A STUDY OF MAIN SEQUENCE EARLY TYPE STARS

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ABSTRACT

A spectroscopic and photometric study of 75 normal main sequence B2-B6 stars has been carried out. From the spectra (12 Å/mm, 3700-4800 Å) are determined: equivalent widths of all measurable lines, line profiles of hydrogen lines and $v \sin i$. The photometric work includes besides uvby and R photometry, also photoelectrically determined line strengths of H_γ and He I 4471 Å. Some preliminary results concerning the relation between the MK types and the atmospheric fundamental parameters (T_{eff} , $\log g$) of the stars are briefly discussed.

Three methods are available for estimating the physical properties of a star: spectrophotometry, direct photoelectric photometry and classification by visual inspection of the spectrum. It is well known that a two-dimensional classification scheme is sufficient for classifying all normal early type stars and that these stars can be characterized adequately by two photometric indices. The reason is the also well known fact that two atmospheric parameters - the effective temperature T_{eff} and the surface gravity g - dominate over all other parameters such as difference in chemical composition, axial rotation, turbulent velocity and magnetic field. The predominant influence of the two parameters also implies that the stellar spectra are highly redundant: the appearance of different spectral lines or regions are strongly correlated to each other as the spectral features mainly carry the same information.

The presence of other parameters and the complexity of the physics involved in the stellar atmosphere give good reasons, however, to suspect that there can be no unique relation between for

example the photoelectric indices in the uvby and ϕ system on the one hand and the MK classes on the other hand. Neither is it to be expected that spectral lines formed in different parts of the stellar atmosphere such as strong lines and faint lines will show a one to one correspondence to the photoelectric indices or the MK type.

The aim of the present work is to look into these problems for a rather restricted and homogeneous group of stars, the main sequence B2-B6 stars which are of great importance both from the point of view of the study of stellar age and distance. Normal B2-B6 stars in the Bright Star Catalogue with $V \leq 6^m$ not classified as supergiants were selected for the investigation. Stars marked as variables, stars with companions closer than $d = 15''$ and/or $\Delta m \leq 4^m$, and stars with variable radial velocity were excluded. The Be stars are included as the e - characteristics have not been considered as abnormal.

The resulting 75 stars within the coordinate limits $6^h 54^m \leq 18^h$, $\delta < -10^\circ$ were observed at ESO, La Silla, in February and March, 1972 with the coude spectrograph of the 152 cm telescope and with the Roden photometer on the ESO 50 cm telescope. The spectrographic material which will be discussed in Astronomy and Astrophysics consists of two 12 Å/mm spectra of each star in the wavelength region 3700-4800 Å and has been used to determine the equivalent widths of all measurable lines and line profiles of strong lines.

The photometric observations consist of Stromgren four color and ϕ indices and indices for the line strengths of H_γ and He 4471. Almost all program stars already had well determined uvby and ϕ indices but since more than 20% of the program stars are Be or suspected Be stars new measurements were made for all stars in the program for checking variability. The reductions were made as recommended by Crawford and Barnes (1970) and Crawford and Mander (1965). The corrections for interstellar reddening were determined using the relations given by Crawford (1975). Comparison with stars in common with Crawford et al. (1970, 1971) omitting all Be stars shows that the mean errors are ± 0.009 in ϕ , ± 0.007 in u-b, ± 0.011 in b-y and ± 0.011 in c_1 . Further details will be published in Astronomy and Astrophysics.

One specific problem will be touched upon in the following: the relation between the MK classes and the fundamental parameters T_{eff} and g . Data for the program stars - the Be stars and a few peculiar stars omitted - are given in Table I where the MK classes are from Hiltner et al. (1969) or Lesh (1968), and data for MK standard stars is contained in Table II. The parameters $\Theta_{\text{eff}} =$

TABLE I
PROGRAM STARS

HD	Spectral Type	(u-b) ₀	β	Θ_{eff}	log g
41814	B3 V	0.305	2.682	0.289	4.09
42927	B3 III	.278	2.664	.283	3.97
51283	B2 III	.130	2.589	.257	3.39
52092	B3 V	.385	2.680	.311	3.89
56342	B3 V	.387	2.679	.312	3.88
57219	B2 IV	.224	2.666	.268	4.12
58286	B2 V	.311	2.649	.294	3.73
61068	B2 III	-.004	2.615	.213	4.10
61831	B2.5 V	.333	2.670	.298	3.90
63465	B2.5 III	.303	2.636	.293	3.61
64740	B1.5 Vp	-.018	2.622	.209	4.23
64802	B2 V	.250	2.658	.276	3.97
65575	B3 IVp	.351	2.659	.304	3.75
65904	B4 V	.386	2.682	.311	3.91
66591	B3 V	.354	2.676	.303	3.92
68217	B2 IV-V	.228	2.638	.272	3.80
69081	B1.5 IV	.032	2.617	.221	4.04
71459	B3 V	.409	2.674	.318	3.78
71510	B2 V	.307	2.666	.291	3.92
74071	B5 V	.487	2.705	.336	3.93
75575	B1.5 III	-.024	2.603	.209	3.99
76538	B5 III	.448	2.649	.333	3.44
77002	B2 IV-V	.223	2.658	.269	4.03
79447	B3 III	.321	2.658	.296	3.80
79735	B4 V	.463	2.677	.332	3.71
86406	B3 IV	.409	2.648	.321	3.52
92938	B4 IV	.444	2.697	.325	3.94
93194	B4 IVn	.406	2.665	.318	3.70
93607	B3 V	.321	2.674	.294	3.97
93845	B2.5 IV	.270	2.677	.280	4.12
98695	B4 V	.391	2.692	.311	4.00
99556	B3 IV	.409	2.634	.324	3.36
100929	B2.5 IV	.326	2.637	.300	3.56
106490	B2 IV	-.001	2.626	.212	4.24
106911	B5 Vn	.525	2.704	.346	3.85
106983	B2.5 V	.270	2.679	.279	4.15
108483	B2 V	.131	2.659	.243	4.29
112078	B4 Vn	.395	2.679	.313	3.87
112092	B2 IV-V	.167	2.655	.253	4.15
113703	B5 V	.432	2.708	.321	4.07
120908	B5 III	.555	2.680	.356	3.57
122980	B2 V	.158	2.657	.251	4.19
125238	B2.5 IV	.246	2.651	.275	3.90
126341	B2 IV	.070	2.620	.232	3.96
128345	B5 V	.437	2.705	.322	4.04
132955	B3 V	.373	2.703	.305	4.16
136298	B1.5 IV	.013	2.616	.216	4.08
136664	B4 V	.345	2.690	.298	4.09
142184	B2.5 V	.293	2.657	.289	3.85
142669	B2 IV-V	.102	2.642	.237	4.16
142883	B3 V	.425	2.713	.320	4.12
142919	B5 IV	.486	2.643	.344	3.31
144294	B2.5 Vn	.237	2.661	.271	4.04
150745	B2 IV-V	.243	2.630	.278	3.66

$\frac{5040}{T_{\text{eff}}}$ and $\log g$ have been derived from the uvby and Q photometry as follows:

1.) The relation

$$\theta_{\text{eff}} = 0.218 + 0.227 (u-b)_0 \quad (1)$$

was derived from the six stars (Table III) within the spectral class range B1-B7 with empirically determined effective temperatures by Code *et al.* (1976) and with uvby indices in the catalogue by Lindemann and Hauck (1973).

2.) From the measurements of the equivalent widths of H_γ and H_δ and from the Q indices of the program stars the relation

$$W_{\gamma\delta}(20) = -73.5 + 29.9Q \quad (2)$$

was found, where $W_{\gamma\delta}(20)$ means the arithmetic mean value of the equivalent widths of H_γ and H_δ within the wavelength limits $\pm 20 \text{ \AA}$ from the line centers. The same quantity, $W_{\gamma\delta}(20)$, was also computed from the grid of models given by Kurucz, Peytremann and Avrett (1974) - in the following called the KPA model - and used with θ_{eff} from relation (1) for obtaining $\log g$.

3.) These $\log g$ values were then used with $(u-b)_0$ to obtain θ_{eff} from the models computed by Relyea and Kurucz (1978). The new values are slightly dependent on the gravity [an approximate relation for the spectral classes in question is $\theta_{\text{eff}} = 0.213 + 0.250(u-b)_0 - 0.014 (\log g - 4.00)$] but still in close agreement with the empirically derived effective temperatures as seen in Table III.

4.) Finally the new θ_{eff} values were used to derive the tabulated $\log g$ from the KPA model. The final $\log g$ values differ from those first derived by less than 0.10.

In order to estimate the internal accuracy of the parameters just obtained the mean error in each of the indices $(u-b)$, $(b-y)$ and Q has been assumed to be ± 0.010 . The corresponding mean error in θ_{eff} is ± 0.007 and in $\log g$ ± 0.12 .

As the importance of the line wings has been suppressed in the present method in calculating the surface gravity, the $\log g$ values have been checked for the program stars by measuring also the H_δ and H_γ line widths at 80% and 90% of the continuum intensity and comparing the widths with the theoretical profiles in the KPA

model. The mean difference, $\Delta \log g$, between the two methods is 0.04 ± 0.17 as computed for all program stars in Table I. No significant systematic effects in $\Delta \log g$ could be detected for different $\log g$ or θ_{eff} .

The standard stars in Table II are plotted in a θ_{eff} , $\log g$ diagram (Fig. 1). Large symbols indicate the primary standards in the MK system, the smaller ones other standards used by Lesh (1968) and by Hiltner et al. (1969). The straight lines separating spectral and luminosity classes are eye estimates of the best fit to the symbols with special regard to the primary standards. The lines separating the spectral classes are rather uncertain, of course, on account of the few stars in each class. The dashed lines connect points derived from the uvby and β indices given by Crawford (1978) for the zero age main sequence and from the average indices given by him for the MK types considered.

Some interesting points derived from the MK standard stars and from Crawford's average indices will be mentioned here.

1. There is a very good agreement between the MK classes and the values of θ_{eff} and $\log g$ for the primary standards.
2. The agreement is also good for the other standards, with a few exceptions such as HD 32612 and HD 197511.
3. The average parameters for luminosity class V fall mainly in the region for luminosity class IV of the standard stars.
4. The average parameters for luminosity class III are generally displaced from the class III standards towards the region for luminosity class IV of the standard stars.

The difference between the $\log g$ values for the average MK luminosity classes III and V is thus smaller than the corresponding difference for the MK standard stars. This is also apparent in the case of the program stars. The difference between the $\log g$ values for the program stars of luminosity classes III and V is 0.25 on an average while the corresponding mean difference for the MK standard stars is 0.50.

A reclassification of the program stars according to Fig. 1 results in changes of luminosity and spectral classes as shown in Table IV, where positive ΔS means a change to a later spectral class and positive ΔL to a higher luminosity class. As seen from Table IV there is a strong correlation between changes in spectral and luminosity classes in such a way that a change to a lower

TABLE II
STANDARD STARS

(Spectral types underlined are primary standards)

HD	Spectral Type	$(u-b)_0$	β	Θ_{eff}	$\log g$
886	B2 IV	0.092	2.629	0.235	4.04
3360	<u>B2 IV</u>	.106	2.625	.239	3.95
4727	B5 V	.478	2.710	.331	4.01
16582	B2 IV	.060	2.624	.227	4.06
22928	B5 III	.574	2.671	.359	3.47
23302	B6 III	.727	2.690	.395	3.40
23338	B6 IV	.638	2.703	.372	3.66
30836	B2 III	.081	2.606	.236	3.76
32612	B2.5 IV	.181	2.665	.254	4.24
32630	B3 V	.355	2.684	.300	4.02
34503	<u>B5 III</u>	.680	2.687	.385	3.44
34759	B5 V	.471	2.722	.329	4.13
35468	B2 III	.057	2.614	.227	3.94
36779	<u>B2.5 V</u>	.112	2.644	.238	4.17
37711	B3 IV	.327	2.672	.293	3.96
90994	B6 V	.558	2.730	.350	4.04
120315	B3 V	.336	2.694	.293	4.18
147394	<u>B5 IV</u>	.447	2.702	.330	3.95
148605	B2 V	.197	2.662	.259	4.16
175191	<u>B2.5 V</u>	.221	2.667	.265	4.16
176502	B4 IV	.337	2.667	.296	3.89
178329	B3 V	.356	2.690	.300	4.08
197511	B2 V	.300	2.651	.288	3.80
207330	B2.5 III	.232	2.617	.275	3.55
215191	B1.5 V	.038	2.633	.221	4.23
216200	B4 III	.321	2.634	.298	3.55

TABLE III

STARS WITH EMPIRICALLY DETERMINED EFFECTIVE TEMPERATURES

HD	Spectral Type	$(u-b)_0$	β	Θ_{eff}	Θ_{emp}
35468	B2 III	0.057	2.614	0.229	0.234 $\pm$.009
87901	B7 V	.824	2.723	.411	.413 .010
116658	B1 V	-.051	2.607	.203	.211 .007
118716	B1 III	-.059	2.610	.199	.196 .009
193294	B2.5 V	.264	2.660	.277	.282 .011
209952	B7 IV	.665	2.727	.375	.359 .014

TABLE IV

CHANGES IN SPECTRAL CLASSIFICATION FOR PROGRAM STARS

ΔS	ΔL		
	-	0	+
+	1	5	4
0	3	14	5
-	15	7	0

Fig. 1. A θ_{eff} vs $\log g$ diagram for MK standard stars. Different symbols are used for the luminosity classes. Primary MK standards are marked with large symbols. Spectral types not in accordance with the empirically drawn grid are indicated. The broken lines connect the average positions (marked as crosses with the spectral class if deviating from the grid) for luminosity class III and V. They are based on the four color and θ indices given by Crawford (1978). The dashed dot line representing the zero age main sequence (ZAMS) is also derived from Crawford's data (1978).

luminosity class is generally coupled to a change to an earlier spectral type. The changes are thus in the direction of constant hydrogen line intensity.

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