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PHOTOMETRIC VARIABILITY OF B- AND A-TYPE SUPERGIANTS

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Photometric observations of 16 early-type (O9 to A3) supergiants have been obtained. All but two of the stars are variable, with a range of about $0^{\mathrm{m}}.05$. The light curves are irregular, but characteristic time scales or "quasi-periods" can be identified. The ratio of the quasi-period to the theoretical period (for pulsation in the fundamental radial mode) varies from 2–10 in the earliest-type supergiants to 0.2–2 in the later-type supergiants. The variability is most likely due to nonradial pulsation, at least in the O–B-type supergiants.

Key words: photometry—stars: early type—stars: supergiant—stars: variable

I. Introduction

Variability has long been recognized in certain types of supergiant stars: classical and Population II cepheids, RV Tauri stars, and massive red SRc variables. It is now apparent, both from statistical studies (Maeder 1980; Schild, Garrison, and Hiltner 1983) and from studies of individual stars (Abt 1957; Buscombe 1974; Sterken 1977; Burki 1978) that variability is a property of virtually all supergiants.

Abt (1957) was perhaps the first to discuss supergiant variability in general. He showed, on the basis of new and existing radial-velocity observations, that most mid-B to late-F supergiants varied in velocity on a time scale consistent with pulsation. Buscombe (1974) amplified his conclusion.

A series of photometric studies in the 1970s by G. Burki, A. Maeder, F. Rufener, and C. Sterken led to the parallel conclusion that most B to G supergiants varied in brightness, also on a time scale consistent with pulsation. Specifically, Maeder (1980) found from an analysis of 2420 observations of 327 supergiants over 20 years that: (1) most supergiants vary in brightness, (2) the amplitude is greater, on the average, for more luminous supergiants, (3) for I*a* supergiants, the average amplitude shows a maximum at B-type, a lower plateau at A- to F-type, and a sharp increase (the cepheid instability strip) at G-type, and (4) for late-type supergiants, there is a strong increase in average amplitude, which occurs at a progressively earlier spectral type with increasing luminosity: at G-type for class I*a* and at M-type for class II. In another large statistical study, Schild et al. (1983) showed that brightness variability is common among early-B supergiants, with typical amplitudes $\Delta V \sim 0^{\mathrm{m}}.1$ for the most luminous supergiants.

The time scale of supergiant variability can be deduced from studies of individual stars. This was first done by Abt (1957) and later by Maeder and Rufener (1972), using data from a relatively small number of stars. Sterken's (1977) discussion is based on his own homogeneous photometric data; Burki's (1978) is based on all data available in the literature: the number of stars is large, but the quality of the data is often low. The time scales are often ill-defined, based on only two or three cycles of irregular variability. Nevertheless, a consistent time scale or "semi-period" or "quasi-period" can be defined: it ranges from about ten days at B2 I*a* to about 90 days at G0 I*a* to more than 300 days for such extreme supergiants as HR 8752 and ρ Cassiopeiae. According to Maeder (1980), the following formula represents the time scale P as a function of M_{bol} and T_{e}:

$$\log P = -0.346\, M_{\mathrm{bol}} - 3 \log T_{\mathrm{e}} + 10.60 \quad . \qquad (1)$$

This formula is in general agreement with what would be expected if the variability was due to pulsation, though the observed time scale is somewhat greater than the expected fundamental radial period. For this and other reasons, Maeder (1980) suggested that the pulsation might be nonradial, perhaps driven by the deep convective zones which occur in the outer layers of luminous stars of all spectral types.

Hour-to-hour variability has also been reported in some early-type supergiants. Sterken (1977) reported observing small-amplitude, short-period fluctuations in one and possibly two luminous early-type supergiants. Smith and Ebbets (1981) reported line-profile variations of a few percent, on time scales of $\leq$ 3 hours, in the B1 I*ab* star ρ Leonis. Elst (1979) reported variations of up to $\Delta B = 0^{\mathrm{m}}.07$ on a time scale of $0^{\mathrm{d}}.1$ in the B1 I*a* star κ Cassiopeiae, but he published no observations of comparison stars, and his result was challenged by Percy (1981*a*) on the basis of the observations shown in Figure 1 of the present paper. Badalia and Gurm (1982) also reported variations of up to $\Delta m_b = 0^{\mathrm{m}}.05$ on time scales of $0^{\mathrm{d}}.072$ and $0^{\mathrm{d}}.058$ in κ Cas, but their light curves are extremely

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noisy, and they also published no observations of comparison stars, so their claim is unconvincing.

We have therefore obtained photometric observations of about a dozen early-type supergiants, most of them previously suspected to be variable, in order to investigate their variability on time scales of hours, days, and weeks. The limitations of our observations are clearly outlined in the following sections; in particular, our observations are suitable for studying variability on time scales $\leq$ 10 days and to a lesser extent on time scales > 10 days. A preliminary report of our work was presented at the Workshop on Pulsating B Stars, Observatoire de Nice, France, June 1981 (Percy 1981*b*).

II. Observations and Analysis

About half of the photometric observations were made by one of us (D.L.W.) in the summers of 1979 and 1980, using the 0.4-m reflector on the St. George Campus of the University of Toronto in downtown Toronto. These observations were made through standard *B* and *V* filters, using a 30″ diaphragm and a DC photometric system. A few observations were made in the summers of 1981 and 1982, by Paul Ford and Robert Spalding, respectively, using the same instrumentation.

The other photometric observations were made by the other author (J.R.P.) mostly in November of 1979 and 1980, using the No. 4 0.4-m reflector at Kitt Peak National Observatory near Tucson, Arizona. These observations were made through standard Strömgren *uvby* filters, using a 20″ diaphragm (usually) and a pulse-counting photometric system.

All photometric observations were made in differential fashion. Magnitude differences were first corrected for differential extinction. At Toronto, the extinction coefficients have been measured on a number of occasions and found to be $k(V) = 0.26 \pm 0.05$ (a.d.) and $k(B) = 0.40 \pm 0.05$ (a.d.); mean coefficients were used. At Kitt Peak, the extinction coefficients were $k(y) = 0.165$, $k(b) = 0.230$, $k(v) = 0.370$, and $k(u) = 0.670$, with very little scatter; again, mean coefficients were used. Corrected magnitude differences were then transformed to the standard system using the following values of ϵ ($\epsilon \equiv (\Delta m \text{ standard} - \Delta m \text{ obs})/\Delta\text{color}$) determined from observations of standard stars: $\epsilon(V,(B-V)) = -0.062$, $\epsilon(B,(B-V)) = +0.050$, $\epsilon\,(y,(b-y)) = 0.000$, $\epsilon(b,(b-y)) = +0.030$.

Amplitudes and time scales of variability were determined first of all by inspection of the light curves; this was especially true of the Kitt Peak observations which were made on nearly consecutive nights. The Toronto observations were analyzed primarily by the autocorrelation method described by Percy, Jakate, and Matthews (1981). Given the irregular nature of the variability, this approach was considered to be better than one which assumed strict periodicity. Nevertheless, the Toronto observations are somewhat sparse compared with other observations which have been subjected to autocorrelation

Table I

List of Program and Comparison Stars

ID	Name	HR	HD	V	B-V	Sp.T.
V	κ Cas	130	2905	4.16	+0.14	B1 Iae
C1		146	3283	5.79	+0.29	A4 III
C2		244	5015	4.82	+0.53	F8 V
V	5 Per	627	13267	6.36	+0.33	B5 Ia
C1		716	15253	6.51	+0.09	A2p shell
C2	11 Per	785	16727	5.77	-0.13	B7 IIIpHg
V		641	13476	6.44	+0.60	A3 Iab
C1	4 Per	590	12303	5.04	-0.08	B8 III
C2	11 Per	785	16727	5.77	-0.13	B7 IIIpHg
V	9 Per	685	14489	5.17	+0.37	A2 Ia
C1	11 Per	785	16727	5.77	-0.13	B7 IIIpHg
C2	4 Per	590	12303	5.04	-0.08	B8 III
V		1040	21389	4.54	+0.56	A0 Iae
C1		1068A	21769	6.40	+0.14	A4 III
C2		1071	21794	6.36	(+0.50)	F7 V
V		7551	187459	6.46	+0.20	B0.5 Ibe:
C1		7550	187458	6.40	+0.44	F4 V
C2		7512	186568	6.05	-0.06	B8 III
C3	17 Cyg	7534	187013	4.99	+0.47	F7 V
V		7573	187982	5.57	+0.71	A1 Ia
C1		7601	188485	5.52	-0.02	A0 III
C2		7656	189944	5.88	-0.12	B4 V
V		7678	190603	5.64	+0.54	B1.5 Iae
C1		7640	189395	5.49	-0.06	B9 Vn
C2		7613	188892	4.94	-0.08	B5 IV
C3	36 Cyg	7769	193369	5.58	+0.06	A2 V
V		7699	191243	6.11	+0.16	B5 Ib
C1		7640	189395	5.49	-0.06	B9 Vn
V	P Cyg	7763	193237	4.81	+0.42	B2 pe
C1		7613	188892	4.94	-0.08	B5 IV
C2		7769	193369	5.58	+0.06	A2 V
V	55 Cyg	7977	198478	4.84	+0.41	B3 Iae
C1	56 Cyg	7984	198639	5.04	+0.20	A4 mδDel
C2	57 Cyg	8001	199081	4.78	-0.14	B5 V
C3	ν Cyg	8028	199629	3.94	+0.02	A1 Vn
V	9 Cep	8279	206165	4.73	+0.30	B2 Ib
C1	ξ Cep	8417	209790	4.29	+0.34	A3 m
C2		8472	210855	5.24	+0.51	F8 V
V	ν Cep	8334	207260	4.29	+0.52	A2 Ia
C1	ξ Cep	8417	209790	4.29	+0.34	A3 m
C2		8472	210855	5.24	+0.51	F8 V
V	13 Cep	8371	208501	5.80	+0.73	B8 Ib
C1		8357	208095	5.71	-0.13	B6 IV-V
C2		8389	209124	6.59	+0.03	A0 III-IV
V	19 Cep	8428	209975	5.11	+0.08	O9 Ib
C1	ξ Cep	8417	209790	4.29	+0.34	A3 m
V	26 Cep	8561	213087	5.46	+0.37	B0.5 Ibe
C1		8537	212495	6.04	+0.05	A1 V
C2	30 Cep	8627	214734	5.19	+0.06	A3 IV
C3		8490	211242	6.11	-0.08	B8 Vn

analysis (e.g., Burki, Maeder, and Rufener 1978), so the results should be judged accordingly. For a few stars, we have also used Deeming's (1975) method of Fourier analysis of unequally-spaced data (as implemented in a computer program written by P. Harmanec and kindly made available to us by C. T. Bolton), despite the *caveat* mentioned above. We note also that, in view of the fact that our Kitt Peak observing runs are ten nights long, we may preferentially select time scales which are of the order of ten days.

Having thus stated the limitations of our observations and analysis, we should state also that we feel that our time scales are *at least* as reliable as most others in the literature, and perhaps more so.

III. Results

Results of the observations of the individual stars are contained in the following tables and figures, are summarized in Table XVII, and are described below. In Table XVII, we have given a "typical" amplitude Δm, and have included the *various* time scales which we can identify in our observations, as well as time scales which have been *reliably* determined by other observers.

In general, the light curves which we obtain are irregular, and contain variability on various time scales from about 2 to > 10 days. Similar results have been found by other observers: for instance, Burki et al.'s (1978) light curve of 9 Persei shows variability on time scales of 34 and seven days. On the other hand, we find absolutely no evidence of hour-to-hour variability in any of our program stars. The possible existence of variability on a time scale of 0.25 to two days is more problematical; it would probably show up as night-to-night scatter (as we have found in HR 7551), but our observations are not well suited to study such variability.

1. HR 2905, HR 130, κ Cas (B1 I*a*e).

Since the 1979 Toronto observations suggested that the star was variable (Table II), the star was observed intensively in b in 1980 at Kitt Peak, and less intensively in $uvby$ in 1981 at Kitt Peak. The comparison star was HR 146, whose constancy was established by five observations in 1979 [ΔV (HR 146 − HR 244) = 0.997 ± 0.009] and by 24 observations in 1980 [Δb (HR 146 − HR 244) = 0.894 ± 0.0035] as shown in Figure 1. Here and throughout, the observational scatter is expressed as an average deviation of each observation from the mean, which is typically 0.009 at Toronto and 0.0035 at Kitt Peak.

Figure 1 shows that κ Cas varies by $\Delta b \sim 0^m.05$ on a time scale of eight days. The less numerous observations in 1981 (Table III) confirm the variability and the amplitude, and suggest that there may be fluctuations on a time scale of 3–4 days. The color variations, based on these limited observations, are $\Delta(b-y)/\Delta y \sim 0.14$ and $\Delta(u-y)/\Delta y \sim 0.24$. There is no significant variability (> $0^m.01$) on a time scale of hours. On JD 2444564, the

Table II

Photometric Observations of HR 130 (κ Cas) Relative to HR 146

JD 2440000+	ΔV(*) or b
4060.786	-1.630*
4088.722	-1.624*
4094.793	-1.631*
4101.721	-1.589*
4116.722	-1.610*
4555.7111	-1.678
4555.7743	-1.670
4556.8688	-1.645
4556.9167	-1.646
4557.6792	-1.648
4557.8410	-1.644
4558.7868	-1.667
4558.8201	-1.671
4558.8604	-1.664
4560.5986	-1.680
4560.6854	-1.687
4560.7778	-1.692
4560.8424	-1.684
4560.8938	-1.685
4562.6090	-1.674::
4562.6493	-1.675
4562.7201	-1.675
4562.7771	-1.691
4562.8438	-1.680
4562.8868	-1.684
4563.6146	-1.666
4563.6653	-1.656
4563.7299	-1.652
4563.8201	-1.640
4563.8757	-1.636

Table III

Photometric Observations of HR 130 (κ Cas) Relative to HR 146, on the Instrumental uvby System

JD 2440000+	Δu	Δv	Δb	Δy
4918.685	-3.419	-1.752	-1.617	-1.567
4919.724	-3.438	-1.778	-1.634	-1.586
4920.835	-3.448	-1.784	-1.642	-1.586
4921.686	-3.468	-1.809	-1.669	-1.615
4924.695	-3.430	-1.765	-1.631	-1.576
4925.678	-3.473	-1.806	-1.662	-1.605

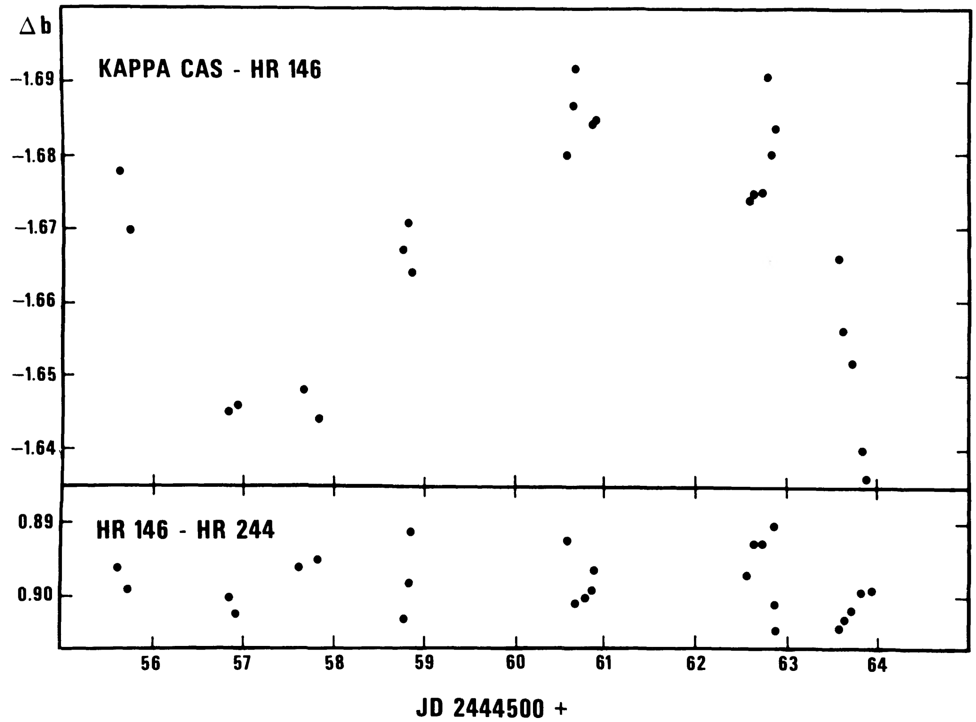

FIG. 1—Photometric variability of κ Cas (B1 Iae), relative to HR 146, in blue light. The lower panel shows the constancy of HR 146.

star faded by 0ᵐ03 in six hours, but this appears to be part of the longer-term variability. Thus the results of Elst (1979) and Badalia and Gurm (1982) are not supported.

2. HD 13267, HR 627, 5 Persei (B5 I*a*).

This star was initially observed relative to HR 716 and HR 641. Not surprisingly, the latter star (A3 I*ab*) was found to be variable. The constancy of HR 716 was therefore established relative to HR 785, which was being used as a comparison star for 9 Per [Δy(HR 716 − HR 785 = 0.856 ± 0.004]. The observations are listed in Table IV. From these limited observations (one cycle!) the time scale appears to be ~8 days.

3. HD 13476, HR 641 (A3 I*ab*).

This star was observed relative to HR 716 (see comments above). From these rather sparse and inadequate observations (listed in Table V), it appears that the time scale is > 14 days.

4. HR 14489, HR 685, 9 Per (A2 I*a*).

This star was observed (Table VI) relative to HR 785, the constancy of which was established by 18 observations relative to HR 590: in 1979, Δy(HR 785 − HR 590) = 0.770 ± 0.0035 and in 1980, Δb(HR 785 − HR 590) = 0.730 ± 0.004; see also Figure 2.

The star varies on time scales of 4 to ≥ 12 days. Abt's (1957) results give a time scale of 5–10 days, but his data are sparse. Buscombe (1974) quotes a period of 10: days, apparently based on Abt's result. Burki (1978) gives a quasi-period of 34 days based on autocorrelation analysis of Geneva photometry by Burki et al. (1978), but secondary fluctuations on a time scale of 7 days are clearly visible in the photometry.

Table IV

Photometric Observations of HR 627 (5 Per) Relative to HR 716

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4094.820	-0.155	V	4560.726	0.078	b
4101.752	-0.138	V	4560.867	0.077	b
4116.750	-0.151	V	4560.976	0.079	b
4555.818	0.049	b	4562.733	0.041	b
4556.909	0.063	b	4562.878	0.044	b
4556.991	0.067	b	4562.947	0.045	b
4557.806	0.072	b	4563.706	0.055	b
4558.835	0.088	b	4563.857	0.054	b

5. HD 21389, HR 1040 (A0 I*ae*).

This star was observed (Table VII) relative to HR 1068A, the constancy of which was determined by 20 observations relative to HR 1071: in 1979, Δy(HR 1068A − HR 1071) = 0.081 ± 0.0035 and in 1980, Δb(HR 1068A − HR 1071) = −0.171 ± 0.003;

Table V

Photometric Observations of HR 641 (V) Relative to HR 590 (C1) and HR 716 (C2)

JD 2440000+	Δb (V-C1)	ΔV (V-C2)
4094.820		-0.082
4101.752		-0.059
4116.750		-0.050
4555.82	-1.831	
4557.81	-1.864	
4560.73	-1.862	
4560.97	-1.876	
4562.88	-1.869	
4562.95	-1.860	
4563.71	-1.849	
4563.86	-1.855	

see also Figure 3.

The star varies on time scales of 6 to ≥ 15 days. Abt (1957) found a time scale of 7.7 days on the basis of 3 to 4 cycles of velocity variation.

6. HD 187459, HR 7551 (B0.5 I*be*:).

This star is a member of an eclipsing binary system with a period of 13.37383 days (Mayer and Chochol 1981). We have observed this system intensively for the last several years, and our observations and analysis will be published elsewhere. As well as the eclipse variability, there is pronounced intrinsic variability (visible also in the light curves of Mayer and Chochol). From an autocorrelation analysis, we suspect that the time scale is 2 to 4 days. It is unlikely that the intrinsic variability would be strictly periodic, because the star is strongly tidally perturbed by its companion once each orbit: the eccentricity of the orbit is 0.33.

According to the *Yale Catalogue of Bright Stars*, this star is a member of the association Cygnus OB5, but this association is not listed in the extensive compilation of Humphreys (1978). The value of M_v in Table XVII is based on the discussion by Mayer and Chochol (1981).

7. HD 187982, HR 7573 (A1 I*a*).

This star was observed relative to HR 7601, the constancy of which was established by 7 observations relative to HR 7656: ΔV (HR 7601 − HR 7656) = −0.305 ± 0.006. Since the scatter of HR 7573, relative to HR 7601 is also ± 0.005 (Table VIII), we conclude that it is not variable. Abt (1957) found small velocity variations with a time scale of a few days. Note that ΔV(HR 7573 − HR 7601) and ΔV (HR 7601 −

Table VI

Photometric Observations of HR 685 (9 Per) Relative to HR 785

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4203.780	-0.586	y	4557.816	-0.247	b
4204.813	-0.593	y	4558.840	-0.223	b
4205.824	-0.612	y	4560.730	-0.241	b
4208.883	-0.605	y	4560.965	-0.236	b
4209.896	-0.600	y	4562.673	-0.208	b
4211.790	-0.602	y	4562.883	-0.202	b
4212.699	-0.599	y	4562.941	-0.199	b
4555.824	-0.254	b	4563.710	-0.206	b
4556.951	-0.262	b	4563.862	-0.198	b

Table VII

Photometric Observations of HR 1040 Relative to HR 1068A

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4203.804	-1.918	y	4558.845	-1.526	b
4204.976	-1.911	y	4560.749	-1.504	b
4205.894	-1.903	y	4560.876	-1.501	b
4208.890	-1.893	y	4560.971	-1.500	b
4209.922	-1.894	y	4562.738	-1.501	b
4211.785	-1.885	y	4562.896	-1.501	b
4212.694	-1.892	y	4562.998	-1.506	b
4555.829	-1.496	b	4563.716	-1.507	b
4556.957	-1.503	b	4563.872	-1.512	b
4557.826	-1.512	b			

Table VIII

Photometric Observations of HR 7573 Relative to HR 7601

JD 2440000+	ΔV
4407.6826	0.015
4411.6632	-0.007
4429.6826	0.020
4430.6493	0.009
4433.6382	0.008
4451.6514	0.007
4455.6410	0.006

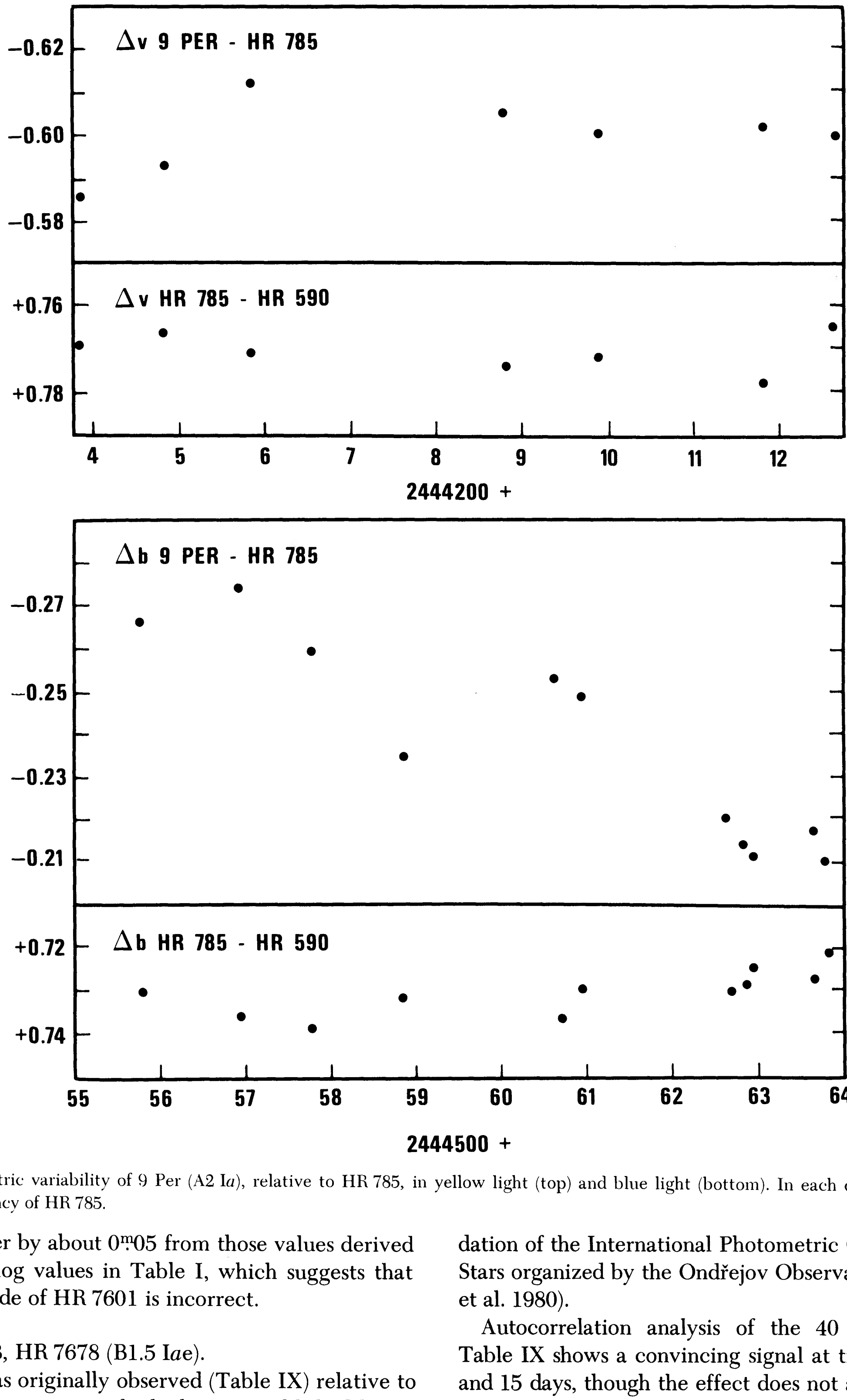

FIG. 2—Photometric variability of 9 Per (A2 I*a*), relative to HR 785, in yellow light (top) and blue light (bottom). In each case, the lower panel shows the constancy of HR 785.

HR 7656) differ by about $0^{m}.05$ from those values derived from the catalog values in Table I, which suggests that the *V* magnitude of HR 7601 is incorrect.

8. HD 190603, HR 7678 (B1.5 I*ae*).

This star was originally observed (Table IX) relative to HR 7640, the constancy of which was established by 17 observations relative to HR 7699: ΔV(HR 7640 − HR 7699) = −0.635 ± 0.008. In 1982, HR 7613 was used as the primary comparison star, on the recommendation of the International Photometric Campaign on Be Stars organized by the Ondřejov Observatory (Harmanec et al. 1980).

Autocorrelation analysis of the 40 observations in Table IX shows a convincing signal at time scales of 7.5 and 15 days, though the effect does not appear to persist for more than two cycles. Not surprisingly the periodograms (Deeming 1975) of each season's observations are complex. The highest peaks are in the vicinity of 10 ± 2 days, but these may not be significant.

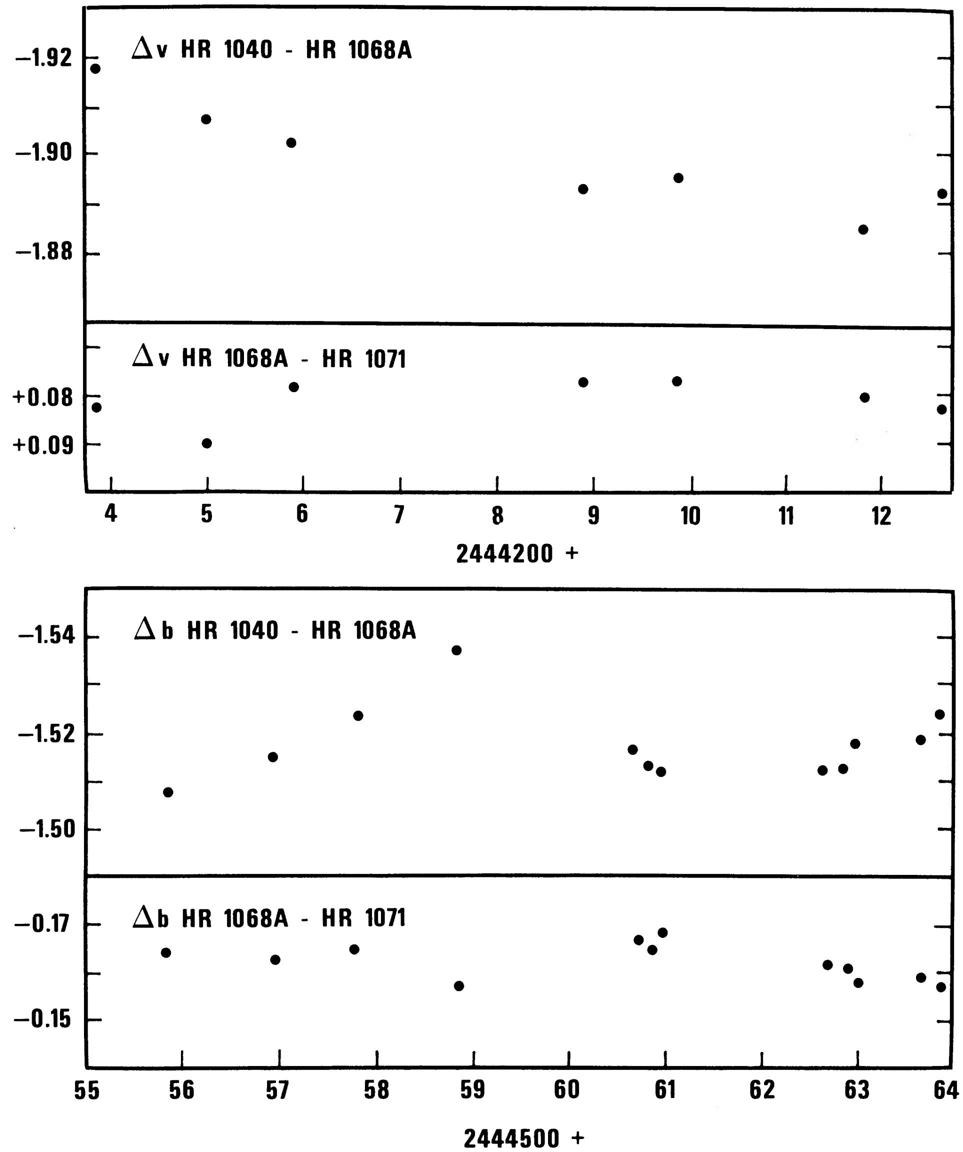

FIG. 3—Photometric variability of HR 1040 (A0 I*a*e), relative to HR 1068A, in yellow light (top) and blue light (bottom). In each case, the lower panel shows the constancy of HR 1068A.

According to the *Yale Catalogue of Bright Stars*, this star is a member of Vulpecula OB2, and lies in the reflection nebula Cygnus R1 at a distance of 1000 pc. Vul OB2 is not listed by Humphreys (1978); the M_v given in Table XVII has been derived by assuming the distance given above.

9. HD 191243, HR 7699 (B5 I*b*).

This B5 I*b* star was initially used as a check star for HR 7678 but, as mentioned above, it was found to be constant.

10. HD 193237, HR 7763, P Cygni (B2 pe).

This star was observed in 1982 using HR 7613 as the primary comparison star, as recommended by the International Photometric Campaign on Be Stars organized by the Ondřejov Observatory. The constancy of HR 7613 was established relative to HR 7769: ΔV(HR 7613 − HR 7769) = −0.638 ± 0.007 and ΔB(HR 7613 − HR 7769) = −0.765 ± 0.007.

Our observations (Table X) show variability on a time scale of 30 to 50 days, with an amplitude ~ 0.15.

There is some uncertainty in the M_v of P Cyg. According to the *Yale Catalogue of Bright Stars*, this star is a member of Cyg OB 1, but it is not listed as such by Humphreys (1978). The M_v in Table XVII, −8.0 ± 0.5, is based on the discussion by De Jager (1980). Maeder (1980) gives $M_{bol} \sim -11$, which corresponds to $M_v \sim -9.5$. Van Schewick (1968) presents evidence that P Cyg is a member of IC 4996, which leads to $M_v \sim -7.4 \pm 0.5$; see Underhill (1982) for a further discussion.

Table IX

Photometric Observations of HR 7678
Relative to HR 7640 or HR 7613 (*)

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4024.741	0.165	V	4455.651	0.130	V
4028.724	0.099	V	4738.749	0.703	B
4036.758	0.123	V	4741.769	0.744	B
4037.720	0.101	V	4756.767	0.731	B
4043.733	0.120	V	4773.789	0.734	B
4044.795	0.123	V	4783.723	0.706	B
4049.721	0.077	V	4792.801	0.748	B
4059.709	0.143	V	4793.792	0.756	B
4060.707	0.165	V	4796.729	0.787	B
4061.792	0.143	V	4817.719	0.729	B
4084.651	0.125	V	4833.699	0.748	B
4088.638	0.134	V	4842.687	0.722	B
4092.644	0.117	V	5105.744	0.688*	V
4094.715	0.124	V	5105.744	1.288*	B
4098.637	0.137	V	5123.712	0.760*	V
4101.645	0.111	V	5123.712	1.311*	B
4116.642	0.120	V	5129.691	0.681*	V
4367.752	0.109	V	5129.691	1.283*	B
4394.720	0.123	V	5134.682	0.699*	V
4395.702	0.137	V	5134.682	1.300*	B
4407.695	0.073	V	5143.749	0.701*	V
4411.673	0.117	V	5143.749	1.321*	B
4429.694	0.147	V	5144.688	0.699*	V
4430.661	0.142	V	5144.688	1.318*	B
4433.647	0.129	V	5152.688	0.663*	V
4451.663	0.143	V	5152.688	1.287*	B

Table X

Photometric Observations of
HR 7763 (P Cyg) Relative to HR 7613

JD 2440000+	ΔV	ΔB
5099.769	-0.060	0.410
5105.752	-0.053	0.431
5123.724	-0.243	0.235
5129.700	-0.121	0.348
5134.690	-0.095	0.380
5143.757	-0.127	0.369
5144.696	-0.124	0.368
5152.695	-0.065	0.431
5171.726	-0.159	0.318
5179.722	-0.128	0.339
5188.717	-0.078	0.388

11. HD 198478, HR 7977, 55 Cygni (B3 I*ae*).

This star was observed relative to HR 7984, using

Table XI

Photometric Observations of HR 7977
Relative to HR 7984

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4024.763	-0.252	V	4429.701	-0.212	V
4028.745	-0.222	V	4430.668	-0.233	V
4037.740	-0.237	V	4433.654	-0.256	V
4043.754	-0.257	V	4451.669	-0.205	V
4049.741	-0.214	V	4455.676	-0.216	V
4059.719	-0.212	V	4555.661	+0.002	b
4060.718	-0.228	V	4555.747	-0.002	b
4061.802	-0.251	V	4557.654	-0.006	b
4084.669	-0.242	V	4560.588	-0.004	b
4088.647	-0.235	V	4560.674	-0.013	b
4092.654	-0.253	V	4560.715	-0.012	b
4094.724	-0.189	V	4562.591	-0.014	b
4098.648	-0.227	V	4562.644	-0.018	b
4101.654	-0.271	V	4562.711	-0.019	b
4116.651	-0.230	V	4563.585	-0.005	b
4407.704	-0.230	V	4563.644	-0.004	b
4411.689	-0.249	V	4563.722	-0.009	b

HR 8001 as a check star. During the summer of 1979, the scatter between the latter two stars seemed rather large: from 15 observations, ΔV(HR 7984 − HR 8001) = 0.283 ± 0.012, so in the summer of 1980, these two stars were observed relative to each other and to HR 8028. From 6 observations, ΔV(HR 7984 − HR 8001) = 0.284 ± 0.003; further observations in the autumn of 1980 (Fig. 4) confirmed that these two stars were constant.

The 1979 observations suggest a range of $\Delta V \sim 0^{m}.05$ but the 1980 Kitt Peak observations show a much smaller range. It is therefore difficult to define a time scale; a guess would be a few days (Fig. 4). The autocorrelation analysis of the Toronto observations suggests a time scale of about 8 days, and the highest peaks in the periodogram of these observations are at about 5 and 10 days, but these are not likely significant. Burki (1978) quotes a time scale of 4.5 days from spectroscopic observations.

12. HD 206165, HR 8279, 9 Cephei (B2 I*b*).

This star was initially observed relative to HR 8417, using HR 8334 as a check star. Not surprisingly, the latter star (A2 I*a*) turned out to be variable. In the summer of 1980, HR 8417 was observed relative to HR 8472. From 6 observations, ΔV(HR 8417 − HR 8472) = −0.989 ± 0.004, suggesting that both stars are constant.

The observations are listed in Table XII and shown in Figure 5. From both seasons of Kitt Peak observations, a time scale of 10 to 12 days and an amplitude of $0^{m}.05$ can be found. Autocorrelation analysis of the Toronto obser-

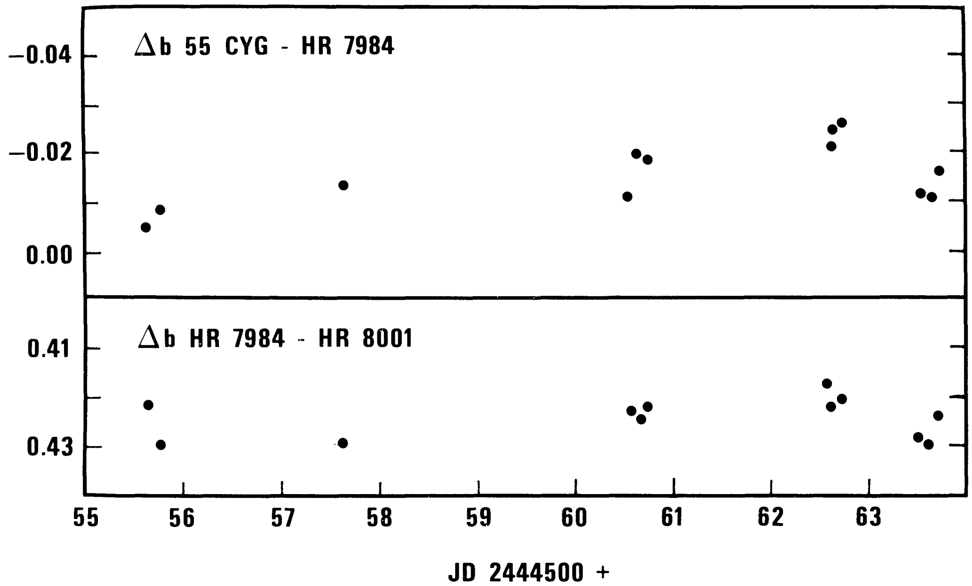

FIG. 4—Photometric variability of 55 Cyg (B3 I*ae*), relative to HR 7984, in blue light. The lower panel shows the constancy of HR 7984.

vations also gives a strong signal at 10 to 11 days.

13. HD 207260, HR 8334, 10 ν Cephei (A2 I*a*).

This star was observed relative to HR 8417, whose constancy is discussed above. Autocorrelation analysis of the observations in Table XIII gives signals at multiples of 5 days, and the strongest peaks in the periodogram of these observations are in the range 5 to 10 days. Buscombe (1974) quotes a time scale of 7.6 days, apparently based on Abt's (1957) result.

14. HD 208501, HR 8371, 13 Cephei (B8 I*b*).

This star was observed relative to HR 8357A (at Kitt Peak) or HR 8357A + B (at Toronto), the constancy of which was established relative to HR 8389: from 13 observations in 1979, for instance, ΔV(HR 8357A + B − HR 8359) = −1.265 ± 0.008; see also Figure 6.

The star shows variability on a time scale of about 12 days or more, as well as fluctuations on time scales of 2 to 3 days. Autocorrelation analysis of the Toronto observations (Table XIV) gives a weak signal at about 15 days.

15. HD 209975, HR 8428, 19 Cephei (O9 I*b*).

A few observations of this star were obtained relative to HR 8417, whose constancy is discussed above. The variations, if any, are small and occur on a time scale of a few days (Table XV).

16. HD 213087, HR 8561, 26 Cephei (B0.5 I*be*).

This star was observed relative to HR 8537, the constancy of which was established relative to HR 8627: in autumn 1979, ΔV(HR 8537 − HR 8627) = 0.849 ± 0.0035 and in autumn 1980, Δb(HR 8537 − HR 8627) = 0.839 ± 0.0045 (see Fig. 7). In the summer of 1979, the

Table XII

Photometric Observations of HR 8279 (9 Cep) Relative to HR 8417

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4024.786	0.490	V	4433.671	0.483	V
4028.766	0.532	V	4451.602	0.496	V
4037.759	0.484	V	4451.748	0.495	V
4043.773	0.446	V	4455.661	0.463	V
4049.759	0.525	V	4455.749	0.484	V
4059.736	0.503	V	4555.694	0.553	b
4060.728	0.498	V	4555.754	0.549	b
4061.811	0.525	V	4556.742	0.533	b
4084.679	0.484	V	4557.660	0.530	b
4088.657	0.500	V	4557.796	0.525	b
4092.664	0.497	V	4558.772	0.542	b
4094.734	0.507	V	4560.644	0.559	b
4101.662	0.508	V	4560.759	0.551	b
4116.660	0.547	V	4562.619	0.563	b
4203.613	0.468	y	4562.706	0.564	b
4204.761	0.469	y	4562.743	0.566	b
4205.670	0.475	y	4563.629	0.572	b
4207.698	0.522	y	4563.742	0.570	b
4208.656	0.516	y	4738.809	0.171	B
4209.680	0.514	y	4756.823	0.427	B
4210.712	0.505	y	4773.851	0.474	B
4211.719	0.513	y	4783.788	0.455	B
4212.615	0.487	y	4792.813	0.438	B
4367.774	0.470	V	4793.802	0.441	B
4394.731	0.474	V	4796.738	0.448	B
4395.713	0.508	V	4817.778	0.407	B
4407.725	0.487	V	4833.769	0.436	B
4411.708	0.490	V	4842.771	0.436	B
4430.690	0.506	V			

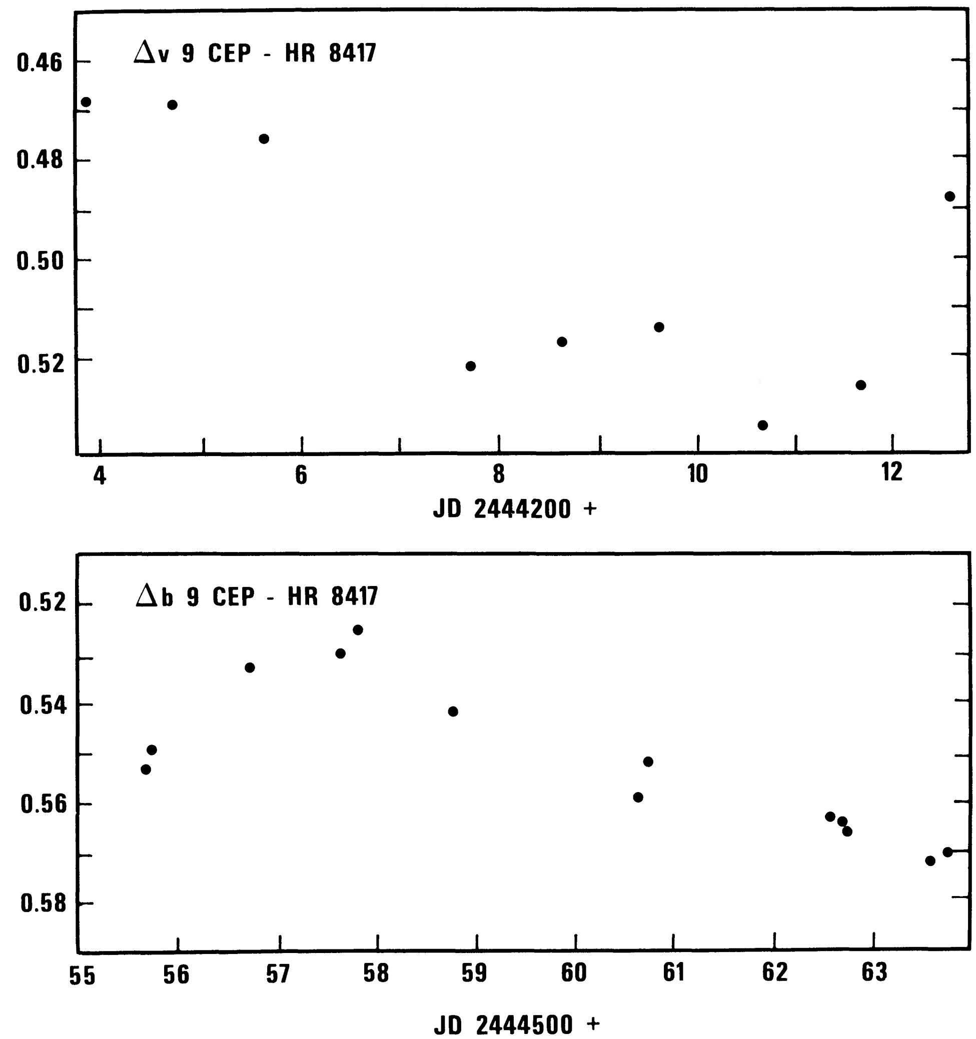

FIG. 5—Photometric variability of 9 Cep (B2 I*b*), relative to HR 8417, in yellow light (top) and blue light (bottom). The constancy of HR 8417 was checked relative to HR 8472.

scatter was ± 0.014; it is possible that one of these stars is slightly variable.

The star varies on time scales of 5 to 10 days or more. Autocorrelation and periodogram analysis of the Toronto observations give signals at about 4.5 days.

According to the *Yale Catalogue of Bright Stars,* this star is a member of the association Cep OB1, but Humphreys (1978) does not list it as such, presumably because its radial velocity differs significantly from that of the association. The calibration of the luminosity classification gives $M_v \sim -6.1$, as does the distance modulus given by Lesh (1968). The absolute magnitude derived from the radial velocity and the galactic rotation law is about a magnitude brighter.

IV. Discussion

We have compared the observed time scales in our program stars with those expected for pulsation in the fundamental radial mode; we will not rediscuss the additional stars listed by Burki (1978) and others.

Combining the definitions of Q, T_e and M_{bol}, we obtain:

$$\log P = \log Q - 0.5 \log \mathfrak{M}/\mathfrak{M}_\odot - 0.3\, M_{bol} - 3 \log T_e + 12.71 \quad . \tag{2}$$

Following Maeder (1980), we have used a mass-luminosity relation based on evolutionary models including mass loss:

$$\log \mathfrak{M}/\mathfrak{M}_\odot = -0.122\, M_{bol} + 0.32 \tag{3}$$

which gives:

$$\log P = \log Q - 0.239\, M_{bol} - 3 \log T_e + 12.55 \quad . \tag{4}$$

Here, P is the theoretical period of pulsation and Q is the corresponding pulsation constant—a function of M_{bol} and $\log T_e$.

Effective temperatures were taken from the com-

Table XIII

Photometric Observations of HR 8334 Relative to HR 8417

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4024.786	+0.004	V	4204.761	-0.006	y
4028.766	+0.015	V	4205.670	-0.008	y
4037.759	+0.055	V	4208.656	-0.006	y
4043.773	-0.010	V	4209.680	-0.006	y
4049.759	-0.013	V	4210.712	-0.012	y
4059.736	+0.030	V	4211.719	+0.006	y
4060.728	-0.008	V	4212.615	-0.031	y
4061.811	+0.007	V	4407.732	0.021	V
4084.679	+0.030	V	4411.717	0.006	V
4088.657	+0.012	V	4430.695	0.012	V
4092.664	-0.006	V	4433.678	0.024	V
4094.734	+0.034	V	4451.686	0.001	V
4101.662	+0.008	V	4455.687	0.050	V
4116.660	+0.025	V			
4203.613	-0.012	y			

Table XIV

Photometric Observations of HR 8371 (13 Cep) Relative to HR 8357 (A+B or A)

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4024.798	0.480	V	4433.687	0.464	V
4028.775	0.421	V	4451.593	0.470	V
4037.771	0.484	V	4451.757	0.470	V
4043.783	0.425	V	4455.670	0.454	V
4049.768	0.442	V	4455.756	0.456	V
4059.745	0.440	V	4555.700	0.648	b
4060.737	0.446	V	4555.759	0.651	b
4084.691	0.431	V	4556.746	0.664	b
4088.673	0.497	V	4557.665	0.635	b
4092.695	0.412	V	4557.811	0.633	b
4094.743	0.484	V	4558.778	0.647	b
4101.670	0.483	V	4560.648	0.633	b
4116.669	0.454	V	4560.694	0.638	b
4203.622	0.042	y	4560.764	0.637	b
4203.791	0.048	y	4562.623	0.621	b
4204.769	0.042	y	4562.678	0.621	b
4205.677	0.056	y	4562.747	0.618	b
4207.703	0.043	y	4563.634	0.631	b
4208.651	0.039	y	4563.696	0.632	b
4209.674	0.055	y	4563.751	0.631	b
4210.682	0.075	y	4783.801	1.310	B
4211.713	0.078	y	4792.822	1.231	B
4212.621	0.071	y	4796.747	1.250	B
4395.734	0.434	V	4817.813	1.246	B
4407.744	0.450	V	4833.837	1.254	B
4411.735	0.466	V	4842.757	1.240	B
4430.705	0.446	V			

Table XV

Photometric Observations of HR 8428 Relative to HR 8417

JD 2440000+	Δy	JD 2440000+	Δy
4203.613	+0.832	4208.656	+0.830
4204.761	+0.853	4209.680	+0.827
4205.670	+0.838	4210.712	+0.835
4207.698	+0.853	4211.719	+0.848

pilation by Underhill (1982). Directly-determined effective temperatures were used for the program stars for which they were available (Underhill's Table 4-1). Otherwise, effective temperatures were determined from the spectral type, using the mean calibration given in Underhill's Figure 4-1 and Table 4-2.

Absolute magnitudes, based on membership in associations, were taken from Humphreys (1978), except as noted in Table XVII and discussed in section III. Bolometric corrections, as a function of effective temperature, were taken from Underhill's Table 4-3.

Theoretical Q values for fundamental radial pulsation were interpolated from the table of calculations by Takeuti (1979). The calculations were for $X = 0.70$, $Z = 0.02$, using Cox and Stewart opacities and including convection in the static models where necessary. In view of the difficulty in constructing models of distended supergiant stars, these calculations by Takeuti should be regarded as the best available in the literature, but not necessarily perfect. The theoretical periods are listed in Table XVII.

Before discussing the implications, we should remember the following general features of our results: (1) there are no significant variations on time scales of hours, (2) there are variations, of an irregular nature, on a variety of time scales from a few days upward, (3) our observations are not designed to efficiently detect variations on time scales of 0.5 to 2 days, but if such variations were present, they would show up as trends in the hour-to-hour observations, and as random scatter in the light curves in Figures 1–7. We conclude that such variations are small or nonexistent, and (4) for some stars our observations are not designed to efficiently detect variations on time scales $\gg$ 10 days.

The following trend is apparent from the data in Table XVII. Whereas for the early-B supergiants ($P_{th} \sim$ 2 days), the ratio P_{obs}/P_{th} is in the range 1–10, for the late-B and early-A supergiants ($P_{th} \sim$ 10 days), the ratio

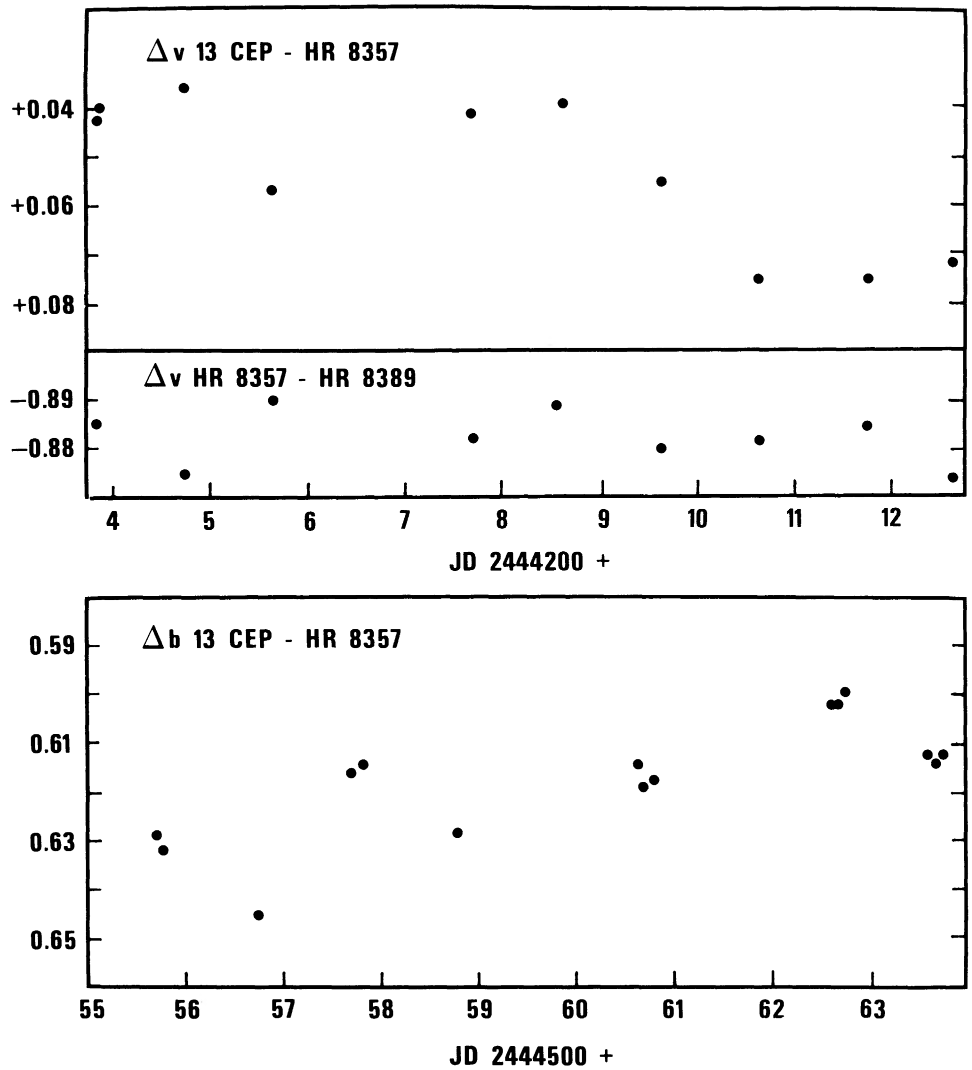

FIG. 6—Photometric variability of 13 Cep (B8 I*b*), relative to HR 8357, in yellow light (top) and blue light (bottom). In each case, the lower panel shows the constancy of HR 8357.

P_{obs}/P_{th} is in the range 0.2–2. For normal F supergiants, i.e., cepheids, this ratio is 1; they pulsate in the fundamental radial mode.

It is interesting to compare our result for the early-B supergiants with that for two other groups of early-B variables: the line-profile-variable 53 Persei stars and the β Cephei stars. The 53 Persei stars occupy a large region of the H-R diagram: O9–B5 I–V; they display different periods (with P_{obs}/P_{th} = 1 to 10) at different epochs; they pulsate in nonradial modes. The β Cephei stars occupy a small region of the H-R diagram: B0.5–B2 III–IV; they often display multiple periods (with $P_{obs}/P_{th} \sim 1$); they pulsate in radial and nonradial modes.

Our results and trends agree with those of Burki (1978) except that (1) he did not consider any I*b* supergiants which in our sample are the ones with the most extreme ratio of P_{obs}/P_{th}, (2) he was usually capable of identifying longer time scales (>20 days), which were not accessible to us, and (3) he lists only one dominant time scale for each star, despite the fact that in some of his stars (9 Per for example), variations are seen to occur on at least two time scales.

The amplitudes of variability are typically $0^m.05$, as found by others from statistical studies (Maeder 1980) and studies of individual stars (Burki 1978). Our observations provide no useful information on the relation between Δm, M_{bol}, and T_e, because we have generally *selected* the program stars on the basis of suspected variability.

Our observations of color variations are fragmentary, and exist only for κ Cas. In this star, the color variations appear small. Schild et al. (1983) observed significant $(U-B)$ color-index variations in several A-type supergiants, but those observed in 56 B-type supergiants were "so marginal and so few, they may not be real". Rufener, Maeder, and Burki (1978) using the Geneva photometric

Table XVI

Photometric Observations of HR 8561 (26 Cep) Relative to HR 8537

JD 2440000+	Δm	F	JD 2440000+	Δm	F
4024.809	-0.542	V	4210.789	-0.573	y
4028.785	-0.543	V	4211.750	-0.569	y
4037.780	-0.542	V	4212.628	-0.554	y
4043.793	-0.580	V	4555.705	-0.294	b
4049.777	-0.537	V	4555.765	-0.295	b
4059.756	-0.531	V	4555.805	-0.295	b
4060.747	-0.565	V	4556.847	-0.288	b
4084.700	-0.558	V	4557.674	-0.272	b
4088.682	-0.555	V	4557.822	-0.279	b
4094.755	-0.527	V	4558.794	-0.282	b
4101.679	-0.566	V	4560.653	-0.281	b
4116.678	-0.531	V	4560.720	-0.284	b
4203.632	-0.581	y	4560.768	-0.281	b
4203.786	-0.560:	y	4562.633	-0.266	b
4204.773	-0.552	y	4562.700	-0.262	b
4205.685	-0.579	y	4562.751	-0.268	b
4207.730	-0.593	y	4563.639	-0.267	b
4208.690	-0.569	y	4563.701	-0.267	b
4209.790	-0.567	y	4563.756	-0.266	b

system, found that, for four B2 to A2 supergiants, the light amplitudes are similar in yellow, blue, and violet light, implying no color (or temperature) variations. This is usually indicative of nonradial pulsation (Stamford and Watson 1979), though no calculations have yet been done for models of supergiant stars.

The important question remains: what is the nature and cause of supergiant variability? It cannot be radial pulsation, at least in the B-type supergiants: the observed periods are a factor of 4 or more higher than the theoretical ones. Agreement could only be obtained if the actual Q-values were a factor of 4 higher than those used, or if the masses were a factor of 16 lower. The former is unlikely (Akatli 1981), as is the latter especially considering that mass loss is already included in equation (3). The errors in Q or m would also have to be a function of T_e, or period.

Nonradial pulsation is a more promising possibility, especially since it has already been proposed by Maeder (1980). It provides an explanation for why $P_{obs}/P_{th} \gg 1$ (but not for why this ratio is a function of T_e, or period). This possibility is also supported by the lack of color variations (at least in the B-type supergiants which also have the most extreme P_{obs}/P_{th} values) and by the close proximity between the 53 Persei stars and the early-B supergiants in the H-R diagram. On the other hand, the variability which we have observed is not strictly periodic. This may indicate that there is frequent mode switching, or that there is a superposition of very many nonradial modes (as in Deneb (Lucy 1976)). It may also indicate that the nonradial pulsation hypothesis is incorrect.

We should also consider the possibility that the variability is related to the rotation of the star. For early-B supergiants, $v \sin i$ is typically 40 to 80 km sec^{-1} and $R/R_\odot$ is typically 25 to 40. The period in days, therefore, is typically (15–50) sin i, somewhat higher than the values observed here. There is the additional problem of what would cause the inhomogeneities necessary for rotational variability. There is no reason to believe that early-B supergiants have strong magnetic fields (which would cause starspots) or large convective cells.

Finally, it is possible that the variability is due to quasi-random surface motions or outflows of matter, with a characteristic time scale but without strict periodicity.

A few of the observations in Tables II–XVI were made in the summer of 1981 and 1982 by R. Paul Ford and Robert Spalding, respectively. One of us (J.R.P.) wishes to thank Kitt Peak National Observatory for access to telescope facilities, and for help and hospitality. This research was supported by the Natural Science and Engineering Research Council of Canada, through an Operating Grant to J.R.P. and an Undergraduate Summer Research Award to D.L.W.

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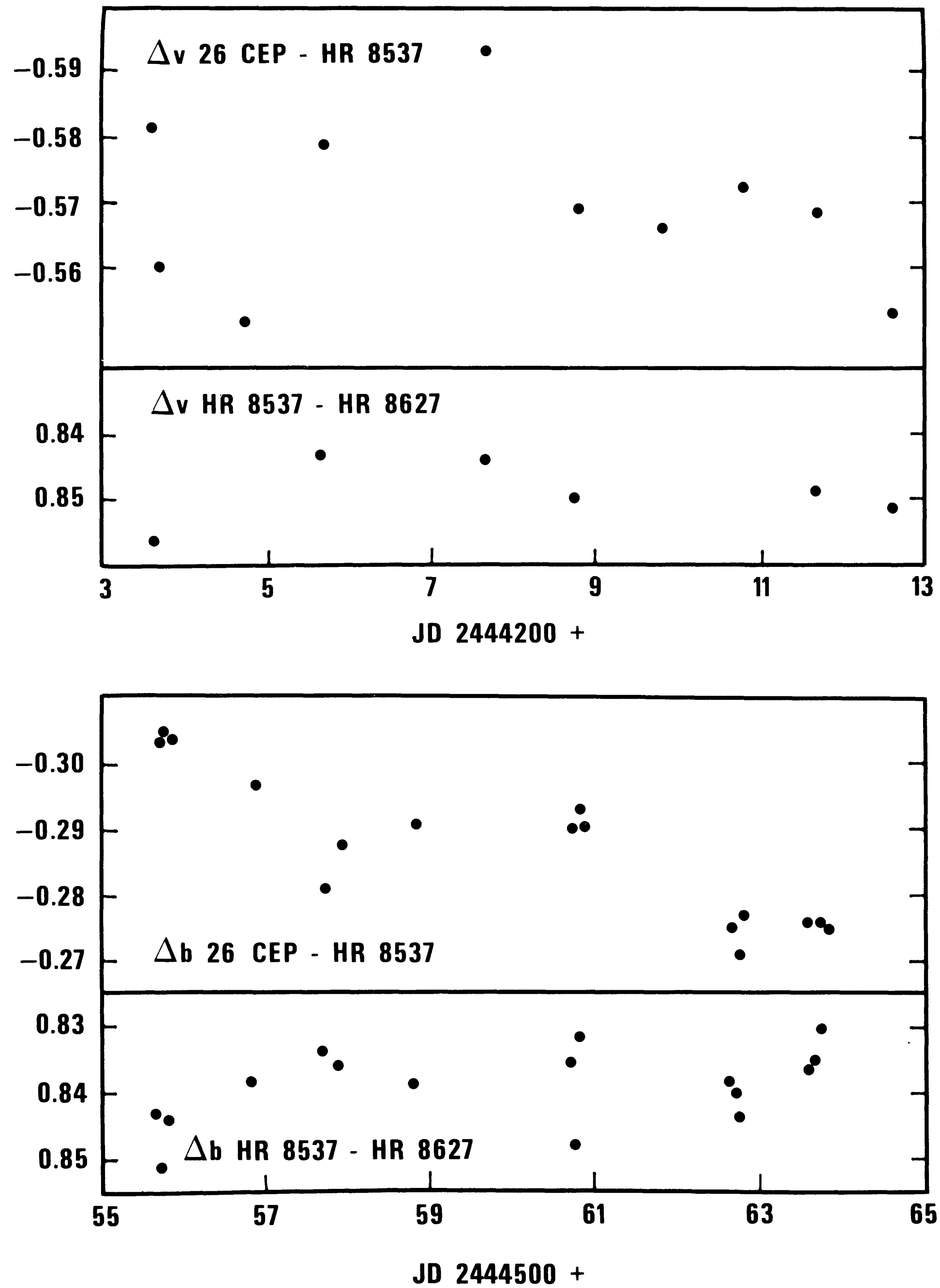

FIG. 7—Photometric variability of 26 Cep (B0.5 I*b*e), relative to HR 8537, in yellow light (top) and blue light (bottom). In each case, the lower panel shows the constancy of HR 8537.

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Table XVII

Physical and Pulsational Properties of the Program Stars

HR	Name	Assoc.[1]	Mv[1]	Sp.T.[1]	log Te	B.C.	Mbol	log Q	Pth	Pobs	Δm
									d	d	
130	κ Cas	Cas OB14	-7.1	B1 Ia	4.303[3]	-1.9	-9.0	-1.36	2.7	3-8	0.05
627	5 Per	Per OB1	-6.7	B5 Ia	4.114[4]	-0.9	-7.6	-1.40	4.2	7½:	0.045
641	-	Per OB1	-6.9	A3 Iab	3.903[4]	-0.1	-7.0	-1.33	15.3	>14:	0.04
685	9 Per	Per OB1	-7.6	A2 Ia	3.929[4]	-0.1	-7.7	-1.30	20	4,(7),(10),≧12,(34)	0.06
1040	-	Cam OB1	-7.1	A0 Ia	3.995[3]	-0.3	-7.4	-1.35	9.6	6,(7.7),≧15	0.03
7551		(5)	-6.0[5]	B0.5 Ibe[2]	4.352[4]	-2.2	-8.2	-1.42	1.1	2-4:	0.03:
7573		Vul OB4	-6.5	A1 Iab	3.954[4]	-0.2	-6.7	-1.36	8.5	(7.7)	Not Var.
7678	-	(5)	-6.7[5]	B1.5 Iae[2]	4.294[3]	-1.9	-8.6	-1.39	2.2	8-10+	0.08
7699		Cyg OB3	-6.5	B5 Ib	4.114[4]	-0.9	-7.4	-1.40	3.8	-	Not Var.
7763	P Cyg	(5)	-8.0	B2 pe[2]	4.086[3]	-0.7	-8.7	-1.30	11.8	40±	0.2:
7977	55 Cyg	Cyg OB7	-6.3	B3 Ia	4.154[3]	-1.1	-7.4	-1.40	2.9	(4.5),5-10:	0.04:
8279	9 Cep	Cep OB2	-6.3	B2 Ib	4.197[3]	-1.4	-7.7	-1.42	2.4	10-11	0.06
8334	ν Cep	Cep OB2	-6.7	A2 Ia	3.929[4]	-0.1	-6.8	-1.35	10.9	5,(7.6),5-10	0.05:
8371	13 Cep	Cep OB2	-6.1	B8 Ib	4.061[4]	-0.6	-6.7	-1.40	3.7	2-3:,12-15:	0.05
8428	19 Cep	Cep OB2	-5.7	09.5 Ib	4.470[4]	-2.8	-8.5	-1.43	0.55	5::	0.02:
8561	26 Cep	(5)	-6.1[5]	B0.5 Ibe[2]	4.352[4]	-2.2	-8.3	-1.43	1.1	4.5,5-10	0.04

Sources and Notes: (1) from Humphreys (1978) unless otherwise noted (2) from the Yale Catalogue of Bright Stars (3) from Underhill (1982), Table 4-1 (4) from Underhill (1982), Table 4-2 (5) see text. With regard to the observed time scales Pobs: values determined by other observers are in brackets, a colon denotes uncertainty, and time scales longer than those listed are generally not ruled out, especially for the stars which were only observed at Kitt Peak. The amplitudes are typical values.