colours together with their errors.

It is interesting to derive an "average" relation between spectral type and intrinsic UV colour. We produced such relations using the entries of our Table 2. We smoothed our results by fitting average relations to the determined points. (The latter method has been applied to some extent by Wesselius et al. 1980).

We have tried to relate effective temperatures to the MK spectral classes. We have applied the relation between $B-V$ colours and effective temperatures given by Böhm-Vitense (1981). The average relation between colour and temperature is given in Table 2. Table 2 gives the mean colour indices of OB stars also for classes for which we do not have direct determinations; the latter are derived by interpolating direct measurements. Such colours are given in Table 2 without standard errors.

A comparison of quasi-continua characterizing stars of the same spectral type but with different luminosity classes proves that spectral gradients get less steep when going from dwarfs to supergiants (Fig. 3). These differences together with those between different spectral types of the same luminosity class confirm the reliability of our determinations.

4. Conclusions

The present paper gives a coherent system of intrinsic UV colour indices determined by using big samples of stars of the same spectral type and luminosity class. The final choice is based on the purely empirical criterion: the ironing out of the 2200 Å bump from the mean spectra of given Sp/L.

It is interesting to compare the present determinations of intrinsic colours with those of other authors. It may be done using Tables 1 and 2. The advantage of the new system of intrinsic colours is that it is based on statistically meaningful samples which reduces the errors of final determinations.

Some of our quasi-continua are compared to the intrinsic spectra determined by PWK in Fig. 4. The coincidence is quite satisfactory. We may conclude that spectral gradients derived from spectral and photometric data are identical. This fact is of basic importance as it emphasizes the reliability of the basic stellar data determined in this paper.

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