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FIVE-COLOUR PHOTOMETRY OF HIGH-LATITUDE BLUE STARS

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Five-colour photometry on the Walraven system is given for 18 high-latitude blue stars listed by Luyten. A number of these stars are found to have peculiar colour indices when compared with those of normal main-sequence stars and it seems likely that measurements of this type may enable various types of high-latitude blue stars to be distinguished photometrically. In particular, the bluest stars of the sample show unusually blue $(V-B)$ colour indices and lie to the left of the unreddened main-sequence relation in a $(B-U)$, $(V-B)$ diagram. The $(B-L)$ indices of these stars seem to be affected by strong hydrogen or ionized helium line absorption. A second group of stars with colours appropriate to spectral type A is characterised by unusually large $(B-U)$ indices which probably are due to unusually large Balmer jumps in their energy distributions. Observations are now being made at Kitt Peak National Observatory using the Strömgren four-colour photometric system and these indicate that stars of the first group are mainly of the subdwarf O class while stars of the second group are similar to stars lying on or above the horizontal branch of a globular cluster colour-magnitude diagram.

1. Introduction

Faint blue stars that are found in high galactic latitudes form an inconspicuous but extremely interesting group of the galactic stellar population. All but a few of these objects are apparently fainter than 10th magnitude and detailed spectroscopic observations are not easily obtained. In recent years wide-band photometry on Johnson's U, B, V system has been published for a large number of these stars (e.g., IRIARTE, 1959; SLETTEBAK, BAHNER and STOCK, 1961; KLEMOLA, 1962; EGGEN and SANDAGE, 1965; GREENSTEIN, 1966; HILL and HILL, 1966). Generally it has been found that the observed $(U-B)$ and $(B-V)$ colour indices do not allow a distinction to be made between faint high-latitude blue stars and bright main-sequence stars, except for those of the white-dwarf class. IRIARTE (1959) found a few stars that appeared to have extremely blue $(B-V)$ colour indices, but these observations have not been confirmed by more recent work. As the author has pointed out (GRAHAM, 1966) this failure is probably due to the poor spectral resolution of the U, B, V photometric system, and it seems that more information can be obtained by using filters with narrow or intermediate passband widths.

One very useful system of intermediate-band photometry has been devised by WALRAVEN and WALRAVEN (1960). The effective wavelengths and band half-widths of this system are shown in table 1. The bands V and B correspond to the V and B bands of the U, B, V system, although the passband of the Walraven B is somewhat narrower. A band L, centred at $\lambda = 3900$ A, is strongly influenced by the strength of the Balmer hydrogen lines, Hϵ, Hζ, Hη, Hθ, and so is a sensitive indicator of surface gravity in stars of early spectral type. In the ultraviolet, two spectral bands, U and W, are measured. To avoid confusion in this paper between the two systems, all magnitudes and colour indices will be referred to by symbols subscripted with J when on the U, B, V system.

TABLE 1

Transmission characteristics of the five-colour system

Band	Effective wavelength (A)	Passband half-width (A)
V	5450	850
B	4295	420
L	3900	300
U	3670	260
W	3270	150

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2. The observations

While the author was stationed in South Africa during 1964, Dr. P. W. Hill suggested that five-colour observations might provide further information about some high-latitude blue stars that had been studied already at Radcliffe Observatory. This Radcliffe work has recently been published by HILL and HILL (1966). The stars on their program were selected from the lists published by LUYTEN (1958, 1959, 1962) who also kindly provided finding charts for use at the telescope. A selection was made of 18 stars which had the bluest $(B-V)$ colours according to Hill and Hill's photometry and these were reobserved with the Walraven photometer attached to the 36-inch reflecting telescope at the Leiden Southern Station, Hartebeestpoortdam, South Africa. The photometer and the photometric system have been described by WALRAVEN and WALRAVEN (1960) and by WALRAVEN, TINBERGEN and WALRAVEN (1964). The standard stars were those given in the latter paper, together with some for which the standard values have not yet been published. Each observation consisted of four one-minute integrations for the star followed by two one-minute integrations for the sky. Unfortunately, most of the program stars could be observed only once in this manner, although it was possible to observe five of the stars on two different nights. The reduction procedure followed the general method outlined by Walraven, Tinbergen and Walraven. On each night of observation, at least two of the bright Walraven standard stars were observed at $1\frac{1}{2}$-hour intervals. Extinction coefficients were determined for the V-band intensity and for the colours $(V-B)$, $(B-L)$, $(B-U)$ and $(U-W)$ by observing two or more standard stars at different zenith distances during the course of each observing night. Most of the numerical work associated with the reductions was carried out with the XI computer of the Leiden University. Following Walraven, the colours $(V-B)$, $(B-L)$, $(B-U)$ and $(U-W)$ were not expressed in magnitudes but as positive logarithms (to the base 10) of the intensity ratios V/B, B/L, B/U and U/W respectively. The visual light-intensity, however, was expressed in magnitudes by using the transformation V (mag) $= 6.88-2.5$ [$\log_{10} I_v+0.08$ $(V-B)$], where $\log_{10} I_v$ is the logarithm of the intensity of the star's visual light. This transformation, which was kindly communicated by Dr. Walraven, is a slight improvement of the one published by WALRAVEN, TINBERGEN and WALRAVEN (1964). These relations have been derived from the observations of a number of bright field stars and give visual magnitudes which agree closely with those measured by the Cape observers on the V_J system.

Since the Walraven standard stars are all brighter than sixth magnitude, it was not possible to use the same condensers in the integrating circuits for these stars and for the much fainter high-latitude blue stars. Although measurements were made of the relative values of all three condenser capacities and of the half-magnitude attenuator resistances, the subsequent analysis of a large number of observations has revealed a zero-point error in the visual magnitudes of the faint stars that were measured with the condenser of lowest capacity in the integrating circuit. This is evident in table 2, which lists five-colour and U, B, V photometry for a number of stars that have been well observed in both systems. With one exception, these stars are almost certainly normal main-sequence stars as distinct from the high-latitude blue stars which are the subject of this paper. The star Van Wijk 19 has the colours of a blue supergiant star and is very probably a member of the Large Magellanic Cloud.

In table 2, the first column gives the star identification. This is an HD number for the bright stars, but, for those fainter than 7th magnitude, an identification is made from references 2 and 3 at the foot of the table. Columns 2 to 6 list the visual magnitude, V, and the four colours $(V-B)$, $(B-L)$, $(B-U)$, $(U-W)$. Column 7 gives the nominal condenser value used for the integration. An asterisk in this column indicates that the neutral incident beam attenuator described by WALRAVEN and WALRAVEN (1960), was used for the observation. Columns 8 to 10 list the published V_J, $(B-V)_J$, $(U-B)_J$ values, while in the last column reference is made to the sources of the U, B, V data.

Table 2 shows that for 11 stars ranging between 3rd and 8th magnitudes, the visual magnitudes agree well with the published values measured on the U, B, V system. Any systematic difference is less than $0^m.01$. For the fainter stars that were measured with the 0.001 condenser, a significant systematic difference is found between the V magnitudes measured on the two systems. For eight such stars, the mean difference $V-V_J =$

TABLE 2

Comparison between five-colour photometry and U, B, V photometry with different integrating condensers

Star	Five-colour data V	$(V-B)$	$(B-L)$	$(B-U)$	$(U-W)$	Condenser	U, B, V data V_J	$(B-V)_J$	$(U-B)_J$	Source
74575	3.67	−0.052	−0.025	−0.014	−0.020	0.1*	3.70	−0.18	−0.87	1
122980	4.36	−0.063	+0.004	+0.035	−0.017	0.1*	4.35	−0.19	−0.76	1
144470	3.95	+0.003	+0.004	+0.007	+0.004	0.1*	3.94	−0.03	−0.81	1
3719	6.86	+0.048	+0.190	+0.450	+0.120	0.01	6.84	+0.11	+0.11	1
36512	4.61	−0.088	−0.047	−0.091	−0.045	0.01*	4.61	−0.27	−1.05	1
39844	5.10	−0.052	+0.044	+0.178	+0.019	0.01*	5.10	−0.15	−0.47	1
SA 193/2509	8.36	+0.061	+0.018	+0.028	+0.025	0.01	8.38	+0.21	−0.75	2
2622	7.89	+0.014	+0.130	+0.418	+0.107	0.01	7.93	+0.04	−0.03	2
111990	6.77	+0.110	+0.032	+0.087	+0.066	0.01	6.78	+0.26		1
163955	4.74	−0.004	+0.124	+0.421	+0.119	0.01*	4.76	−0.04	−0.07	1
Van Wijk 1	10.23	+0.082	+0.208	+0.439	+0.127	0.001	10.24	+0.22	+0.02	2
19	12.09	+0.016	−0.029	−0.048	−0.019	0.001	12.04	−0.02	−0.90	2
SA 141/21	9.11	+0.121	+0.093	+0.386	+0.145	0.001	9.04	+0.31	+0.01	2
139	9.34	+0.157	+0.196	+0.361	+0.166	0.001	9.28	+0.38	+0.01	2
SA 158/667	10.34	+0.103	+0.216	+0.499	+0.173	0.001	10.31	+0.25	+0.03	2
1231	11.17	+0.068	+0.161	+0.456	+0.143	0.001	11.12	+0.17	−0.01	2
Roslund 122	11.06	+0.119	+0.080	+0.150	+0.060	0.001	11.00	+0.30	−0.44	3
123	10.27	+0.015	+0.063	+0.157	+0.040	0.001	10.22	+0.03	−0.48	3

1. A. W. J. COUSINS and R. H. STOY, 1963, *Roy. Obs. Bull.* No. 64
2. B. J. BOK and P. F. BOK, 1960, *Mon. Not. Roy. Astr. Soc.* **121** 531
3. C. ROSLUND, 1964, *Medd. Lunds Astr. Obs.* Ser-I No. 207

$= +0^m.045$, with a standard deviation per star of $0^m.026$. This difference seems certainly real and evidently is associated with the use of the 0.001 condenser. It is necessary, therefore, to apply a correction of $-0^m.04$ to all magnitudes determined with the 0.001 condenser if the V magnitudes are to correspond to the V magnitudes of the U, B, V system. The cause of this systematic disagreement is obscure. Since the observations were made, the equipment has been dismantled and, although it is now in operation again, it is not possible to reproduce the original observing conditions. One possible explanation is a leakage across the 0.001 condenser, which was not appreciable when the higher-capacity condensers were used.

In view of this discrepancy, it is important to make sure that a similar error is not present in the colour indices. A check can be made for two of these, $(V-B)$ and $(B-U)$, by comparing them with the analagous

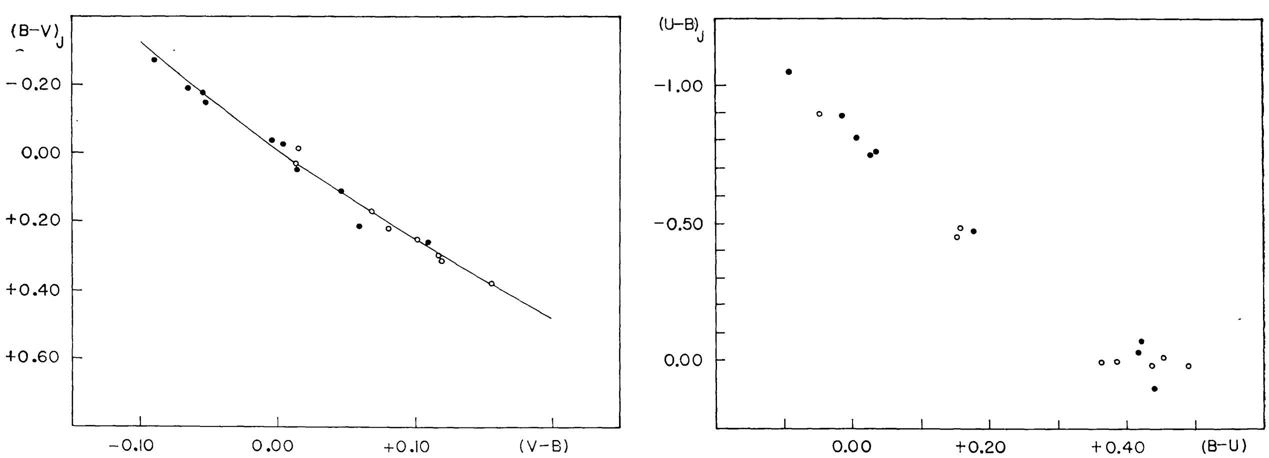

Figure 1. Comparison between colour indices $(V-B)$ and $(B-V)_J$ and between $(B-U)$ and $(U-B)_J$. The bright standard stars are denoted by dots and the faint standard stars by open circles.

colours, $(B-V)_J$ and $(U-B)_J$, of the U, B, V system for the stars listed in table 2. Unfortunately, a similar check cannot be made for the $(B-L)$ and $(U-W)$ colour indices since there are no corresponding colours in the U, B, V system. Even for the V, B, and U transmission bands, the effective wavelengths and bandwidths differ considerably and non-linear and even multi-valued relations between analagous colour indices are to be expected. In the left-hand part of figure 1, a comparison is made between $(V-B)$ and $(B-V)_J$ and in the right-hand part between $(B-U)$ and $(U-B)_J$. The faint 10th to 12th magnitude stars that were measured with the 0.001 condenser are represented by open circles, while the brighter stars are represented by dots. In addition, the "field star" relation found by Walraven, Tinbergen and Walraven is drawn in the left-hand part of the figure. It is clear that the bright and faint stars of table 2 satisfy the same relations in the figure. Any systematic errors depending on apparent magnitude or integrating condenser are small and well within the observational uncertainties. The apparently large scatter near $(B-U) = 0.450$ is due to the complex, multivalued relation between the two photometric indices near spectral type A0.

TABLE 3

Five-colour photometry of high-latitude blue stars

Star	V	$(V-B)$	$(B-L)$	$(B-U)$	$(U-W)$	Spectral type
LB 1502	12.98	−0.019	+0.074	+0.293	+0.066	A
	13.01	−0.039	+0.081	+0.287	+0.048	
	12.99	−0.029	+0.077	+0.290	+0.057	
1514	12.97	−0.003	+0.152	+0.484	−0.040	
1516	12.98	−0.102	+0.006	−0.035	−0.067	(B)–A*
	12.94	−0.082	−0.016	−0.050	−0.047	
	12.96	−0.092	−0.005	−0.042	−0.057	
1521	12.51	−0.010	+0.124	+0.419	+0.107	
1526	13.48	−0.118	−0.058	−0.142	−0.082	? DA wk
	13.49	−0.116	−0.067	−0.147	−0.073	
	13.48	−0.117	−0.062	−0.144	−0.078	
1529	12.93	+0.031	+0.166	+0.502	+0.168	
3126	11.98	+0.016	+0.139	+0.452	+0.105	
1538	12.19	+0.021	+0.172	+0.497	+0.128	
1559	12.42	−0.089	+0.003	−0.024	−0.043	B8:
	12.40	−0.078	−0.008	−0.025	−0.044	
	12.41	−0.084	+0.002	−0.024	−0.043	
1566	13.15	−0.114	−0.074	−0.156	−0.086	O8:
	13.12	−0.102	−0.089	−0.168	−0.039	
	13.13	−0.108	−0.081	−0.162	−0.062	
3186	11.19	−0.021	+0.098	+0.303	+0.038	B9:
3193	12.71	−0.045	+0.000	+0.122	−0.048	
3241	12.78	−0.109	−0.057	−0.123	−0.082	
3303	11.35	+0.016	+0.077	+0.046	−0.014	DA
1662	13.24	−0.055	+0.033	+0.113	+0.036	
1735	13.64	−0.059	+0.031	+0.145	−0.060	
1776	12.05	−0.035	+0.117	+0.345	+0.025	
L133–B6	11.18	−0.072	−0.018	−0.003	−0.032	

* Dr. Thackeray kindly communicated privately a revised spectral classification for LB 1516. He suspects that the spectrum may be variable.

Table 3 contains the results of the five-colour photometry for the high-latitude blue stars. The individual observations as well as the adopted average values are listed for the five stars that were observed twice. From these repeated observations, one can form an estimate of the accuracy of the single observations. It is certain that the precision of the five-colour data could have been improved if it had been possible to make more observations. Table 3 is arranged in seven columns as follows:

1. Luyten blue star number.
2. Visual magnitude from five-colour photometry (the correction of $-0^m.04$ discussed above has been applied).
3, 4, 5, 6. The colours $(V-B)$, $(B-L)$, $(B-U)$ and $(U-W)$ expressed as logarithms to the base 10 of the relevant intensity ratio.
7. The spectral type assigned by Thackeray and listed by Hill and Hill.

A comparison can be made between the visual magnitudes given in table 3 and those measured by Hill and Hill for the same stars. The mean systematic difference $V_{\text{Graham}} - V_{\text{Hill and Hill}}$ is $-0^m.001$ with a mean standard deviation of each difference of $0^m.047$. If one considers the accuracy of the present measurements and that quoted by Hill and Hill, the agreement between the two sets of visual magnitudes is certainly satisfactory. The values listed in table 3 for the star LB 1662 are somewhat unreliable since the one observation for this star was carried out just before deteriorating sky conditions terminated observations for the night.

3. Anomalous colour indices for some high-latitude blue stars

Some interesting results are found when the values in table 3 are plotted in two-colour diagrams. In figures 2 and 3, the $(B-U)$ and $(B-L)$ colour indices are plotted against $(V-B)$. In each diagram a curve is drawn which represents the mean relation for unreddened main-sequence stars. These curves have been determined by Dr. Th. Walraven from a large number of observations of bright, nearby, early-type stars. Dr. Walraven very generously made these results available prior to their publication. A number of points representing bright, little reddened main-sequence stars of spectral types B and A are also plotted. All these stars are a) 6th magnitude or brighter; b) at least 15° from the galactic plane, so that interstellar reddening is small.

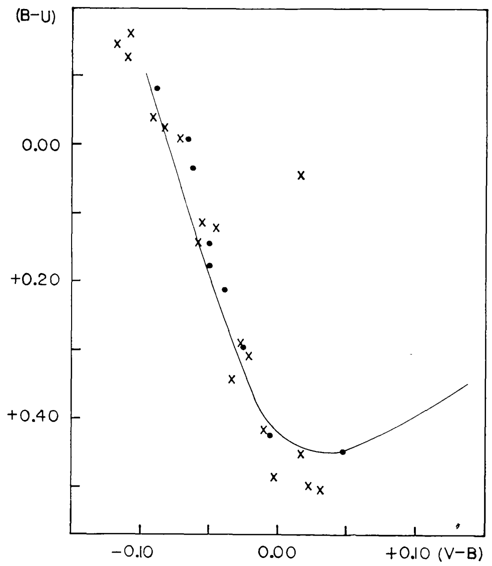

Figure 2. $(B-U)$ plotted against $(V-B)$ for the high-latitude blue stars (crosses) and for some bright, little reddened main-sequence stars (dots). The unreddened main-sequence relation derived by Walraven is drawn in.

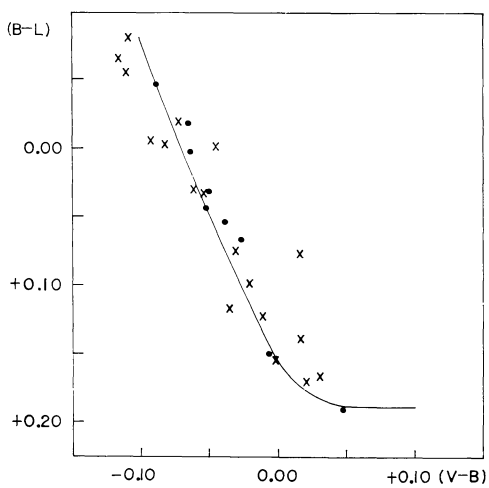

Figure 3. $(B-L)$ plotted against $(V-B)$ for the high-latitude blue stars (crosses) and for some bright, little reddened main-sequence stars (dots). The unreddened main-sequence relation derived by Walraven is drawn in.

Figures 2 and 3 illustrate some differences between the distribution of points representing the faint, high-latitude blue stars and those representing the bright main-sequence stars. In figure 2, the bluest stars of the high-latitude sample lie noticeably to the left of the unreddened main-sequence relation and the bright main-sequence stars. A second feature is that the high-latitude stars with $(V-B)$ close to zero have $(B-U)$ indices up to 0.050 units ($0^m.12$) greater than the corresponding bright main-sequence stars. It is instructive to compare figure 2 with the analogous diagram of the U, B, V system. Figure 4 has been constructed with the same notation as figure 2 by using the U, B, V data of Hill and Hill for the faint high-latitude blue stars and data from the Cape compilation (Cousins and Stoy, 1963) for the bright main-sequence stars that are plotted in figure 2. For one bright star, HD 104337, U, B, V photometry does not seem to be available. The unreddened main-sequence relation according to Eggen (1963, 1965) is drawn in. Significantly, no separation of the two groups of stars can be seen even though the same stars are represented in both figure 2 and figure 4.

Figure 3 is a plot of $(B-L)$ against $(V-B)$. The colour $(B-L)$ is sensitive to the amount of hydrogen line absorption near 3900 A and is useful as an indicator of surface gravity for early-type stars. On this

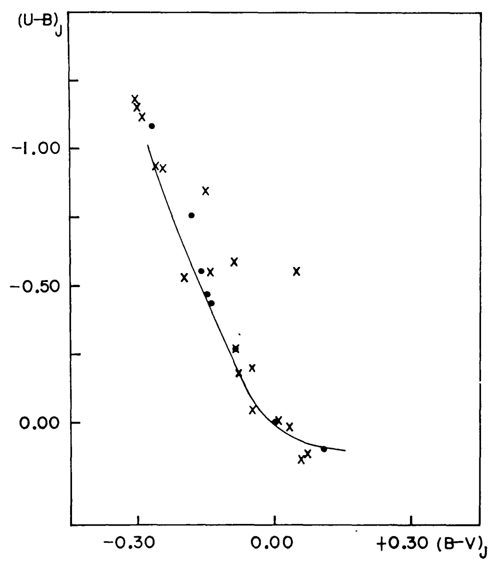

Figure 4. $(U-B)_J$ is plotted against $(B-V)_J$ for the high-latitude blue stars (crosses) and for the same bright, little reddened main-sequence stars (dots) as in figures 2 and 3. Eggen's unreddened main-sequence relation is drawn in.

diagram, the five bluest stars lie to the left of the main-sequence relation, thus suggesting that these stars have somewhat stronger hydrogen lines than normal for stars with their $(V-B)$ colours. In all three figures, the unusual position of the point representing the star LB 3303 should be noted. This star is a known white dwarf of spectral class DA (THACKERAY, 1961). Thackeray's more recent spectral classifications, which are given in table 3, suggest that the very blue star LB 1566 is a subdwarf O star, while LB 1526 may be a very hot, weak-lined white dwarf.

WALRAVEN and WALRAVEN (1960) have shown that the colour index $(U-W)$ can be used in conjunction with $(B-U)$ to classify normal B-type stars according to temperature and luminosity. In figure 5 these two

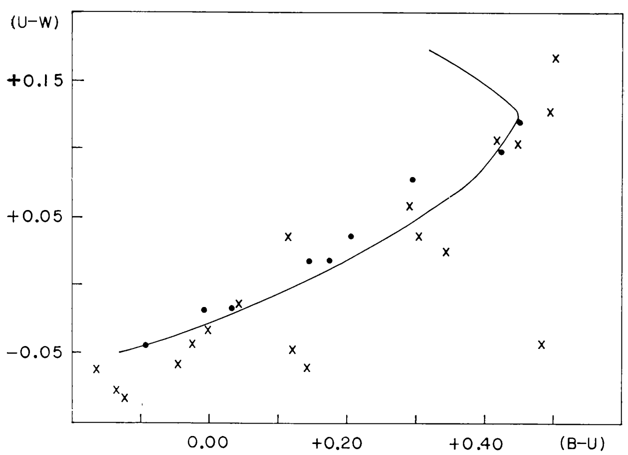

Figure 5. $(U-W)$ is plotted against $(B-U)$ for the high-latitude blue stars (crosses) and for some bright, little reddened main-sequence stars (dots). The unreddened main-sequence relation derived by Walraven is drawn in.

colours are plotted against one another for the same stars, with the same notation as in figures 2 and 3. The points representing the high-latitude blue stars in this diagram tend to lie below those representing the bright main-sequence stars and the unreddened main-sequence relation. An inspection of figure 8 in the paper of WALRAVEN and WALRAVEN (1960), which is a nearly similar diagram of $(U-W)$ versus $(B-U)$ showing the relation of various luminosity classes, suggests that these stars lie on what might be termed a subdwarf sequence. One star, LB 1514, has unusually strong radiation in the far ultraviolet according to the one observation. If this should be confirmed then LB 1514 might prove to be a very interesting object.

One naturally suspects that the source of these unusual photometric characteristics of high-latitude blue stars may be systematic errors in the observations. However, the comparison that has already been made in figure 1 shows that this is unlikely for the colours $(V-B)$ and $(B-U)$ at least. It does not seem possible to attribute these effects to the neglect of either interstellar reddening corrections or errors in the unreddened main-sequence relations. Independently of these, the relative positions of the points in figures 2 and 4 should be similar, whereas a comparison shows that this is certainly not the case.

Figure 6 is a plot of $(B-V)_J$ against $(V-B)$ for the high-latitude blue stars and the same bright main-sequence stars as in figures 2 to 5. As in figure 1, the "field star" relation given by Walraven, Tinbergen and Walraven is drawn. The displacement of the bluest high-latitude stars to the left of the normal relation is very marked. A rough computation indicates that no more than a small part of this can be attributed to the influence of high-order Balmer lines on the Johnson B colour, even when allowance is made for the considerable line broadening often found in very blue stars below the main sequence. The extreme cases have $(V-B)$ indices that correspond to a $(B-V)_J$ of nearly $-0^m.40$, according to the normal relation, and it is not surprising that these stars are displaced to the left of unreddened main-sequence relations in colour-colour diagrams.

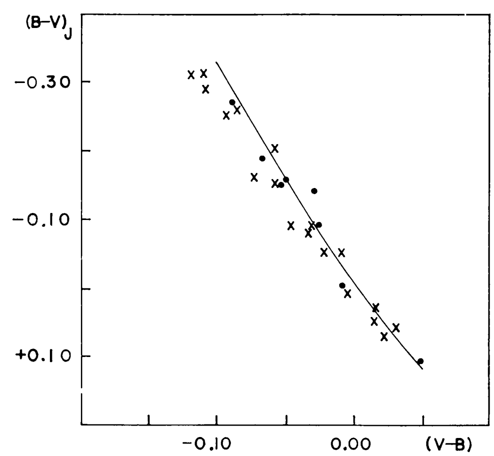

Figure 6. Comparison between the colour indices $(B-V)_J$ and $(V-B)$ for the high-latitude blue stars (crosses) and some bright, main-sequence stars (dots). The mean relation that was found by Walraven, Tinbergen and Walraven to be applicable for field stars, is drawn in.

4. Preliminary results of four-colour (*u*, *v*, *b*, *y*) photometry of other high-latitude blue stars

If the photometric peculiarities noted above are a characteristic of the high-latitude blue stars, one would expect similar results when other intermediate-band systems are employed. At present, the author is engaged in a study of similar objects in the northern hemisphere, with the intermediate-band four-colour system developed by STRÖMGREN (1963) and by CRAWFORD (1966). Special attention is being paid to objects whose spectra have been studied in some detail. Only preliminary results are available at present, but these completely confirm the photometric characteristics found with the Walraven five-colour system. The diagrams in figure 7 are analogous to those in figures 2 and 4, but refer, of course, to a different sample of stars. In the left-hand part of figure 7, the $(u-b)$ index is plotted against the $(b-y)$ index for some high-latitude blue stars and also for some little reddened main-sequence stars. The unreddened main-sequence relation is an estimate by the author. The *U*, *B*, *V* data for the same stars (mostly from IRIARTE *et al.*, 1965; COUSINS and STOY, 1963; KLEMOLA, 1962; EGGEN and SANDAGE, 1965) are plotted in the right-hand part of figure 7 together with the unreddened main-sequence relation tabulated by EGGEN (1963, 1965). In the plot of $(u-b)$ against $(b-y)$ in figure 7, the two bluest stars are found to lie considerably to the left of the main-sequence relation. These stars, Feige 66 and H.Z. 44 are known subdwarf O stars (GREENSTEIN, 1966). Hß line-intensity measurements with interference filters indicate Hß equivalent widths of 3 to 5 ångströms, which are strong for stars of this colour. For stars as hot as these, some of this absorption may be due to ionized helium. Again, the stars near spectral type A0 have $(u-b)$ indices greater than the corresponding main-sequence stars. Two of these, HD 109995 and HD 161817, have been studied by WALLERSTEIN and HUNZIKER (1964) and by KODIARA (1964). Both have high velocities and marked metal deficiencies and, according to OKE, GREENSTEIN and GUNN (1966) are probably similar to those stars found on the horizontal branch of globular cluster colour-magnitude diagrams. It is notable that there is no indication in the *U*, *B*, *V* plot in figure 7 that these stars are at all peculiar.

5. Conclusion

It seems that intermediate-band photometric systems such as those devised by Walraven and Walraven and by Strömgren may prove more useful than wide-band

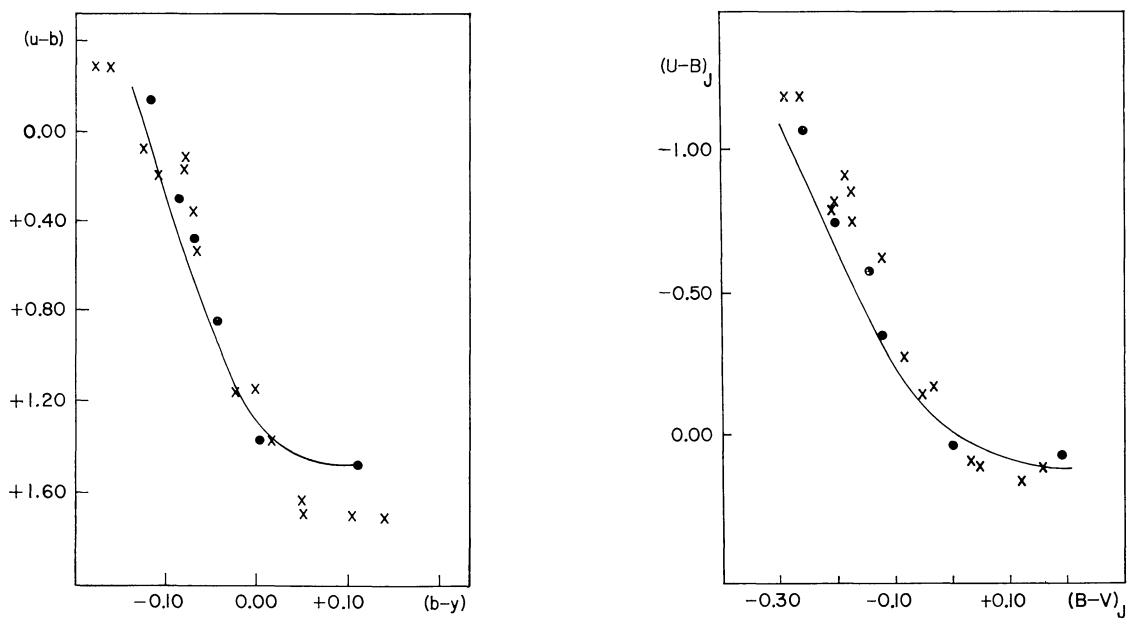

Figure 7. Four-colour and *U*, *B*, *V* photometric results for some high-latitude blue stars. These diagrams are analogous to figures 2 and 4.

U, *B*, *V* photometry in distinguishing between the various types of high-latitude blue stars. From five-colour photometry on the Walraven system of 18 faint blue stars from Luyten's lists, two groups of stars with unusual colours can be discerned. One group has exceptionally blue (blue-yellow) colour indices and the other unusually large (blue-ultraviolet) indices which are probably indicative of large Balmer discontinuities in their energy distributions. The first group seems to contain subdwarf O stars and possibly hot, weak-lined white dwarfs. The second group is probably made up of stars similar to those found on the horizontal branch of globular cluster colour-magnitude diagrams. This interpretation is supported by the work of Oosterhoff and Walraven (1966) who found very similar effects in their five-colour photometry of some RR Lyrae and short-period variable stars. As Philip (1966) has shown, stars of this second group may well be quite common at these magnitudes in the direction of the galactic poles.

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