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ASTRONOMY AND ASTROPHYSICS

Research Note

VBLUW photometry of solar-type stars*

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Summary. *VBLUW* photometric observations of 35 solar-type stars are presented and discussed in terms of abundance, T_{eff} and gravity ($\log g$). Using the empirical transformation between the *VBLUW* and *UBV* systems, for four stars being very similar to the Sun we derive $(B-V)=0.656\pm 0.011$.

Key words: solar-type stars – photometry

1. Introduction

Stellar solar analogs (abbreviated: SA) are important standards for the transformation of colour diagrams of cooler stars into colour – T_{eff} and luminosity – T_{eff} diagrams (Hardorp, 1978–1982; Hardorp et al., 1983; Spite, 1969; Reitsema, 1977; Perrin and Spite, 1981; Chmielewski, 1981; Cayrel de Strobel et al., 1981; Greve and Wamsteker, 1984; Haisch and Basri, 1985). A good SA is required since the Sun is not directly accessible to photometric observations (see, for instance, Tüg and Schmidt-Kaler, 1982). Dependent on the method of comparison: photometry, narrow band spectrophotometry, line shape analysis etc., somewhat different results are obtained with respect to the degree of solar analogy; however, all methods indicate 16 Cyg B as closest SA.

With the Walraven *VBLUW* photometer at ESO, Chile, we have measured 35 stars – including 5 Hyades stars – selected by Hardorp (1978) from the BSC as being solar-like or SA. Unfortunately, from the southern latitude we cannot observe 16 Cyg B. By means of *VBLUW* colour diagrams (CD) and model grids in terms of abundance (A), T_{eff}, and gravity ($\log g$) we illustrate how well the degree of solar analogy is represented in the set of observed stars. For stars deviating significantly from the Sun, the corresponding positions in the CDs with respect to A, T_{eff}, $\log g$ agree with values when given by Cayrel de Strobel et al. (1980, 1983, 1985; abbreviated CS). Small deviations from the Sun – though evident in the CDs – are difficult to evaluate quantitatively, mainly because of uncertainties in T_{eff} values of stars used for calibration and uncertainties in theoretical colours derived from model atmospheres which do not include, in particular, molecules (Kurucz, 1979).

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* Based on observations collected at ESO, La Silla, Chile

The *VBLUW* system does not provide a new criterion for the selection of SA. In particular, we do not find a useful correlation involving the L pass band flux containing the 3830 A and CN 3850 A absorption features which can be used as an indicator of solar analogy (Hardorp, 1980a, b, 1982).

2. *VBLUW* system; observations

Observations of 35 stars, mainly selected from Hardorp's (1978) list of solar-like candidates, were made with the *VBLUW* photometer attached to the 90 cm Dutch telescope at ESO, Chile. The photometer and the photometric system is described by Walraven and Walraven (1960), Rijf et al. (1969), and Lub and Pel (1977). Table 1 gives effective wavelengths, λ_{eff}, and FHW of the pass bands used since 1980. The L pass band covers the 3830 A and CN 3850 A absorption features.

Table 2 gives the *VBLUW* parameters (in log. intensity) of the observed stars. The accuracy of the measurements is 0.004 for V and 0.003 for the colour indices. In Table 2, the conversion of V into apparent visual magnitude, V_J, of the *UBV* system (corresponding quantities are denoted by the subscript J) follows from the relation given by Pel (1983)

$$V_J = 6.889 - 2.5\,[V + 0.039\,(V-B)]\,.$$

3. Colour diagrams: $(V-B)/(B-L)$, $(V-B)/(B-U)$, $(V-B)/(U-W)$

Dependent on the stellar UV spectral distribution with respect to the Sun, Hardorp (1978) grouped the candidate stars into 8 classes as given and explained in Table 2. SA belong to class 1. For our set of stars, Hardorp (1980a) and Hardorp et al. (1982) indicate HD 44594 and VB 64 as close SA. In the region 3000 Å–8500 Å the

Table 1. Filters of the Walraven *VBLUW* system (1980), λ_{eff} and FHW for $I(\lambda)=$ const., in Å

	W	U	L	B	V
λ_{eff}	3233	3616	3835	4277	5406
FHW	154	228	219	490	703

Table 2. *VBLUW* colours of solar type stars selected from Hardorp (1978) (System 1980). Observations: Nov.–Dec. 1980, in brackets repeated Jan. 1983

HD/VB Number	V	$V-B$	$B-U$	$U-W$	$B-L$	V_J (mag.)	SP	Class
	(log. intensity)							
1461*	0.157	0.301	0.367	0.237	0.334	6.46	G0	8
1581*	1.056	0.254	0.301	0.209	0.240	4.22	G2V	7
1835*	0.189	0.291	0.360	0.230	0.315	6.39	dG2	3
(1835	0.182	0.292	0.364	0.228	0.313	6.41)		
2151*	1.626	0.277	0.332	0.232	0.264	2.98	G2IV	7
4308	0.126	0.290	0.319	0.239	0.275	6.55	G3V	7
9562	0.444	0.283	0.361	0.242	0.306	5.75	dG2	4
10800	0.391	0.272	0.320	0.203	0.265	5.88		7
14802*	0.667	0.273	0.330	0.228	0.274	5.19	G1V	7
16417*	0.436	0.292	0.355	0.241	0.303	5.77	dG1	4
20619	−0.073	0.289	0.320	0.226	0.287	7.04		7
20630*	0.815	0.299	0.349	0.234	0.313	4.82	G5V	3
(20630	0.804	0.296	0.353	0.229	0.313	4.85)		
20766*	0.539	0.289	0.318	0.227	0.280	5.51	G2V	7
20794*	1.040	0.322	0.344	0.261	0.315	4.26	G5V	8
20807*	0.654	0.269	0.302	0.217	0.255	5.23	G1V	7
30455*	−0.040	0.272	0.313	0.235	0.265	6.96	G2V	7
30495*	0.551	0.282	0.331	0.224	0.284	5.48	dG1	7
30562*	0.437	0.273	0.368	0.238	0.309	5.77	dG0	6
31966	0.042	0.293	0.369	0.249	0.317	6.75	G5V	6
32008	0.590	0.357	0.399	0.283	0.354	5.38	dG4	8
(32008	0.568	0.357	0.405	0.284	0.359	5.43)		
39881	0.100	0.290	0.334	0.243	0.289	6.61	dG0	6
42807	0.181	0.301	0.336	0.225	0.293	6.41	G8V	4
44594	0.104	0.290	0.359	0.236	0.310	6.60	G0	1
45184	0.195	0.281	0.336	0.225	0.288	6.37	G0	6
(45184	0.193	0.276	0.337	0.225	0.288	6.38)		
45701	0.167	0.295	0.364	0.236	0.316	6.44	G0	8
59967	0.090	0.290	0.322	0.216	0.272	6.64	G5	7
65907	0.517	0.256	0.292	0.216	0.227	5.57	G2V	7
67228*	0.626	0.284	0.359	0.245	0.311	5.30	G2IV	7
76151*	0.348	0.301	0.352	0.229	0.313	5.99	G3V	3
78418*	0.356	0.295	0.359	0.233	0.314	5.97		3
89010	0.356	0.291	0.357	0.242	0.308	5.97		3
VB 63	−0.479	0.284	0.348	0.225	0.302	8.06	G1V	6
VB 64	−0.494	0.287	0.362	0.228	0.318	8.10	G8V	1
VB 73	−0.392	0.263	0.347	0.216	0.290	7.84	G2V	7
VB 106	−0.441	0.285	0.359	0.228	0.316	7.96		~1
VB 142	−0.589	0.297	0.354	0.229	0.315	8.33		~1

Notes to Table 2

Classes taken from Hardorp (1978):

1: spectra indistinguishable from solar,

3: spectra very close to solar,

4: spectra similar to solar, some absorption features weaker,

6: some absorption features appreciably weaker than solar,

7: much weaker absorption features than solar,

8: much stronger absorption features than solar.

The spectral types (SP) are given by Hardorp (1978). For the stars (*) values $T_{\rm eff}$, [Fe/H], $\log g$ are available from Cayrel de Strobel et al. (1980, 1983)

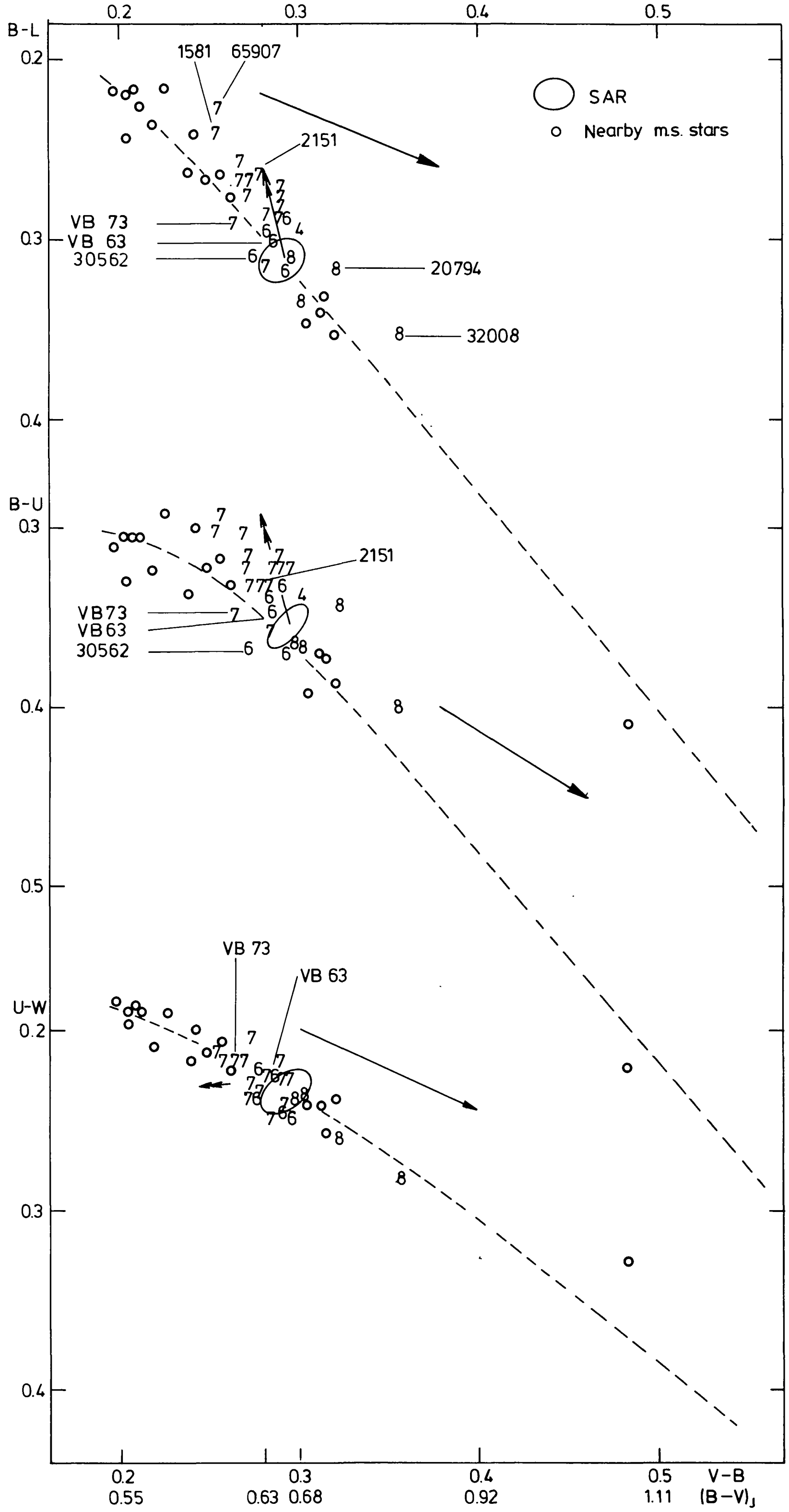

Fig. 1. *VBLUW* colour diagrams of solar-type stars. Observed stars (Table 2) are indicated by the class numbers taken from Hardorp (1978). Some stars are indicated by HD/VB numbers. Stars of class 1–4 are confined to the "solar analog region" (SAR). Open circles indicate ms stars used to define the ms line (dashed). The arrows give the reddening direction. The double arrow is the blanketing vector for a metal deficiency of $A = 0.316\,A_{\odot}$ ([Fe/H] $= -0.50$)

stars VB 106 and VB 142 are undistinguishable from VB 64 (Hardorp, 1980a, b, 1982), hence we classifiy these stars as ~1, see Table 2.

Figure 1 shows the observed stars in the *VBLUW* colour diagrams; for comparison we also give the $(B-V)_J$ scale (in mag) derived from $(V-B)$ by means of an empirical relation. The empirical main sequence (ms) is based on observations of bright, nearby ms stars made by E.R. Deul and L. de Lange, and data taken from Brand (1985). In the CDs the reddening direction is indicated. For all stars, except HD 32008 (see below), we may

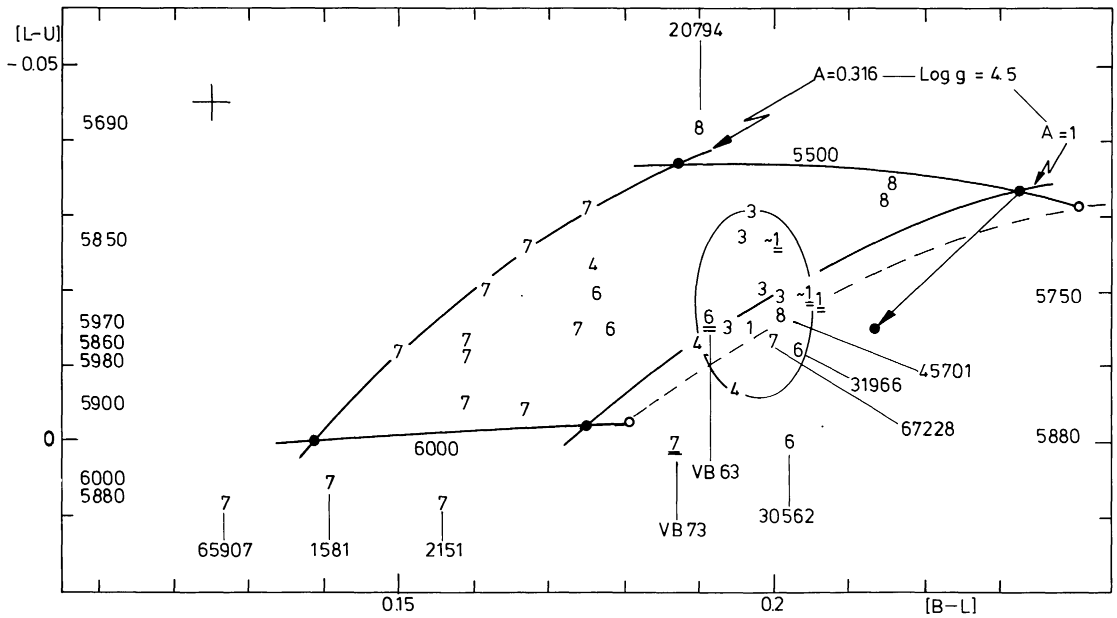

Fig. 2. Extinction-independent colour diagram. Hyades stars are double underlined. The grid is derived by Lub and Pel (1983) from models calculated by Kurucz (1979). The endpoint of the arrow indicates $\log g = 4.0$. $T_{\rm eff}$ values of some of the observed stars taken from Gehren (1981) and Cayrel et al. (1985) are shown on the left and right hand side, respectively

assume negligible reddening because of distances from the Sun smaller than 30 pc according to the parallaxes given by Gliese (1969). This assumption is confirmed by polarization measurements of Tinbergen (1982) which give $A_{V_J} < 0.002$ mag for stars within 30 pc distance. The double arrow in Fig. 1 is the theoretical blanketing vector for a metal deficiency $A = 0.316 A_\odot$ ([Fe/H] = − 0.50) derived by Lub and Pel (1983) from models calculated by Kurucz (1979).

In the CDs, the observed stars are indicated by the class numbers taken from Hardorp (1978), see Table 2. Stars of class 1–4 are confined within the ellipse, i.e. the "solar analog region" (SAR), except HD 42807 which is too blue in $(B-L)$ and $(B-U)$.

The similarity of the $(V-B)/(B-L)$ and $(V-B)/(B-U)$ diagrams indicates that the strengths of the absorption lines in the L and U pass bands change in a similar way. The L pass band is too broad to exhibit a dominant influence of the 3830 Å and CN 3850 Å absorption features.

4. $[L-U]/[B-L]$ and $(L-U)/(V-B)$ diagrams

Information on A, $T_{\rm eff}$, $\log g$ is derived from the *extinction independent* $[L-U]/[B-L]$ diagram, shown in Fig. 2, and the $(L-U)/(V-B)$ diagram, shown in Fig. 3. The colour indices are

$$(L-U) = (B-U) - (B-L)$$

$$[L-U] = (L-U) - 0.22\,(V-B)$$

$$[B-L] = (B-L) - 0.39\,(V-B)$$

with 0.22, 0.39 the slopes of the reddening lines. $[B-L]$ is sensitive to metal abundance; $[L-U]$, $(L-U)$ and $(V-B)$ are sensitive to temperature. By comparing the positions of the stars in the CDs with respect to the theoretical relations for $T_{\rm eff}$ and $\log g$ as function of A, and using the fact that each colour index has a characteristic sensitivity to one of these parameters, it is often possible to disentangle temperature, gravity, and abundance effects.

Figures 2 and 3 show theoretical grids for $\log g = 4.5$ and $T_{\rm eff} \sim 5500$ K–6000 K, $A = 0.316 A_\odot$–$1.0 A_\odot$. The endpoint of the gravity vector indicates $\log g = 4.0$. The grids are derived by Lub and Pel (1983) from models calculated by Kurucz (1979). We applied a shift of $\Delta[L-U] = -0.016$, $\Delta[B-L] = 0.11$ to the theoretical grids to obtain a better fit with the observations. We estimate these shifts are accurate within 50%. These corrections take into account:

that $T_{\rm eff}$ (Sun) = 5770 K (Neckel and Labs 1972, taken from Allen, 1973) coincides with the center of the SAR

$T_{\rm eff}$ values of some of the observed stars determined by Gehren (1981) and Cayrel et al. (1985)

that the Hyades stars fit the line $A = 1.32 A_\odot$ (dashed line in Fig. 2) following the determinations by Cayrel et al. (1985): $1.32 A_\odot$, Nissen and Gustafsson (1978): $1.48 A_\odot$, Hardorp (1978): $1.35 A_\odot$.

5. Discussion of the colour diagrams

Compared with the MS and the direction of the blanketing vector (Fig. 1), stars of class 6–7 (weaker absorption features than the Sun) are either metal deficient (with maximum values approaching $A \approx 0.3 A_\odot$) and/or have higher temperatures than the SAR stars. HD 31966 (class 6) and HD 67228 (class 7) lie within the SAR. Figure 2 indicates that these stars are metal rich with slightly higher temperatures than the SAR stars. For HD 67228, CS give $T_{\rm eff} \approx 4800$ K, [Fe/H] = 0.22. HD 1461 and HD 45701, both of class 8 (stronger absorption features than the Sun) lie within the SAR. Again, these stars are metal rich with slightly higher temperatures than the SAR stars. For HD 1461, CS give $T_{\rm eff} \approx 5600$ K, [Fe/H] ≈ 0.35.

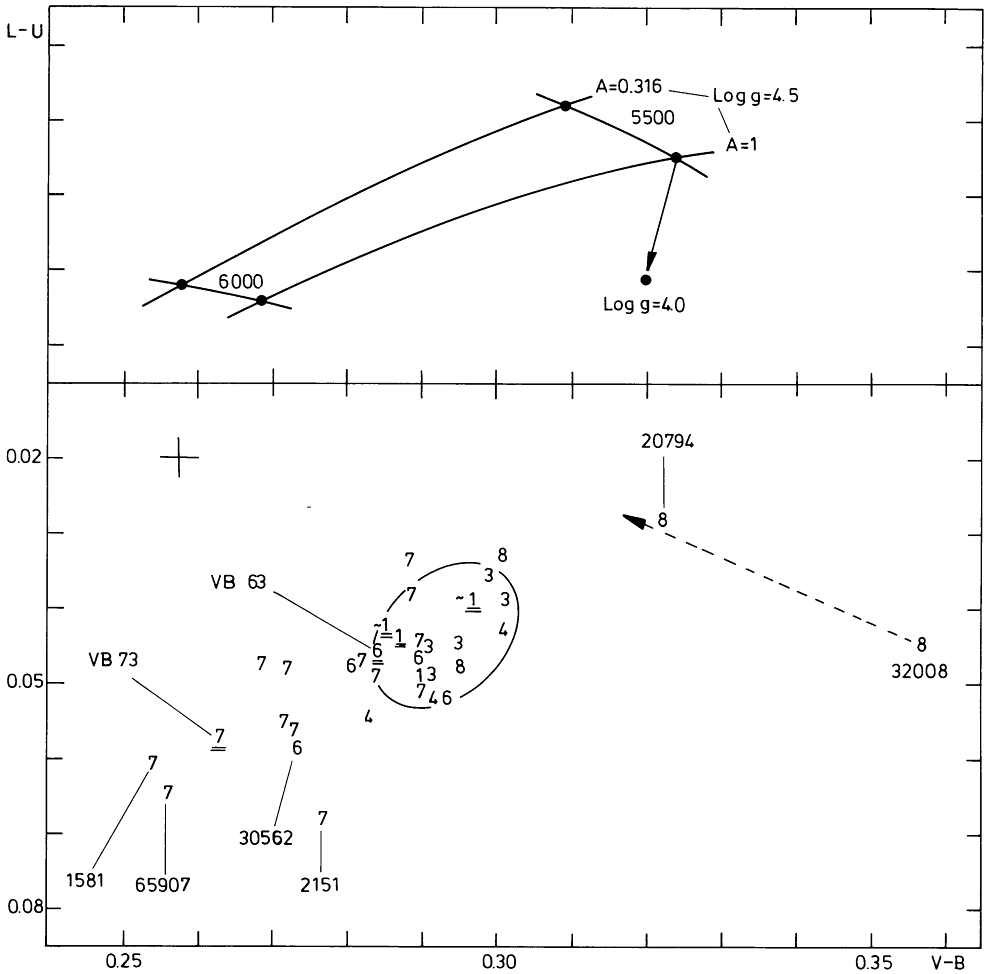

Fig. 3. Upper panel: grid (with relative scales) derived by Lub and Pel (1983) from models calculated by Kurucz (1979). Lower panel: observed stars. The reddening correction for HD 32008 is shown by the dashed line

Several stars of class 7 approach a metal deficiency $A \approx 0.3\,A_{\odot}$, these stars also eshibit a large variety in $T_{\rm eff}$ between $\approx$5600 K–6100 K. In particular we find $T_{\rm eff} \approx 6000$ K for HD 1581 and HD 65907, assuming $\log g = 4.5$. For HD 1581, CS give $T_{\rm eff} \approx 6000$ K, [Fe/H] = -0.10.

The position of HD 20794 (class 8) suggests $A \approx 0.3\,A_{\odot}$ and $T_{\rm eff} \approx 5500$ K assuming $\log g = 4.5$. This interpretation is consistent with the values given by CS, i.e. $T_{\rm eff} \approx 5400$ K, [Fe/H] = -0.34.

Figure 2 suggests $T_{\rm eff} \gtrsim 6000$ K for HD 2151 (class 7), however, Fig. 3 indicates a more acceptable interpretation of a lower gravity $\log g = 4.0$ with $T_{\rm eff} \approx 6000$ K. For this star CS give $T_{\rm eff} \approx 5600$–5700 K, [Fe/H] = -0.30, $\log g \approx 3.8$–4.0.

The position of HD 30562 (class 6) suggests a star of $T_{\rm eff} \approx 6000$ K and high metal content $A \approx 4\,A_{\odot}$, assuming $\log g = 4.5$. For this star CS give $T_{\rm eff} \approx 5900$ K, [Fe/H] = 0.13, $\log g = 3.7$. The lower gravity may be a better interpretation than the high value A.

For HD 4308, HD 20619, HD 59967, HD 65907 (all of class 7), not given by CS, the figures indicate $A \approx 0.3\,A_{\odot}$. The positions of VB 63 and VB 73 indicate values A and $T_{\rm eff}$ higher than those of the SAR stars.

The Hyades stars do not lie on the metal rich side of the main band of Fig. 3. In this diagram the gravity has an important influence on the distribution of the stars. The inconsistency in the position of the Hyades stars may be explained by a higher value of $\log g$, i.e. $\log g \approx 4.7$. However, since most of the Hyades seem to be covered by star spots we may assume that they exhibit anomalous colours (Campbell, 1984; Campbell and Cayrel, 1984). Active magnetic regions heat the lower chromosphere which reduces the line blanketing giving bluer $(B-V)_J$ colours. The positions of the observed Hyades stars can be explained by assuming that the $(V-B)$ colours are too blue by $\approx$0.01.

The position of HD 32008 in Fig. 2 (reddening independent CD) indicates a normal star with $A \approx A_{\odot}$ and $T_{\rm eff} \approx 5500$ K. However, this star has an extreme position in Fig. 3 which may be explained by reddening. Adopting a correction of $E(V-B) \approx 0.04$, i.e. $E(V-B)_J \approx 0.09$ mag or $A_{V_J} \approx 0.3$ mag, the star moves to the ms and a more acceptable position indicated in Fig. 3. The reddening corrected colours indicate a late G or K0 ms star as was also derived from UV observations by Greve and Wamsteker (1984). Zwaan and Rutten (priv. comm.), however, classify this star as subgiant so that $\log g$ is smaller than 4.5, its distance $\approx$40 pc and $A_{V_J} \lesssim 0.3$. The reddening of $A_{V_J} \approx 0.3$ seems unlikely for a star at galactic latitude $b = -29°$ ($l = 210°$) with 12–40 pc distance (dependent on the spectral classification). The somewhat peculiar image of HD 32008 on the red Palomar Sky Atlas plate suggests material surrounding the star which may be the source of the reddening. Recent new plates taken by R. Windhorst with the same Schmidt telescope, however, show a normal red stellar image.

HD 32008 and the surrounding nebulosity, if present, will be studied in more detail.

6. Conclusion

The stars HD 44594, VB 64, VB 106, VB 142 are photometrically similar and closest to the Sun. Using the empirical transformation between the *VBLUW* and *UBV* systems, we derive for these stars $(B-V)_J = 0.656 \pm 0.011$. Stars of class 1–4 are only slighty different from the Sun in photometric respect, these stars cluster in a small region SAR. Some stars of class 6–7 (metal lines much weaker than solar) and of class 8 (metal lines much stronger than solar) lie in the SAR. This coincidence is accidental and caused by a combination of considerably different temperatures and abundances than the Sun. A difference in gravity may be another cause. Therefore, "photometric distances" as used by Haisch and Basri (1985), and photometric boxes for instance of the Geneva system, are only of limited value to select SA. Unfortunately, theoretical grids cannot be used to derive accurate absolute values A, $T_{\rm eff}$, $\log g$ because the models calculated by Kurucz (1979) do not contain, in particular, molecules. However, relative differences of the stars are well exhibited in the colour diagrams.

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