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Photometry of Silicon Stars

H. Hensberge[1], C. De Loore[1], E. J. Zuiderwijk[2] and G. Hammerschlag-Hensberge[2]

[1] Astrophysical Institute, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium
European Southern Observatory, La Silla, Chile

[2] Astronomical Institute, University of Amsterdam, Roetersstraat 15, Amsterdam, The Netherlands
European Southern Observatory, La Silla, Chile

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Summary. Five of the brighter silicon stars in the list of Bidelman and Mac Connell (1973) i.e. HD 3580, HD 187473, HD 206653, HD 207188 and HD 212432, were observed at the ESO, La Silla, to search for variability in the *uvby*-photometric system. All of them turned out to be variable in the four channels showing obviously their largest amplitude in *u* ($>0^m.2$ in the case of HD 187473) and periods could be derived for all of them. One of the comparison stars, i.e. HD 185183, also turned out to be variable. Colour indices, amplitude, character and periodicity of the variations and a 12 Å/mm spectrogram suggest that this star might be a broad-lined silicon star.

Key words: Ap-stars — photometry — Si-stars

1. Introduction

In continuation of our search for periodicities among peculiar A stars (Hensberge et al., 1976) we present in this paper four-colour *uvby* photometry of five southern silicon stars of the list of Bidelman and Mac Connell (1973): HD 3580, HD 187473, HD 206653, HD 207188 and HD 212432. The stars were selected because of their brightness. One of the comparison stars, HD 185183, turned out to be a variable peculiar star itself.

In §2 we give a short description of the observations and reduction methods. The results for each program star separately are discussed in §3. In § 4 our conclusions are summarised.

2. Observations and Reductions

The observations were made by E. Zuiderwijk with the 50 cm Danish telescope at La Silla between July 25 and August 23, 1975. This telescope is equipped with a photometer for simultaneous measurements in the Strömgren *uvby* system. The photometer is used in combination with a photon counting system and is described in detail by Grønbech et al. (1976).

Each observation sequence contained measurements of the program star (P) and three comparison stars (C1, C2, C3) as follows: C1-P-C2-P-C3-P-C3-P-C2-P-C1. Extinction corrections were computed in the usual way. The observations of two comparison stars were reduced to the magnitude of the third one by using the mean difference in magnitude over the entire observation run. The dispersion of these differential magnitudes around their mean was low enough to permit this procedure. The differential magnitude for the program star was obtained as the average of all measurements of two consecutive sequences. The standard deviation of this differential magnitude is practically always less than $0^m.005$.

Standard indices were computed by transformation to the *uvby* system of the catalogue of bright southern stars (Grønbech et al., 1975). The transformation formulae appear to reproduce the catalogue indices with errors smaller than $0^m.01$. However, the majority of program and comparison stars have not yet been measured in the *uvby* system.

The period of variation is determined by a method based on the technique used by Lafler and Kinman (1965). For a sequence of trial periods, the phase ϕ_i of each measurement x_i is calculated. Assuming that the x_i are arranged according to their phase, S is defined as:

$$S=\frac{\sum_{n=1}^{N}(x_{n+1}-x_n)^2}{\sum_{n=1}^{N}(x_n-\bar{x})^2}.$$

N is the number of observations; for x_{N+1} the x_1 value has to be adopted and $\bar{x}$ is the average of the x_n's. Obviously S is a function of the guess periods since the arrangement according to phase depends on the adopted

Send offprint requests to: H. Hensberge

Table 1. Summary of results. Consecutive columns denote: HD number, silicon or comparison star, number of observing nights and number of differential magnitudes, visual brightness—denoted by (V) since transformation from y to (V) is somewhat tentative for Ap-stars because of the complicated variability in this wavelength region—, Strömgren indices $b-y$, $m1$ and $c1$ and, for the variable stars, the period of variation

HD number	Type	$n(N)$	(V)	$b-y$	$m1$	$c1$	P (days)
3580	Si	11 (19)	6.64/6.63	−0.065	0.119	0.53/0.50	1.480±0.005 or 2.94±0.02
3581	comp.	—	7.104	0.267	0.162	0.491	—
4247	comp.	—	5.233	0.226	0.142	0.554	—
4622	comp.	—	5.586	−0.029	0.131	0.975	—
187473	Si	15 (21)	7.36/7.23	−0.04/0.00	0.15/0.18	0.73/0.55	4.75±0.04
185183	comp. var.	—	6.75/6.71	−0.03/−0.05	0.09/0.12	0.56/0.53	~1.737
187578	comp.	—	7.666	0.032	0.096	0.874	—
190285	comp.	—	7.239	0.053	0.147	1.089	—
206653	Si	13 (16)	7.24/7.18	−0.04/−0.02	0.135	0.63/0.50	1.788±0.005
205348	comp.	—	6.775	−0.043	0.112	0.764	—
205417	comp.	—	6.226	0.008	0.151	1.133	—
209468	comp.	—	7.543	0.011	0.174	1.009	—
207188	Si	11 (15)	7.65/7.60	−0.041	0.152	0.54/0.58	2.67±0.01
205705	comp.	—	7.446	−0.033	0.101	0.699	—
207439	comp.	—	7.559	0.159	0.189	0.769	—
208482	comp.	—	6.757	0.035	0.182	1.059	—
212432	Si	9 (12)	7.52/7.49	−0.05/−0.06	0.248	0.69/0.63	4.69±0.05
210739	comp.	—	6.197	0.091	0.193	0.920	—
210931	comp.	—	7.401	0.014	0.184	1.005	—
214172	comp.	—	7.421	0.058	0.191	0.960	—

trial period. For the true period of variation, S is expected to be near its minimum value for each of the filters. Generally, when $S<0.5$ for each of the filters, the correlation is good (in the case $N \approx 20$); in excellent cases $S \approx 0.2$. As a rule, only for a very small number of trial periods S does not exceed 1.

This technique was used by Lafler and Kinman (1965) for the case of Cepheids. For that special case the shape of the light curve is well known and the number of observations ranges roughly between 30 and 50. When the number of observations is smaller, i.e. less than 20, the sum S may contain a term arising from the comparison of observations with rather large phase differences. Moreover, when the light curve is essentially a double wave curve, it may be expected that it contains none or at least very few observations between succeeding extrema. In this extreme case, it is exactly this term which may produce the major contribution to S and which might lead to the rejection of the trial period (although the observations are not in contradiction with this period).

To avoid this difficulty we decided to add an extra parameter Q, the phase difference for which the increase in magnitude in the case of a double-wave light curve never exceeds the probable error on the observations by a considerable amount. Terms in S, arising from phase points which differ more than Q are omitted. We compute

$$S^* = \frac{N \sum_{n=1}^{N} (x_{n+1}-x_n)^2 \delta(n, n+1)}{N^* \sum_{n=1}^{N} (x_n-\bar{x})^2}$$

where

$$\delta(n, n+1)=1 \quad \text{if} \quad f_{n+1}-f_n \leqq Q$$
$$=0 \quad \text{if} \quad f_{n+1}-f_n > Q$$

and N^* is the number of δ's differing from zero.

This S^*, depending on Q, is assumed to be a better indicator for the period of the Ap stars than S. If Q is overestimated double-wave periods may be overlooked (in fact $Q=1$ in the original version). If Q is underestimated, the test is not selective enough. This latter fact imposes a lower limit on Q in the case of large amplitude. $Q=0.1$ seems to be a reasonable choice in most cases.

Table 2. Differential magnitudes after transformation to the *uvby* system of the catalogue of bright southern stars (Grønbech et al.)

JD= 2442600+	Δy	Δb	Δv	Δu
HD 3580 – HD 4622				
19.890	1.150	1.115	1.064	0.563
24.883	1.149	1.114	1.065	0.554
34.815	1.154	1.119	1.066	0.569
37.732	1.153	1.117	1.065	0.564
37.884	1.155	1.124	1.071	0.571
38.741	1.146	1.110	1.061	0.551
38.888	1.146	1.112	1.063	0.559
39.695	1.153	1.116	1.063	0.552
39.883	1.139	1.108	1.052	0.532
40.697	1.153	1.120	1.068	0.569
40.886	1.155	1.121	1.067	0.572
41.688	1.145	1.107	1.060	0.551
41.875	1.148	1.113	1.063	0.560
42.718	1.146	1.113	1.060	0.542
42.889	1.143	1.109	1.054	0.532
46.702	1.155	1.120	1.066	0.568
46.877	1.155	1.121	1.071	0.571
47.673	1.148	1.111	1.064	0.558
47.867	1.148	1.113	1.066	0.561
HD 185183 – HD 190285				
19.578	−0.525	−0.618	−0.747	−1.415
19.795	−0.504	−0.593	−0.731	−1.396
21.573	−0.504	−0.589	−0.718	−1.383
23.583	−0.479	−0.562	−0.697	−1.364
24.554	−0.531	−0.621	−0.757	−1.437
24.770	−0.524	−0.619	−0.753	−1.419
34.608	−0.521	−0.611	−0.743	−1.427
34.792	−0.530	−0.629	−0.752	−1.434
35.711	−0.488	−0.567	−0.703	−1.363
37.709	−0.494	−0.582	−0.709	−1.378
38.716	−0.525	−0.616	−0.749	−1.418
39.508	−0.503	−0.589	−0.724	−1.394
39.751	−0.530	−0.619	−0.748	−1.432
40.510	−0.507	−0.605	−0.734	−1.393
40.747	−0.498	−0.583	−0.712	−1.379
41.502	−0.515	−0.607	−0.737	−1.418
41.734	−0.518	−0.618	−0.742	−1.418
42.691	−0.502	−0.570	−0.707	−1.364
45.551	−0.523	−0.621	−0.752	−1.424
46.741	−0.513	−0.608	−0.741	−1.417
47.703	−0.489	−0.579	−0.706	−1.373
HD 187473 – HD 187578				
19.578	−0.320	−0.383	−0.382	−0.557
19.795	−0.310	−0.376	−0.382	−0.539
21.573	−0.425	−0.466	−0.435	−0.732
23.583	−0.330	−0.404	−0.399	−0.598
24.554	−0.317	−0.379	−0.381	−0.541
24.770	−0.315	−0.376	−0.382	−0.539
34.608	−0.343	−0.398	−0.390	−0.583
34.792	−0.371	−0.422	−0.409	−0.625
35.711	−0.420	−0.461	−0.432	−0.728
37.709	−0.338	−0.406	−0.399	−0.602
38.716	−0.312	−0.377	−0.379	−0.535
39.508	−0.361	−0.413	−0.403	−0.620
39.751	−0.395	−0.442	−0.414	−0.673

Table 2.

JD= 2442600+	Δy	Δb	Δv	Δu
HD 187473 – HD 187578				
40.510	−0.420	−0.467	−0.436	−0.722
40.747	−0.409	−0.474	−0.435	−0.688
41.502	−0.345	−0.415	−0.414	−0.569
41.734	−0.332	−0.408	−0.398	−0.566
42.691	−0.335	−0.403	−0.397	−0.596
45.551	−0.401	−0.457	−0.437	−0.677
46.741	−0.334	−0.403	−0.407	−0.590
47.703	−0.324	−0.393	−0.386	−0.572
HD 206653 – HD 205348				
19.687	0.404	0.423	0.465	0.243
23.818	0.451	0.454	0.479	0.346
24.796	0.407	0.416	0.459	0.248
35.623	0.405	0.421	0.461	0.240
37.758	0.418	0.430	0.467	0.271
38.765	0.438	0.442	0.471	0.325
39.583	0.427	0.434	0.470	0.287
39.835	0.443	0.449	0.477	0.334
40.720	0.417	0.425	0.458	0.273
41.581	0.437	0.443	0.474	0.325
41.829	0.455	0.460	0.483	0.365
42.740	0.404	0.418	0.458	0.240
43.569	0.449	0.453	0.477	0.354
46.807	0.425	0.439	0.468	0.297
47.558	0.449	0.448	0.475	0.345
47.812	0.425	0.435	0.467	0.297
HD 207188 – HD 205705				
19.827	0.153	0.142	0.187	0.068
23.850	0.179	0.170	0.210	0.127
24.687	0.189	0.180	0.222	0.118
24.862	0.176	0.167	0.211	0.097
34.841	0.189	0.176	0.218	0.127
35.676	0.159	0.152	0.197	0.080
37.808	0.195	0.189	0.226	0.136
38.642	0.149	0.144	0.190	0.070
38.827	0.164	0.156	0.199	0.085
39.723	0.186	0.178	0.222	0.135
40.589	0.196	0.187	0.228	0.129
40.821	0.179	0.173	0.215	0.104
41.712	0.193	0.187	0.229	0.118
42.567	0.180	0.173	0.215	0.126
42.804	0.184	0.177	0.217	0.125
HD 212432 – HD 210931				
19.861	0.100	0.030	−0.107	−0.601
24.839	0.104	0.036	−0.100	−0.580
34.869	0.113	0.053	−0.085	−0.541
37.682	0.102	0.025	−0.108	−0.597
37.860	0.094	0.025	−0.111	−0.601
38.798	0.102	0.033	−0.099	−0.585
39.808	0.114	0.054	−0.082	−0.542
40.618	0.096	0.026	−0.102	−0.576
40.846	0.096	0.026	−0.103	−0.577
41.801	0.103	0.037	−0.097	−0.563
42.596	0.093	0.024	−0.110	−0.600
42.841	0.091	0.019	−0.112	−0.615

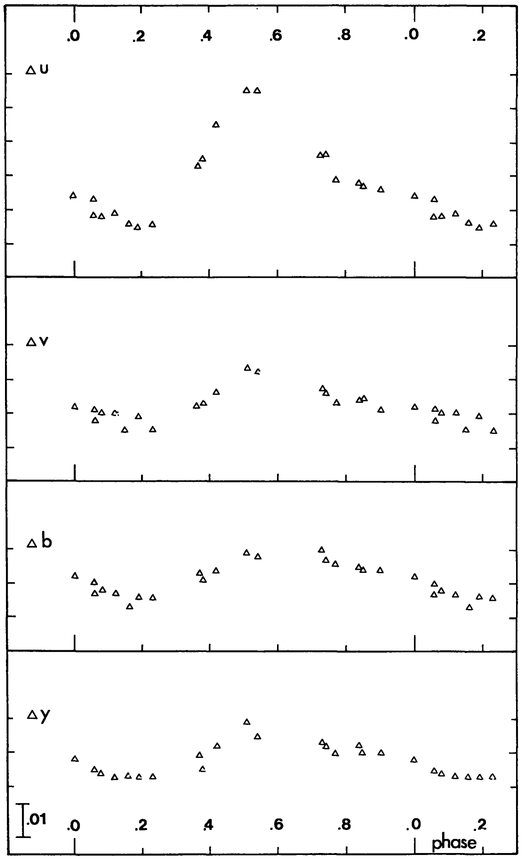

Fig. 1. Photometric variations of HD 3580 in the instrumental system of the Danish 50 cm telescope at La Silla, plotted with respect to a period of $1^{\mathrm{d}}.48$ and phase zero at JD 2 442 619.890

Let us focus on HD 3580 and HD 212432. In the following section it is argued that the period of HD 3580 is either $P_1=1^{\mathrm{d}}.48$ or $P_2=2^{\mathrm{d}}.94$. Inspection of the light curves for each of the two cases does not lead to a final choice. The second period induces a double-wave light curve. The S-test prefers P_1: $S(P_1)\approx 0.35$ while $S(P_2)>0.6$ in all filters. The S^*-test gives $S^*(P_2)\approx S^*(P_1)\approx S(P_1)$.

The case of HD 212432 is more illustrative. According to the S-test $P_1=1^{\mathrm{d}}.65$ and $P_2=2^{\mathrm{d}}.52$ are the best candidates. However $S\gtrsim 0.6$ in both cases in all filters. The plots of the observations for periods P_1 or P_2 are not convincing. The S^*-test prefers P_2 to P_1; the u-variation, which has the largest amplitude and hence should be the best indicator of the period, gives no satisfying result ($S^*\approx 0.6$). However $P=4^{\mathrm{d}}.7$ happens to be an excellent candidate with $S^*<0.15$ in each of the four filters. This candidate could easily be discarded in the S-test, since $S(P_3)\approx 1$ as a consequence of the large phase-gaps containing no observations in this double-wave light curve. In these S^*-tests a Q value of 0.1 was adopted.

Therefore it may be concluded that the S-test favours the selection of single-wave light curves. However, as many Ap stars are known to possess light curves with a secondary extremum, the S^*-test is more selective in the case of period determination for these stars, especially when only a restricted number of observations is available.

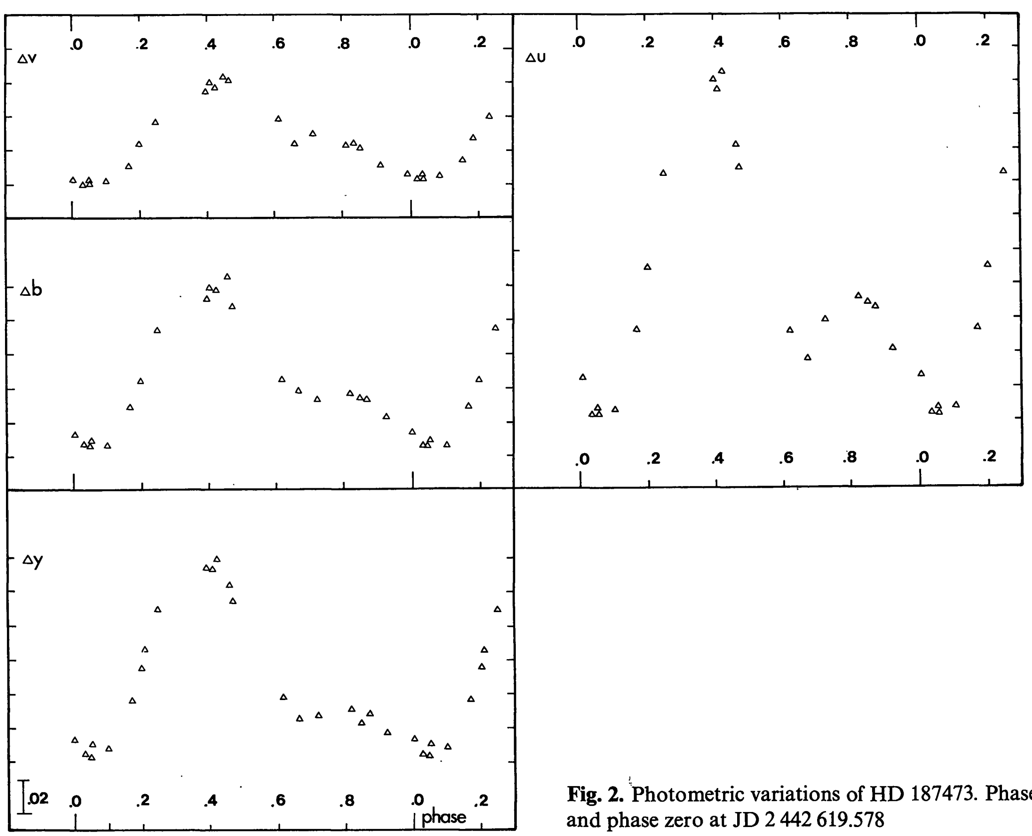

Fig. 2. Photometric variations of HD 187473. Phases were computed with $P=4^{\mathrm{d}}.75$ and phase zero at JD 2 442 619.578

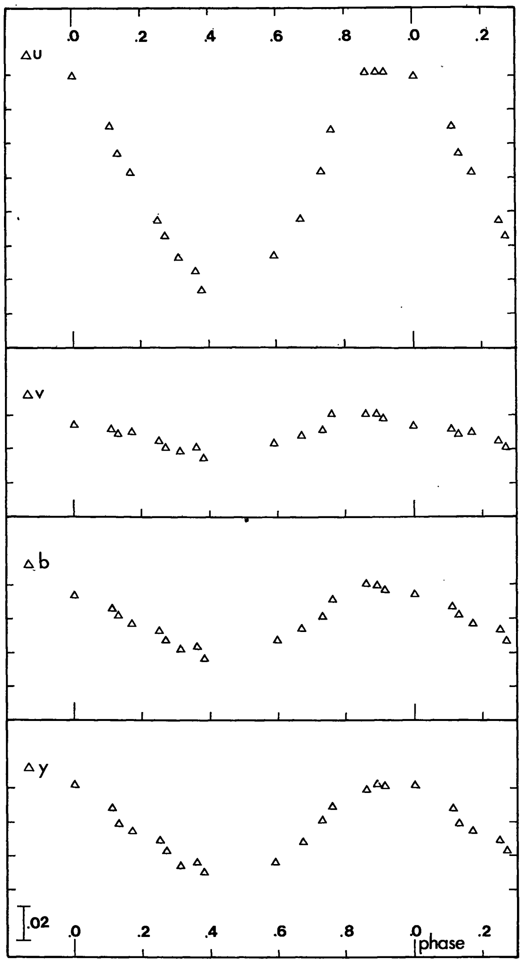

Fig. 3. Photometric variations of HD 206653, plotted in a period $P=1^{\mathrm{d}}.788$. Phase zero corresponds to JD 2 442 619.687

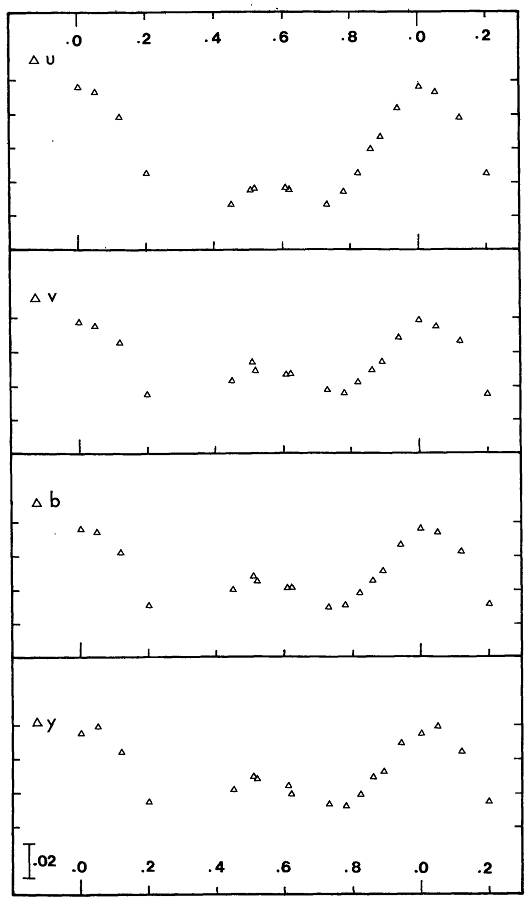

Fig. 4. Photometric variations of HD 207188. Phases were computed with $P=2^{\mathrm{d}}.67$ and phase zero at JD 2 442 619.827

3. Results

A summary of our results, including standard indices, amplitude and periodicity of variations, is listed in Table 1. The standard indices enable us to estimate the effective temperature of the silicon stars involved, since $u-b$ is a relevant temperature indicator (Megessier, 1971). Stars showing the silicon anomaly generally have $1.3>u-b>0.45$ corresponding to effective temperatures between 11000 K and 18000 K. Our program stars have $u-b\approx 0.62$ (HD 3580), 0.77 (HD 206653), 0.78 (HD 207188), 0.93 (HD 187473) and 1.05 (HD 212432). This places HD 3580 at the same temperature as 41 Tau and somewhat hotter than Babcock's star HD 215441.

In the subsequent section we discuss the results for each of the variable stars separately. One should notice that the plots represent the variations in the instrumental system. Phase zero is chosen arbitrarily at the time of the first observation. The transformed differential magnitudes are given in Table 2.

A. HD 3580

The observations are plotted in Figure 1; phases are computed with respect to a period of $1^{\mathrm{d}}.48$. All light curves are in phase with each other. Although the variations are rather small, the lightcurves are well defined. The $b-y$ and $m1$ indices are intrinsically constant.

However, also $P=2^{\mathrm{d}}.94$ represents the observations equally well. In this case, all curves show secondary extrema. Unfortunately, the curves with this period are not as well defined as with $P=1^{\mathrm{d}}.48$ because there remain three gaps of 0.2 in phase where no observations exist. This is, however, not a sufficient reason for eliminating this longer period.

According to the accuracy of the measurements—demonstrated by the accuracy of differential magnitudes between comparison stars—we can place the following limits on the value of P: $1^{\mathrm{d}}.480\pm0^{\mathrm{d}}.005$ or $2^{\mathrm{d}}.94\pm0^{\mathrm{d}}.02$.

B. HD 187473

Since the comparison star HD 185183 proved to be variable, only two comparison stars were used. HD 187473 is variable with extra-ordinary amplitude: about $0^{\mathrm{m}}.1$ in y and b, $0^{\mathrm{m}}.07$ in v and more than $0^{\mathrm{m}}.2$ in u. Weak secondary extrema show up in u; they are less pronounced in the other channels. Maximum brightness in y corresponds to a maximum in $b-y$, which shows no secondary extrema anymore. The variation in $m1$ is

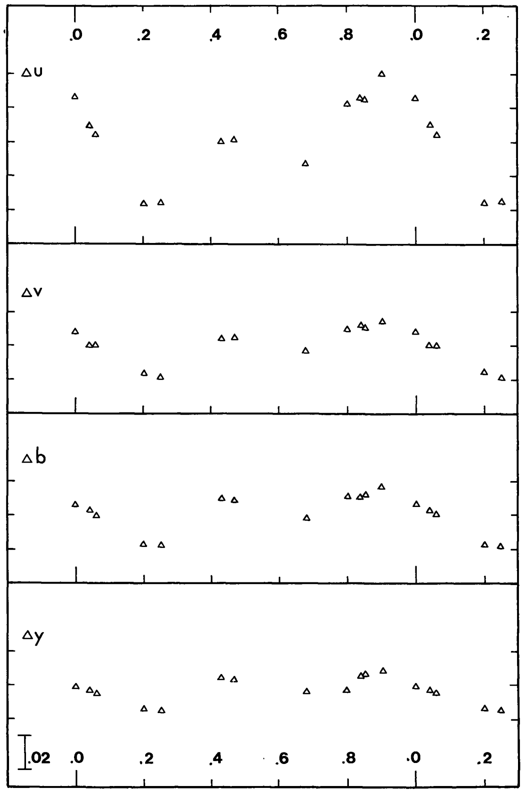

Fig. 5. Photometric variations of HD 212432. Phases were computed with $P=4^{\mathrm{d}}.69$ and phase zero at JD 2 442 619.861

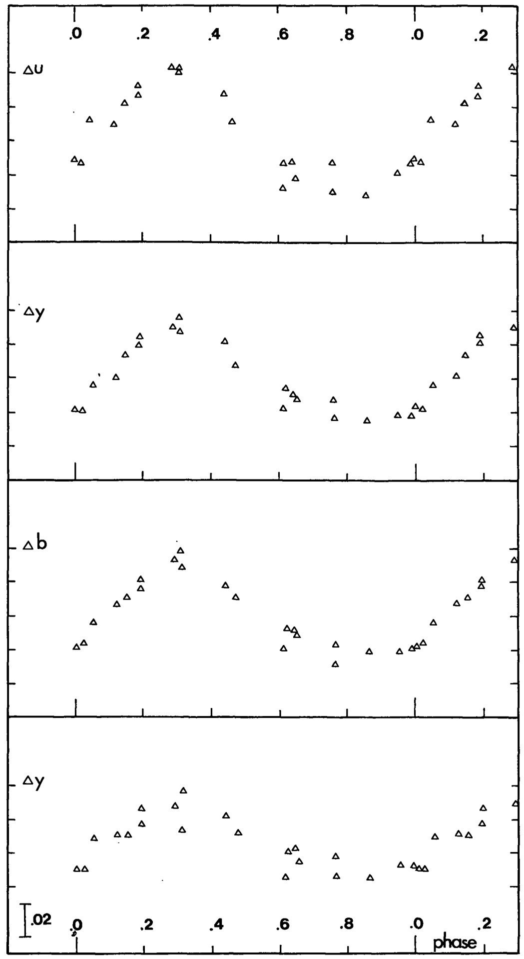

Fig. 6. HD 185183 proved to be variable in the *uvby* system. The observations are plotted with respect to a period $P=1^{\mathrm{d}}.737$ and phase zero at JD 2 442 619.578

less clear. All curves are in phase with the period $P=4^{\mathrm{d}}.75\pm0^{\mathrm{d}}.04$ (Fig. 2).

C. HD 206653

The observations are well represented with $P=1^{\mathrm{d}}.788\pm0^{\mathrm{d}}.005$ (Fig. 3). All curves are well defined single waves in phase with each other; $b-y$ varies slightly, $m1$ remains constant.

D. HD 207188

Figure 4 shows the results plotted in the period $P=2^{\mathrm{d}}.67$. Secondary extrema occur in the four channels, but less pronounced in u; $b-y$ and $m1$ are constant. Obviously observations are lacking around primary minimum. The frequent observations which define the slope between phases 0.7 and 0.0 permit to rely on the period up to $\pm0^{\mathrm{d}}.01$.

E. HD 212432

Differential magnitudes are plotted in Figure 5. Phases are computed with $P=4^{\mathrm{d}}.69$. The accuracy of P is $\pm0^{\mathrm{d}}.05$. Pronounced secondary extrema should exist but they are scarcely defined by lack of observations between phases 0.25 and 0.65—except two points near phase 0.45. Again, $m1$ is constant and the $b-y$ variation is hardly detectable. Further observations are required to confirm this first set. However no alternative value of P is consistent with our observations within the accuracy limits set by differential magnitudes between comparison stars.

This star is rather at the cool end of stars with silicon anomaly. Consequently, the importance of the contribution of line blocking due to metals is probably growing, resulting in a much larger $m1$ index.

F. HD 185183

This star was selected as comparison star of HD 187473. The reductions showed that this star is obviously variable in the four channels within a range of $0^{\mathrm{m}}.08$. The star is classified in the Henry Draper catalogue as B9. The effective temperature derived from the $u-b$ value of 0.68 is about 14 500 K; its mean colour indices and the amplitude of the variations, as well as its T_{eff} are similar to those of silicon stars. We therefore decided to search for a periodicity in the order of days. The best correlation was found near $P=1\overset{d}{.}737$. The dispersion around the mean curves displayed in Figure 6 is larger, however, than in other diagrams, above all in y. This can be partially due to the fact that each comparison star was observed less frequently than a program star as appears from Section 2. So one blue 12 Å/mm spectrogram was taken in May 1976 by De Loore at the ESO. The star appears to have relatively strong but broad silicon lines. We therefore suggest that this might be a broad-lined silicon star.

5. Conclusions

All five silicon stars are variable. Variations in the four channels are in phase; the largest amplitude occurs in all cases in u. One of the stars, HD 187473, shows extra-ordinary large amplitudes, comparable among silicon stars only with those of HD 215441 (Babcock's star). It should be noticed that at least three and possibly four stars show more or less pronounced secondary extrema.

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