PHOTOMETRIC VARIABILITY OF A COMPLETE SAMPLE OF NORTHERN WOLF-RAYET STARS

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ABSTRACT

At least half of a complete, magnitude-limited sample of northern W-R stars shows systematically modulated continuum light variability, of amplitude $\geqslant$0.02 mag. With the exception of the well-established binary W-R systems, we can make no definitive claims for the remaining stars as to the source of the variability among random wind fluctuations, pulsation or rotation effects, or phase-dependent binary modulations involving a wide O type companion or a close low-mass companion. Light variations of the well-known binaries can be accounted for by occultation effects and random wind variations. WN8 stars appear to show the highest level of random noise among W-R stars.

I. INTRODUCTION

Wolf-Rayet stars are believed to be the final stages in the evolution of massive ($\gtrsim$ 30–40 M_0) stars before they explode as supernovae. They are characterized by fast, dense, hot winds composed of CNO cycle H-burning (WN) or triple-α He-burning (WC) products. Many W-R stars are known to show continuum light variability, due in principle to any combination of the following mechanisms: (1) binary orbit modulation (strictly periodic), (2) pulsation (radial, with periods of minutes to about an hour, or nonradial, with multiple periods in the range of hours to days: Maeder 1985; van Genderen 1985), (3) rotation (of hot or dense spots, quasi-periodic over the lifetimes of the individual spots), or (4) random temporal variations in wind density or temperature, localized or global. The purpose of this investigation is to collect high-precision, broadband photoelectric photometry of an unbiased, complete sample of W-R stars. This is the first time a *systematic* search of this kind has been undertaken. We can then begin to check the above hypotheses with these data.

II. OBSERVATIONS

a) Choice of Stars

Ideally for statistical purposes, the best selection would include all stars in a given volume. In practice, however, this is difficult to realize since it requires precise knowledge of the distance to each star. With a scatter of typically $\sigma_{M_v} \sim 0.5$ mag (Lundström and Stenholm 1984) for a given W-R subtype, this can lead to grossly false and biased estimates of the distances. *Observationally* it is preferable to limit the selection to stars down to a given apparent magnitude so that high photometric precision can be obtained in a reasonable time for each object. We have proceeded in this way for the present sample, which is further constrained to the northern hemisphere by the location of the Wise Observatory used for this project. The present observations, obtained in broadband B with the 1 m telescope, are thus limited by the following conditions: $b \lesssim 11.5$ mag and $\delta \gtrsim -5°$. The blue magnitudes are photoelectric narrowband observations in the continuum at λ 4270 Å (FWHM 70 Å) in the system of Smith (1968), as listed in the catalog of van der Hucht *et al.* (1981). Exceptions to these selection criteria were made in several cases of special interest: WR 123 ($b = 11.74$) and WR 124 ($B = 12.15$) were selected for study because of their possible extreme runaway (binary?) nature (Lamontagne, Moffat, and Seggewiss 1983; Moffat, Lamontagne, and Seggewiss 1982); WR 156 ($b = 12.06$) was included because it belongs to the subclass WN8, suspected of being peculiar compared to other luminous WN stars (cf. Moffat 1983); WR 125 ($b = 14.83$) was chosen for its special status as being an unusual source of relatively hard x-rays (Pollock 1985) and thus a potential candidate for an accretion disk around a compact companion. This star is classified WC7 but its linewidths correspond to WC5, similar to the bright WC7 star WR 140, which is also a strong x-ray source. Finally, WR 133 (HD 190918, $b = 7.61$) and WR 157 (HD 219460, $b = 10.55$) were deleted due to crowding effects, the former being the brightest star (also a long-period double-line binary: Fraquelli 1977) in the center of the open cluster NGC 6871, the latter being a close (sep. 1″) visual binary (but with constant radial velocity, RV: Turner *et al.* 1984) in the open cluster Mark 50. Our total sample thus includes 20 stars (cf. Table II) with four slightly fainter than the $b = 11.5$ limit and two comparitively bright stars excluded. *This sample includes six well-established spectroscopic binaries (SB)*: WR 127, 139, 141, 148, 153, and 155. These will serve as control stars on the variability properties of unquestionable binaries. We also include seven SB candidates: WR 123, 124, 128, 134, 136, 138, and 140. All of the latter group have been claimed to have low-amplitude RV amplitudes (see references below). Most references for individual objects are given later. Besides the WR identification numbers from the van der Hucht *et al.* (1981) catalog, common alternative names (e.g., HD) for each star are given in Table II.

b) Mode of Observation

The bulk of our data were obtained during a contiguous 14 night run in 1984 July using the Nather photometer in single-channel, pulse-counting mode at the 1 m telescope of the Wise Observatory, Israel. Photometric skies prevailed for nearly the whole run. The photometer was equipped with a blue-sensitive, uncooled photomultiplier tube. A diaphragm of diameter 20″ was used. Normally, the observing sequence

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consisted of a series of 10 s integrations each of sky -c-WR-c′-WR-c in broadband B. The sky was measured 45″ to the northeast in 2 s of integration for each 10 s on the star by wobbling a secondary mirror. The symbols c and c′ refer to two nearby comparison stars for each WR star, chosen to have as similar magnitudes and colors as possible compared to the respective W-R star; they are identified in Table I.

Basically, the broad B band will be mainly sensitive to continuum light. In most cases, the emission lines will not contribute more than $\sim 10\%$ of the total light in the filter, although some very strong-line WC stars may approach 50%. The B filter was chosen to create a definite bandpass (as opposed to white light) with a relatively high count rate. Color information was not considered necessary since the continuum variations observed previously in WR stars have often been found to be wavelength independent or nearly so. Nevertheless, broadband V observations were obtained during one night in order to allow correction for secondary extinction on all nights. Emission-line variations, on the other hand, can probably best be studied using precise spectrophotometry.

We also include the observations of nine of these stars made one year earlier (1983 June) at the same telescope, but with the photometer in the twin-channel mode. These observations were made with the W-R star always placed in the central, direct channel, while the comparison star was deflected to the side channel. Both channels were equipped with B filters and blue-sensitive, uncooled tubes. The measuring sequence consisted of 10 s pairs of integrations of the sky, then WR,c, followed by WR,c′, and again WR,c. These data cover a contiguous interval of seven nights. There was no detectable drift between the two channels over the whole interval. Despite generally nonphotometric skies during most of the 1983 run, the overall photometric precision of the dual-channel photometry is better than 1%. Whether clouds were present or not, we always strived to obtain a given number of counts for each integration. The diaphragm size was 30″ in each channel and the wobble the same as in 1984. Even though they precede the 1984 data, we will treat the 1983 data as secondary in importance because of the poorer observing conditions and shorter-duration run. Note that even though the same comparison stars may have been used in 1983 and 1984 (and even if none of the comparison stars is variable on a long time scale), the mean magnitude differences WR − c and WR − c′ will not necessarily be the same for each year; only the difference c − c′ measured in the same channel in 1983 can be expected to be so. Often it was not appropriate to choose the same comparison stars for each year, due either to already detected variability in 1983 or to positional constraints using the two-channel mode.

c) Reduction of the Observations

After subtracting off the sky and weeding out unreliable measures, magnitude differences WR − c, WR − c′, and c − c′ were obtained for each sequence of measurements leading to one final data point, which is an average covering 15–30 min, depending on the stellar magnitude. Final values were then obtained by correcting for secondary extinction, assuming a mean coefficient $k''_B = -0.06$. These values were then plotted versus time in Figs. 1–17. Stars with large variations and well-known periods (WR 139, 153, and 155) are plotted only versus phase in later figures. To save journal space, the original data are not given in tabular form; they can be reconstructed from the plots with a precision of better than ± 0.05 days $= \pm 1.2$ hr in time and ± 0.001 mag. They are also available on request from A.F.J.M.

The next step is to establish which W-R stars are variable and which are constant within some well-defined level of significance. This would be an easy matter if all the comparison stars were constant. One could then use $\sigma(\mathrm{c}-\mathrm{c}')$ as a measure of the instrumental scatter and the ratio $\sigma(\mathrm{WR}-\mathrm{c})/\sigma(\mathrm{c}-\mathrm{c}')$ could be used as a quantitative test for intrinsic variability of the WR star, assuming that $\sigma(\mathrm{WR}-\mathrm{c})\simeq\sigma(\mathrm{c}-\mathrm{c}')$ in the absence of variability. This assumption was found to be a good approximation even for different total counts accumulated for different stars, since atmospheric scintillations dominate over Poisson statistics for all but the faintest stars, for which longer integrations were carried out. Figure 18 supports this statement.

The sharpest test to apply here is the F test, which can be used to check for differences of the variances of samples drawn from two normal distributions. When one of the stars is intrinsically variable, it will not necessarily be in such a way that it will yield a normal distribution when observed even randomly with time (e.g., for a sine-wave modulation). However, we will assume this to be only a second-order effect and we will apply the test in any case. The reliability of the test can also be judged from the results for stars of known or expected behavior.

From Table I it is apparent that many of the comparison stars are in fact variable. This is borne out in Fig. 18, where we plot $\sigma(\mathrm{c}-\mathrm{c}')$ versus b mag of the fainter star for all pairs of comparison stars in 1983 and 1984. This figure suggests a dichotomy, with intrinsically constant stars grouped around $\sigma(\mathrm{c}-\mathrm{c}') = 0.005$ mag and intrinsically variable stars occurring above $\sigma(\mathrm{c}-\mathrm{c}') = 0.008$ mag. The former dispersion corresponds to the expected instrumental scatter for this kind of observation in good observing conditions.

Assuming $\sigma_{\mathrm{inst}} = 0.005$ mag to be a good estimate of the instrumental noise level, an F test would imply that stars with $\sigma(\mathrm{c}-\mathrm{c}') > 0.010$ in 1983 and > 0.008 in 1984, where there are more data, are intrinsically variable at the $> 95\%$ confidence level. Here we take the points above $\sigma(\mathrm{c}-\mathrm{c}') = 0.008$ to indicate that at least one of the comparison stars is probably variable. As we shall see later for the W-R star WR 127, for which $\sigma(\mathrm{WR}-\mathrm{c}) = 0.0125$ and $\sigma(\mathrm{c}-\mathrm{c}') = 0.006$, this cutoff limit is reasonable, since this star shows a convincing phase-modulated light curve with a dip at phase zero when the W-R star passes in front.

The next question is to determine which comparison star of the pair, if any, is variable and search for simple periodic variability among the suspected variable comparison stars. This has been done by fitting a series of sine waves of arbitrary phase and amplitude for periods ranging from 0.5 to 30 days and incremented in equal frequency steps $\Delta\nu = 1/(20T)$, where T is the total time span of the data. When the scatter around the sine curve is a minimum, we explore the reality of a period by plotting magnitude versus phase. This is shown in Fig. 19 for the most significant periods found among the more extensive 1984 data. Note that the light curves presented here are not all sine waves. However, for period searching, a sine wave is a satisfactory, expedient approximation. For the number of observations available here, this method is more suitable than the nonparametric period-search algorithms such as that of Lafler and Kinman (1965). The periods (if found, otherwise possible secular variability) and amplitudes of the variable comparison stars

TABLE I. Properties of the comparison stars.

Star	Year used	$(\Delta\alpha \cos\delta)'$	$\Delta\delta'$	ΔB (mag)	$\Delta(B-V)$ (mag)	$\sigma(c-c')$ (in mags) 83	$\sigma(c-c')$ (in mags) 84	Remarks
C1-WR 123	83, 84	+ 7.1	− 7.0	− 0.64	+ 0.63	0.012	0.010	Var., $P = 0.82$ days, $A = 0^{m}02$
C4-WR 123	83, 84	− 8.5	− 9.0	+ 0.50	0.00			
C2-WR 124	83	− 8.1	− 3.1	− 0.39	− 0.34	0.016	—	Var., $P = 4.75$ days, $A = 0^{m}05$
C3-WR 124	83	− 8.0	− 1.4	+ 1.06	+ 1.11			
C1-WR 124	84	+ 13.5	− 1.3	− 3.41	− 0.09	—	0.009	Var., $P = 3.81$ days, $A = 0^{m}02$
C4-WR 124	84	+ 11.4	− 1.4	− 0.45	− 0.22			
C2-WR 125	84	+ 4.7	+ 1.6	− 3.80	− 0.94	—	0.006	
C4-WR 125	84	+ 4.3	+ 0.7	− 2.06	− 0.82			
C1-WR 127	84	− 3.9	+ 3.4	− 1.64	− 0.09	—	0.006	
C2-WR 127	84	− 3.7	− 2.3	− 1.36	− 0.07			
C1-WR 128	83	− 3.6	+ 1.9	− 0.30	− 0.03	0.012	—	Var., secular?, $A \geqslant 0^{m}02$
C2-WR 128	83, 84	+ 5.3	+ 0.8	− 0.97	+ 0.18	—	0.005	
C3-WR 128	84	+ 3.3	+ 10.0	− 2.12	+ 0.09			
C1-WR 134	83	− 1.7	+ 5.8	+ 2.25	+ 1.85	0.014	—	Var., secular?, $A \geqslant 0^{m}03$
C2-WR 134	83	− 6.0	− 6.4	+ 2.57	+ 0.12			
C5-WR 134	84	− 0.5	+ 1.0	+ 0.51	+ 0.03	—	0.004	
C6-WR 134	84	0.0	− 1.4	+ 2.09	+ 0.44			
C2-WR 135	83	+ 1.4	− 6.6	+ 3.68	+ 0.50	0.016	—	Var., $P = 5$ days, $A = 0^{m}04$
C1-WR 135	83, 84	+ 2.6	− 7.7	+ 1.33	+ 0.13	—	0.010	Var., $P = 5.88$ days, $A = 0^{m}025$
C5-WR 135	84	− 2.3	− 6.8	+ 2.61	+ 0.36			
C1-WR 136	83	+ 1.4	+ 5.2	+ 0.74	+ 0.97	0.006	—	
C2-WR 136	83	− 8.0	+ 2.9	+ 1.31	+ 0.81			
C3-WR 136	84	+ 7.8	− 7.4	+ 1.71	+ 0.33	—	0.010	Var., $P = 8.2$ days, $A = 0^{m}02$
C4-WR 136	84	− 9.7	− 7.3	+ 1.47	+ 0.16			Var., $P = 3.28$ days, $A = 0^{m}015$
C3-WR 137	83	+ 1.6	+ 5.3	− 0.27	+ 1.00	0.007	—	
C1-WR 137	83, 84	− 5.4	− 3.1	− 1.69	− 0.14	—	0.005	
C2-WR 137	84	− 8.2	− 2.3	+ 0.44	+ 0.20			

TABLE I. (continued).

Star	Year used	$(\Delta\alpha \cos\delta)'$	$\Delta\delta'$	ΔB (mag)	$\Delta(B-V)$ (mag)	σ(c − c′) (in mags) 83	84	Remarks
C2-WR 138	83	− 1.4	+ 5.6	+ 1.48	+ 0.89	0.010	—	Var., $P = 2.5$ days, $A = 0^m02$
C1-WR 138	83, 84	− 3.6	+ 1.6	− 0.23	+ 0.02			
C3-WR 138	84	− 3.6	+ 6.6	+ 0.61	− 0.07	—	0.004	
C1-WR 139	84	− 0.4	+ 5.2	+ 1.73	+ 0.03			
C3-WR 139	84	+ 7.1	+ 6.1	− 0.27	− 0.42	—	0.011	Var., $P = 3.42$ days, $A = 0^m025$
C1-WR 140	84	+ 6.7	− 10.2	+ 1.98	− 0.12			
C2-WR 140	84	+ 8.4	− 5.0	+ 3.32	− 0.08	—	0.003	
C1-WR 141	84	− 6.9	+ 1.5	− 1.81	− 0.33	—	0.020	Var., $P = 0.516$ days, $A = 0^m06$
C2-WR 141	84	+ 4.1	− 3.9	− 0.18	− 0.58			Var., $P = 3.74$ days, $A = 0^m03$
C1-WR 148	83, 84	− 4.9	− 1.9	− 0.27	− 0.10			
C2-WR 148	83, 84	− 2.7	− 6.6	− 0.16	− 0.08	0.004	0.004	
C2-WR 153	84	− 1.8	+ 3.9	− 0.23	+ 0.40			
C3-WR 153	84	+ 7.4	+ 4.6	− 0.93	+ 0.70	—	0.004	
C1-WR 155	84	− 10.3	+ 5.2	− 0.54	+ 0.02			
C2-WR 155	84	+ 5.4	+ 10.8	+ 1.42	+ 0.01	—	0.005	
C2-WR 156	84	+ 1.4	− 2.2	− 1.99	− 0.60			
C3-WR 156	84	+ 3.6	+ 3.1	+ 0.31	− 0.16	—	0.007	
C1-WR 1	84	− 6.9	− 3.1	+ 0.17	+ 0.17			
C2-WR 1	84	− 9.6	− 3.7	+ 0.26	+ 0.19	—	0.005	
C1-WR 3	84	− 3.2	− 1.4	+ 0.42	+ 0.99			
C4-WR 3	84	− 13.3	+ 8.2	+ 0.02	+ 0.80	—	0.011	Var., $P = 2.82$ days, $A = 0^m03$
C1-WR 4	84	− 4.8	+ 6.6	− 0.97	+ 0.14			
C2-WR 4	84	+ 8.7	− 9.3	− 1.20	+ 0.28	—	0.012	Var., $P = 4.3$ days, $A = 0^m035$

Notes to TABLE I

The coordinates are offsets from the W-R star.

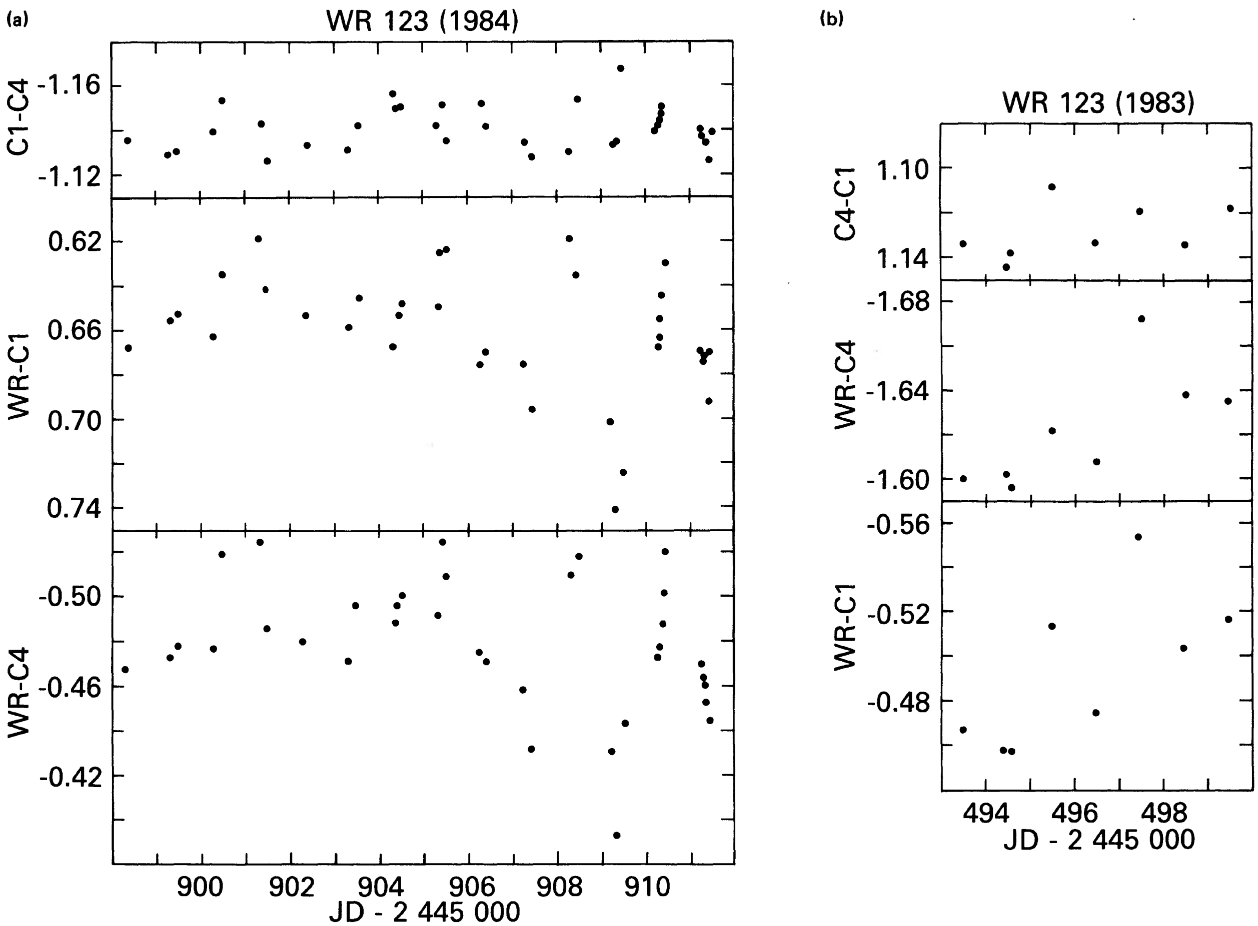


FIG. 1. *B* magnitude difference versus time for WR 123 in (a) 1984 and (b) 1983.

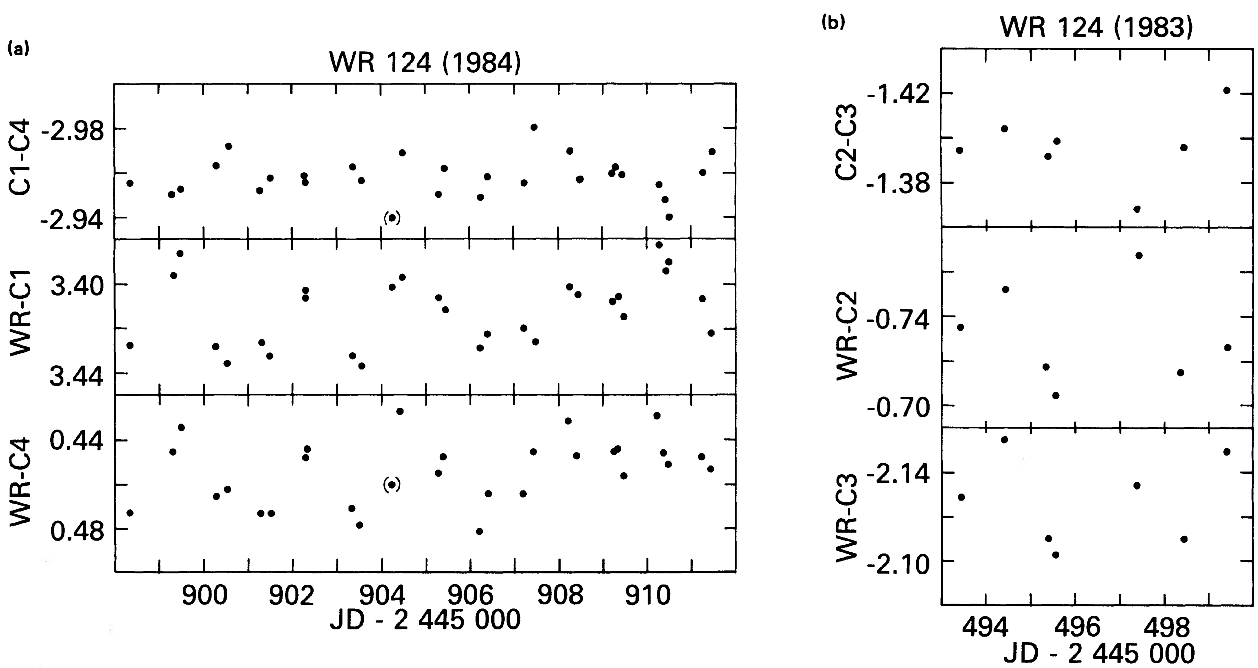


FIG. 2. *B* magnitude difference versus time for WR 124 in (a) 1984 and (b) 1983.

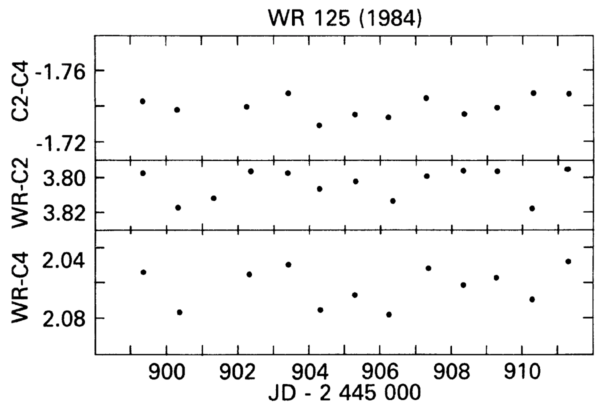


FIG. 3. *B* magnitude difference versus time for WR 125 (1984). Star C4 for JD 2 445 901.3 was inadvertently measured with a different sky position which contained a faint star, and hence is omitted.

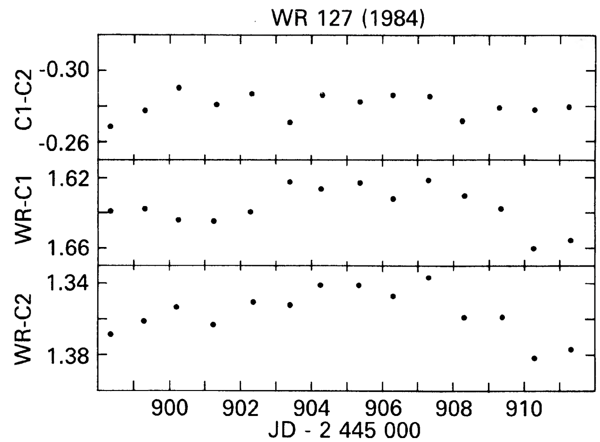


FIG. 4. *B* magnitude difference versus time for WR 127 (1984).

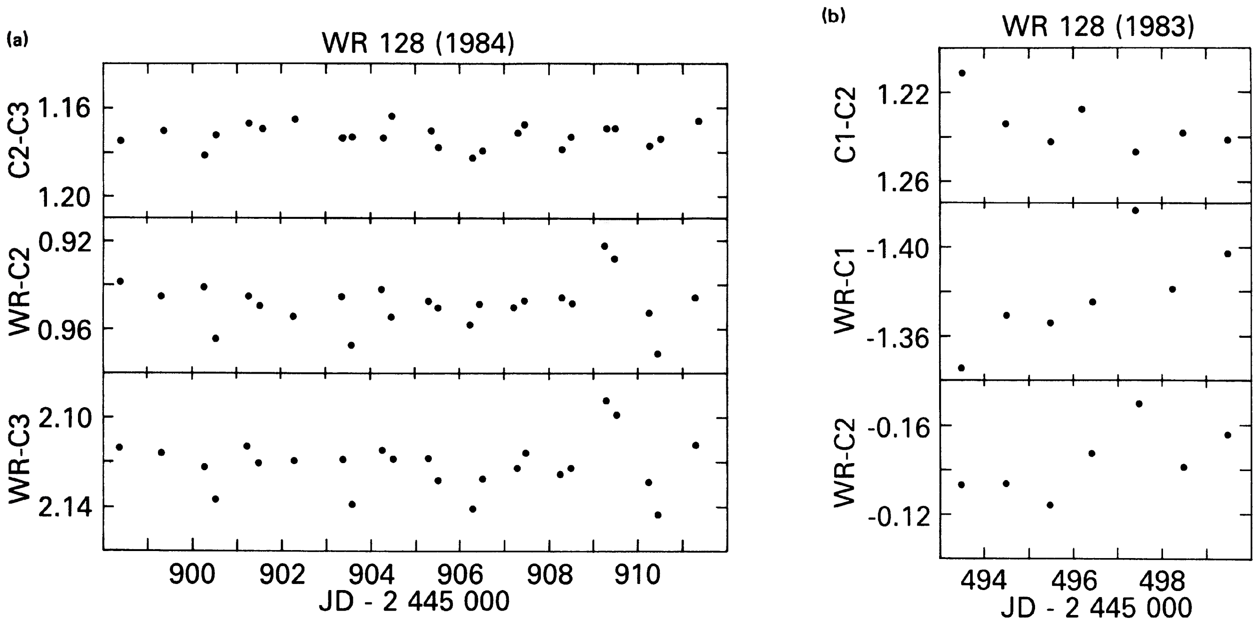


FIG. 5. *B* magnitude difference versus time for WR 128 in (a) 1984 and (b) 1983.

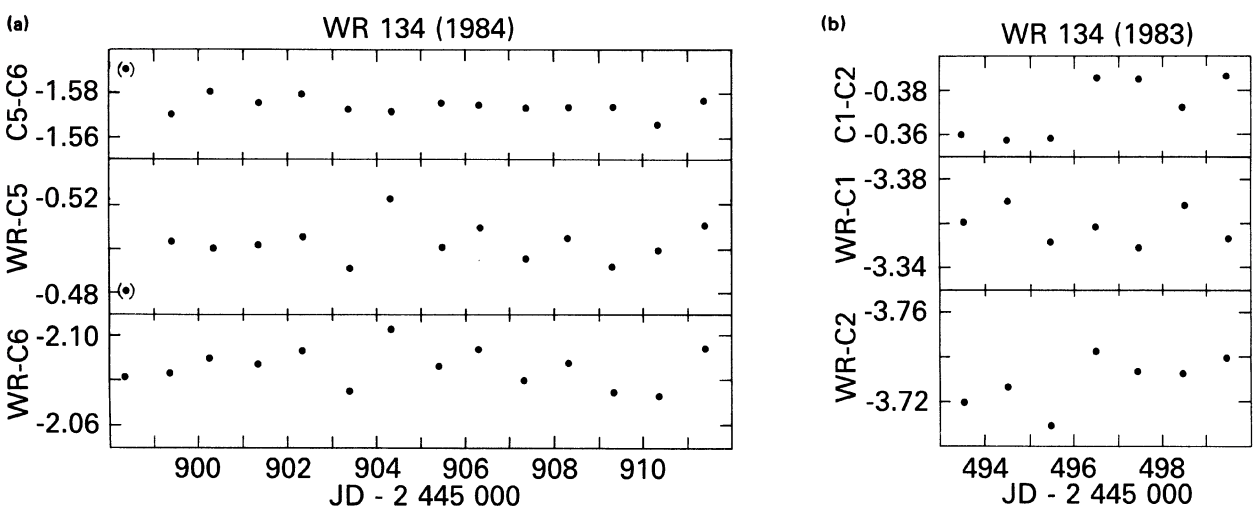


FIG. 6. *B* magnitude difference versus time for WR 134 in (a) 1984 and (b) 1983.

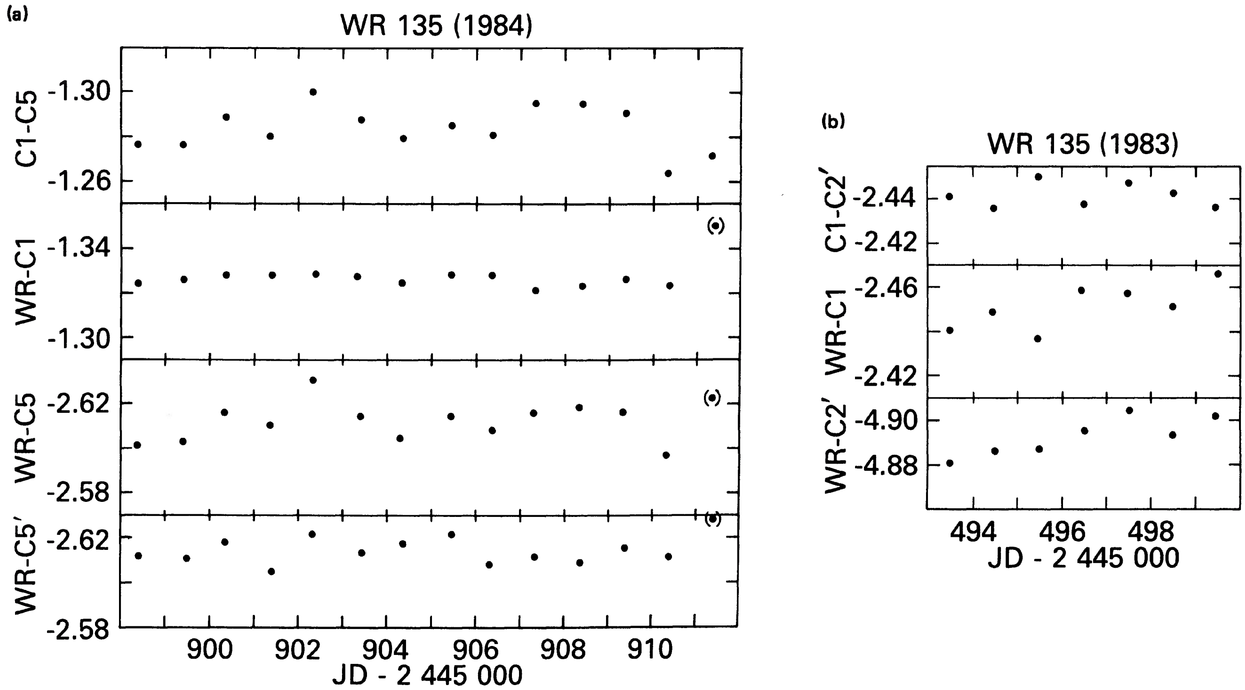


FIG. 7. B magnitude difference versus time for WR 135 in (a) 1984 and (b) 1983. A prime on the comparison-star name means that low-order correction curves for variability have been applied. This convention is used for all stars (except c,c′ without a specific name).

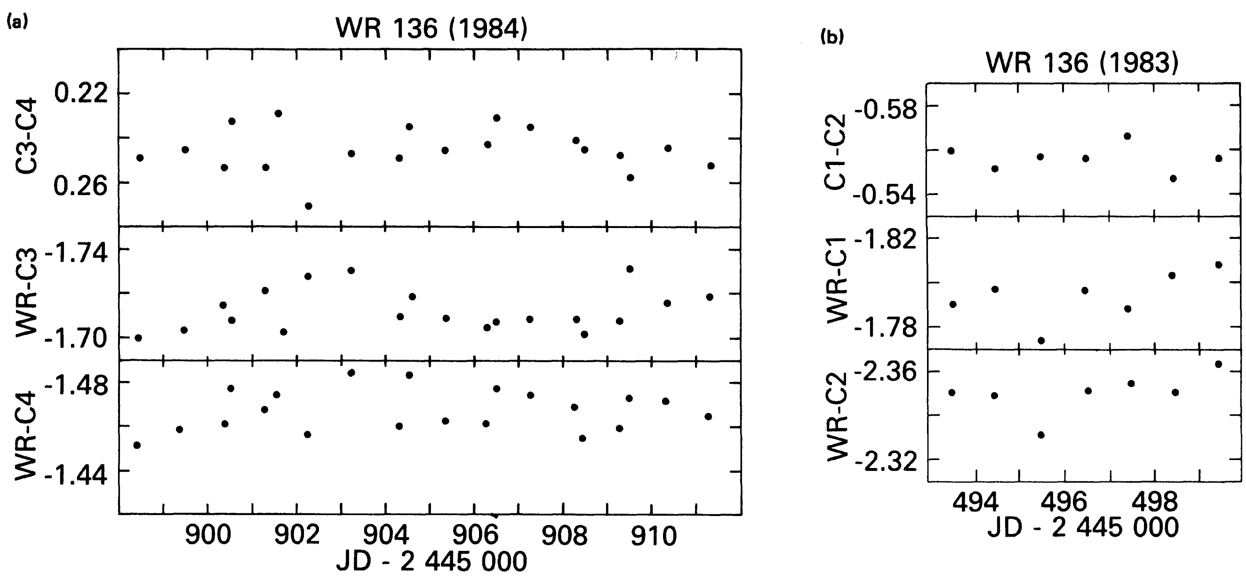


FIG. 8. B magnitude difference versus time for WR 136 in (a) 1984 and (b) 1983.

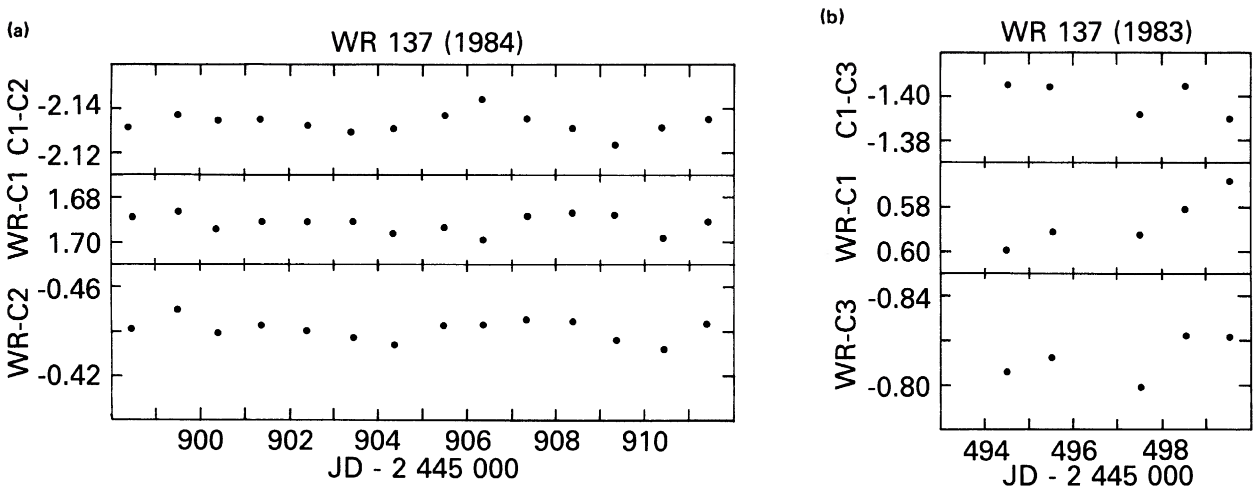


FIG. 9. *B* magnitude difference versus time for WR 137 in (a) 1984 and (b) 1983.

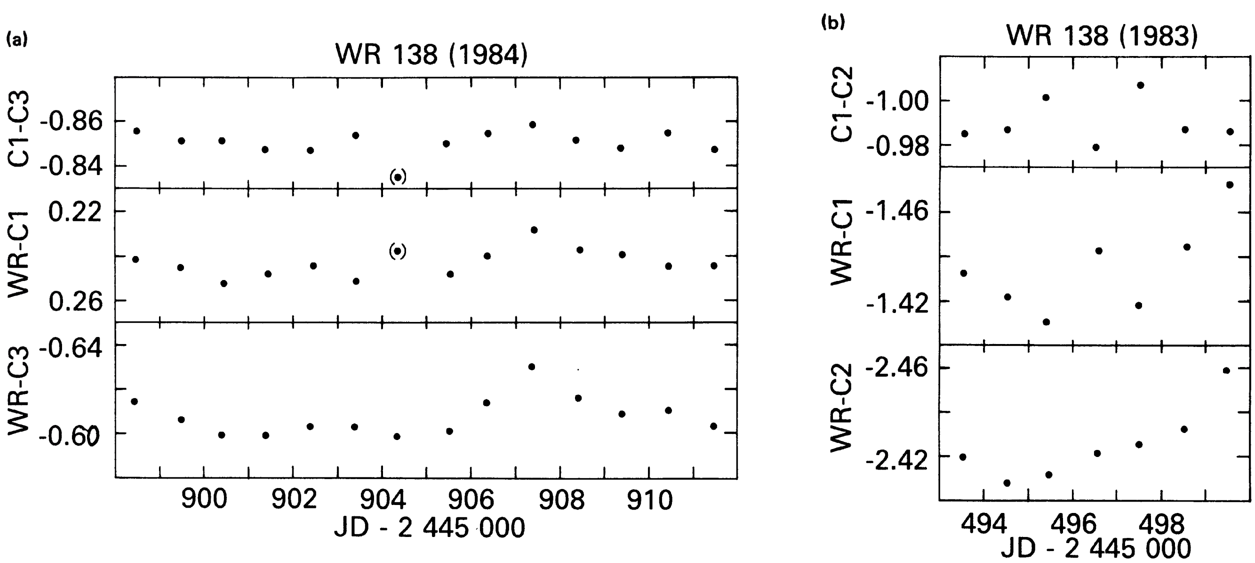


FIG. 10. *B* magnitude difference versus time for WR 138 in (a) 1984 and (b) 1983.

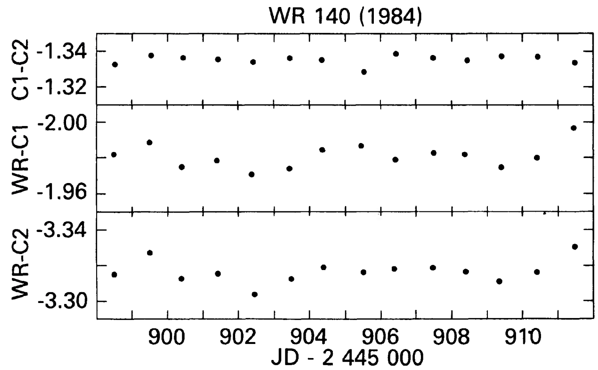


FIG. 11. B magnitude difference versus time for WR 140 (1984).

are noted in Table I. To determine which of the two comparison stars was variable we noted which of WR — c or WR — c′ also revealed the same period as seen in c — c′, in addition to any WR periodicity. It is encouraging to note that the O — C scatter about the c — c′ light curves generally falls below 0.009 mag, with most around 0.005 mag, like the instrumental scatter. This supports the reality of the periods found and the light curves drawn, although aliasing may eventually require revision of the actual periods in some cases.

We draw attention to the fact that of the 50 randomly chosen comparison stars, 15 (30%) are suspected variables with amplitudes generally > 0.02 mag, with a maximum of 0.06 mag. Most of these show periods, while two of the variables show only secular variations during the 13 day interval spanning the data. It is possible judging from Fig. 18 that there may not be a continuum of variation; either a star varies with an amplitude $A > 0.02$ or it does not vary at all ($A < 0.005$). The smooth trends through the comparison stars are used to correct the magnitudes of the star that is variable.

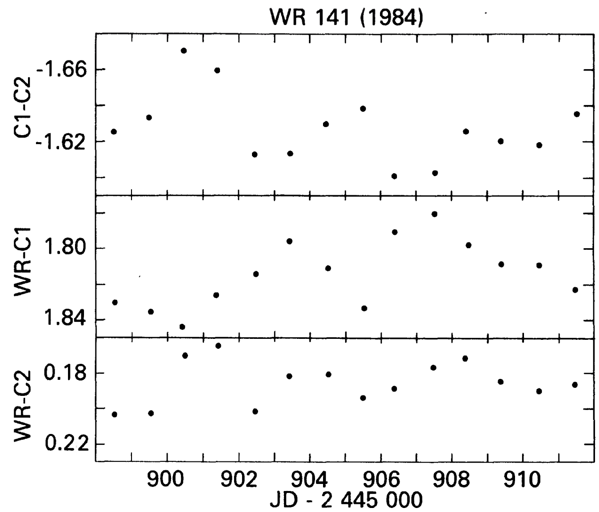


FIG. 12. B magnitude difference versus time for WR 141 (1984).

Now that we have essentially eliminated the effects of variable comparison stars we can proceed to determine which WR stars are variable. The results of this determination are given in Table II. Besides presenting basic data for each WR star, this table gives information on standard deviations and the significance of intrinsic variability. σ_1 and σ_2 refer to the standard deviations about a simple mean, of the magnitudes $m_{WR} - m_c$ and $m_c - m_{c'}$, respectively. If the observed ratio σ_1/σ_2 is greater than the critical values listed under "F test" for 99% and 95%, the star is considered to be significantly variable at that level or better. When the probability of intrinsic variability exceeded ~95%, we carried out a period search, again using a sine-wave fit algorithm. This was done for the 1984 data only; the 1983 data

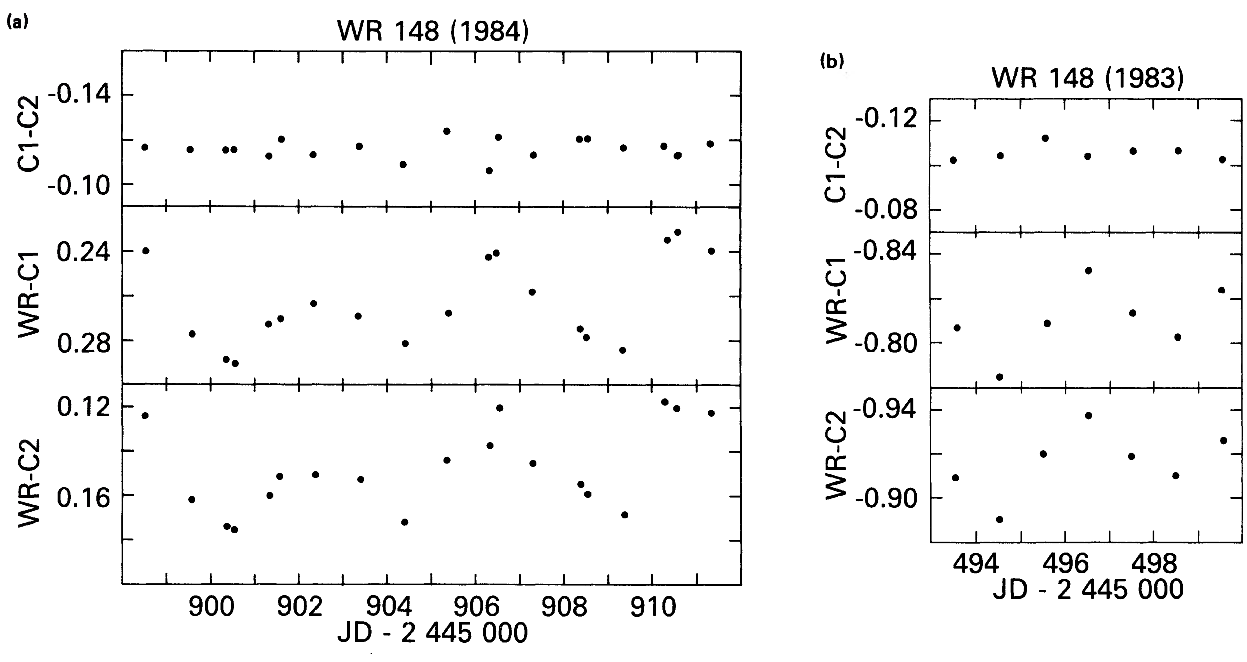


FIG. 13. B magnitude difference versus time for WR 148 in (a) 1984 and (b) 1983.

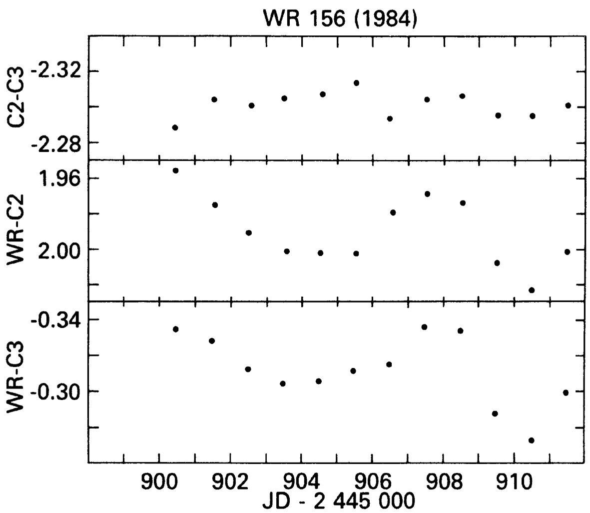


FIG. 14. *B* magnitude difference versus time for WR 156 (1984).

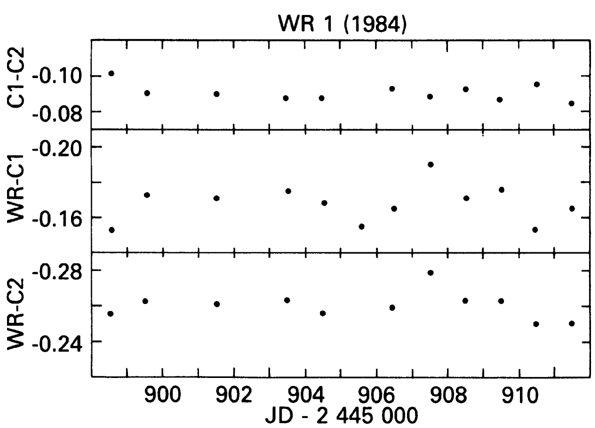


FIG. 15. *B* magnitude difference versus time for WR 1 (1984). Note that the observation of C2 at JD 2 445 905.6 is missing.

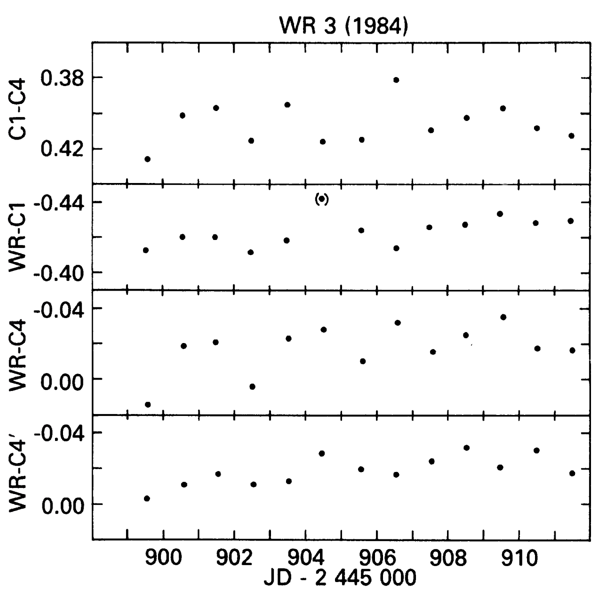


FIG. 16. *B* magnitude difference versus time for WR 3 (1984).

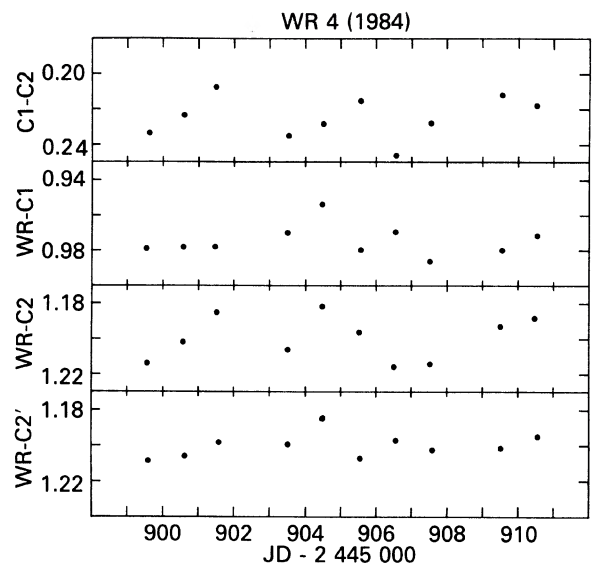


FIG. 17. *B* magnitude difference versus time for WR 4 (1984).

are too sparse for this purpose, although they can be used to check for compatibility with the 1983 or other data. Table II also indicates the results of the period search, with only the most significant period listed. The technique is illustrated in Fig. 20 for three stars. We note that the most significant periods in Table II never yield a magnitude scatter significantly less than the instrumental scatter, i.e., $\sigma_{O-C} \ll \sigma(c-c')$; if the scatter is greater, this is often due to intrinsic, random noise (but not another period) and/or a nonsinusoidal light curve (see below). If the scatter had turned out to be significantly less in some cases, one could have argued that the periods so obtained were spurious. Our present evaluation is to say that the newly found, listed per-

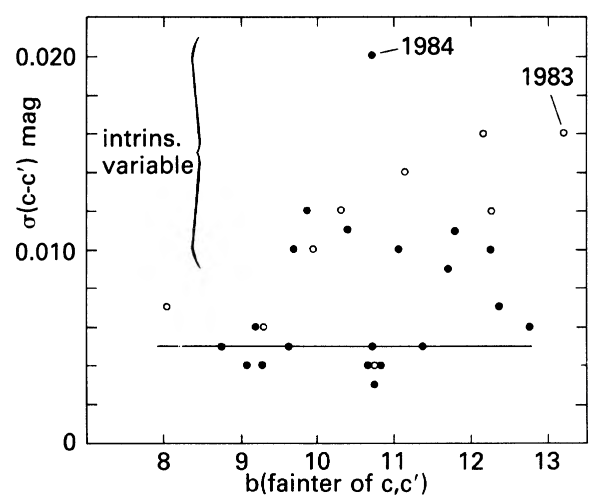


FIG. 18. Standard deviation about a constant mean value of the magnitude difference of the comparison-star pairs in Table I, versus the fainter *B* magnitude of the two stars. The horizontal line indicates the probable mean level of instrumental scatter. At least one of the stars in the pair is probably intrinsically variable above the 95% significance level if $\sigma(c-c') > 0.009$ mag.

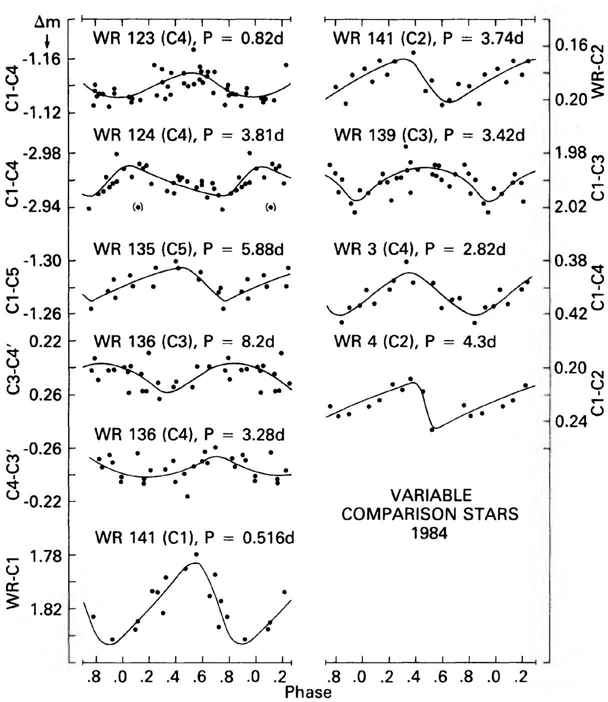


FIG. 19. Phased light curves for variable comparison stars (1984). Stars indicated by a prime have been corrected for variability by a smooth, low-order curve drawn through the data. A zero point in time, of JD 2 445 900.0, was arbitrarily adopted for all stars.

iods are the most likely ones if the variations in excess of the noise are truly periodic.

Finally, we present phased light curves of all stars observed for which (a) variability is certain and the most likely period found by sine-wave fitting is relatively short, or (b) a previous period has been published but may not be evident in the present data. *We cannot and do not claim that these curves "prove" periodic variability, except in the cases of well-known binaries.* Rather, they are convenient visual representations of the data; all suggested periods must be tested with further observations extending over long, contiguous runs. The light curves appear in Figs. 21–35. Stars with suspected secular variation (cf. Table II) can be seen in the appropriate figures, which show *B* magnitude plotted as a function of time.

III. DISCUSSION OF THE RESULTS

We present a discussion of each star, starting with the undisputable binaries and ending with stars for which evidence of periodicity is the weakest or non-existent.

a) Well-Known SBs

This group includes WR 127, 139, 141, 148, 153, and 155 in the present program. For the long-period binary WR 133, a partial light curve exists elsewhere (Cherepashchuk 1975). Despite the claim by Cherepashchuk of no intrinsic variability in this star, we take the slow parabolic trend clearly seen in his photometric data (his Fig. 2, center) to imply a low-amplitude, long-period light variability with minimum light occurring near phase zero. We note that ephemeri are calculated using the best recent estimate of the period, while the zero point is consistently chosen to coincide with the passage of the W-R star in front (for WR 133, cf. Fraquelli and Horn 1982, quoted in Massey 1981b).

1) WR 139=HD 193576

Of the six program stars, WR 139 = V444 Cyg is probably the best-known system, with a WN5 and an O6 star plainly visible in the spectrum. It has always been a key object for determining basic parameters such as T_{eff} of a WN5 star (cf. recent work of Cherepashchuk, Eaton, and Khaliullin 1984; Pauldrach *et al.* 1985). The newly found high effective temperature has strong implications for the structure and evolution of WR stars. Our data (Fig. 28) confirm the ephemeris of Cherepashchuk and Khaliullin (1973), who found no evidence for a period change. Within the noise limitations of our data, there is no evidence for variations from a smooth light curve beyond the instrumental scatter seen in the comparison stars, after correction for variability of c3.

2) WR 155=HD 214419

The single-line system WR 155 = CQ Cep is the shortest-period W-R binary known. It is therefore not surprising that it has the largest amplitude, as confirmed in Fig. 33. Here, we use the ephemeris of Walker *et al.* (1983) to determine the phases. Again, as for V444 Cygni, we confirm the lack of an apparent period change. We note that primary minimum occurs at phase 0.5, when the unseen O star passes in front. In most W-R binary systems this occurs at phase 0.0 (W-R component in front), although the secondary minimum in CQ Cep at phase 0.0 is almost as deep as the primary minimum.

3) WR 153=HD 211853

WR 153 appears to be a quadruple system (Massey 1981a) in which the O star reveals two different orbital motions, one in antiphase with the WN6 star and another independent one associated with a second unseen star, probably of O type. This is confirmed in Fig. 32, where both stars show eclipses at independent, unrelated times. Allowing for mutual light dilution, each eclipse would actually be deeper than that seen here. Evidently the ephemeris of the W-R component is quite well established with only a small shift in the time of minimum ($\Delta\phi \sim 0.03$). On the other hand, the ephemeris of the O component does not yield minimum light at or near O star phase 0.0 or 0.5, as seen in the light curves of Hjellming and Hiltner (1963) and Stepien (1970) when plotted with the Massey (1981a) ephemeris. A similar deviation occurs in the light curve of Cherepashchuk (1975). This is unlikely to be due to effects of a long-period orbit between the two close pairs since the W-R system does not show the same effect. We suspect that the period of the O + O system is subject to revision. We further note that our data show no hint of a secondary eclipse in the W-R system at phase 0.5, while the closer O system shows a more rounded light curve with a suggestion of a secondary minimum displaced ~ 0.5 in phase from the primary minimum. This secondary minimum of the O star pair is clearly evident in the appropriately plotted light curves of Hjellming and Hiltner (1963) and Stepien (1970). Note that the scatter about the light curves corresponds to the instrumental scatter, as in the case of WR 139.

4) WR 127=HD 186943

The WN4 + O9.5 V binary WR 127 has a well-determined orbit (Massey 1981a). Our light curve (Figs. 4 and

TABLE II. Photometric results for the Wolf-Rayet stars.

WR	HD	Sp	v	$b-v$	year	n	σ_1 (WR − c)	σ_2 (c − c′)	σ_1/σ_2	F test 99%	F test 95%	Prob. intr. var.	best sine-wave fit (WR-c) $P(d)$	σ_{O-C}	like $\sigma_2(c-c')$?	Light curve ampl. (mag)
(123)	177230	WN8	11.27	+0.47	83	8	0.030	0.010	3.0	2.6	2.0	> 99%	compatible with 1984			0.06:
					84	35	0.0275	0.007	3.9	1.5	1.3	> 99%	2.37	0.021	no: (a) + (b)	0.06
(124)	(209 BAC)	WN8	(11.08)	(+1.07)	83	7	0.0215	0.007	3.1	2.9	2.1	≳ 99%	compatible with 1984			0.04
					84	29	0.0155	0.006	2.6	1.6	1.4	> 99%	2.73	0.011	no: (a)	0.03
(125)	(MR 93)	WC5	13.48	+1.35:	84	13	0.0095	0.006	1.6	2.1	1.7	≲ 95%	4.6	0.007	yes	0.015
127	186943	WN4 + O9.5 V	10.36	+0.21	84	14	0.0125	0.006	2.1	2.0	1.6	≳ 99%	9.55*	0.007	yes	0.03
128	187282	WN4	10.56	+0.02	83	7	0.0165	0.008	2.1	2.9	2.1	95%	compatible with 1984			0.03:
					84	24	0.0115	0.005	2.3	1.6	1.5	99%	(3.85*)	0.010	no: (b?)	0.02
134	191765	WN6	8.31	+0.25	83	7	0.0085	0.008	1.1	2.9	2.1	—	(comp. stars noiser than 1984)			0.01:
					84	14	0.0085	0.004	2.1	2.0	1.6	≳ 99%	1.81	0.005	yes	0.02
135	192103	WC8	8.51	−0.06	83	7	0.0095	0.006	1.6	2.9	2.1	—	— (Secular variation?)			> 0.01:
					84	14	0.004	0.006	0.7	2.0	1.6	—	—			< 0.005
136	192163	WN6	7.73	+0.25	83	7	0.0105	0.006	1.8	2.9	2.1	< 95%	?			0.02:
					84	20	0.0075	0.007	1.1	1.7	1.5	—	(0.45*)	0.005	(yes)	0.01:
137	192641	WC7 + abs	8.18	+0.15	83	5	0.011	0.007	1.6	4.0	2.5	—	— (secular variation?)			> 0.01:
					84	14	0.0045	0.005	0.9	2.0	1.6	—	—			< 0.005
138	193077	WN5 + abs	8.21	+0.26	83	7	0.0205	0.003	6.8	2.9	2.1	> 99%	~ compatible with 1984			> 0.03:
					84	14	0.0075	0.004	1.9	2.0	1.6	~ 98%	11.6:	0.005	yes	0.02
139	193576	WN5 + O6	8.27	+0.38	84	26	0.084	0.008	10.5	1.6	1.4	> 99%	4.21*/2	0.058	no: (b!)	0.30/0.16
140	193793	WC7 + abs	7.19	+0.24	84	14	0.0065	0.003	2.2	2.0	1.6	≳ 99%	6.25	0.005	yes:	0.01
141	193928	WN6(+O)	10.15	+0.75	84	14	0.008	0.007	1.1	2.0	1.6	—	(21.64*)		(yes)	< 0.01
148	197406	WN7	10.50	+0.42	83	7	0.0155	0.004	3.9	2.9	2.1	> 99%	compatible with 1984			0.04
					84	19	0.019	0.004	4.8	1.7	1.5	> 99%	4.32*	0.010	no: (a) + (b)?	0.04
153	211853	WN6 + O	9.20	+0.32	84	21	0.0355	0.004	8.9	1.7	1.5	> 99%	6.69*	0.027	no: (b!)	0.09,(0.04)
155	214419	WN7(+O)	8.94	+0.33	84	20	0.1425	0.005	28.5	1.7	1.5	> 99%	1.64*/2	0.029	no: (b)	0.42/0.38
(156)	(MR 119)	WN8	11.18	+0.88	84	12	0.0195	0.007	2.8	2.1	1.7	> 99%	6.5	0.009	yes:	0.05
1	4004	WN5	10.54	+0.56	84	12	0.0095	0.005	1.9	2.1	1.7	~ 97%	6.1	0.007	yes:	0.015
3	9974	WN3 + abs	10.79	0.00	84	13	0.0075	0.006	1.2	2.1	1.7	—	— (secular variation?)			≳ 0.015
4	16543	WC5	10.61	+0.23	84	10	0.008	0.005	1.6	2.3	1.8	≲ 95%	10:	0.005	yes	0.01

Notes to TABLE II—General Notes

WR name in parentheses indicates star fainter than $b = 11.5$. Spectral subclass and v, $b - v$ from van der Hucht *et al.* (1981). σ_1 (WR − c) is the rms mean of the dispersions in WR − c and WR − c′ after correction for variability of the comparison star(s).

σ_2(c − c′) is the dispersion of c − c′ after correction for variability if necessary for either or both of c and c′.

F test is the *expected* ratio of σ_1/σ_2 for $n - 1$ degrees of freedom in each variable, where n = no. of observations.

σ_{O-C} is the scatter (std. dev.) about a fitted sine wave with the indicated period. Periods with an asterisk are well-established binary periods from RV orbits. Parentheses indicate that the previously published period was not seen in these data.

(a) noise, (b) non-sine.

Notes to TABLE II—Individual Stars

WR 123: The alias periods 1.76 and 0.70 days are also seen, but at an inferior level of significance. No other periods down to $P = 0^{\rm m}2$ are seen (cf. Fig. 20).

WR 124: Other aliases of inferior significance are seen (cf. Fig. 20).

WR 125: The data are not sufficient to eliminate short-period aliases.

WR 127: The 0.9/1.1 day aliases are of similar significance (cf. Fig. 20) but can be rejected from knowledge of the true orbital period.

WR 128: No significant periods show up in these data.

WR 134: The 2.24 day alias is inferior although other shorter aliases cannot be eliminated.

WR 136: Since both comparison stars (1984) appear to be variable, the results here are not as convincing. However, in the uncorrected data, we do see a shallow dip in the periodogram at $P = 0.45$ days.

WR 138: The best alias, close to $P \sim 1.1$ days, cannot be excluded.

WR 140: cf. WR 125.

WR 156: cf. WR 125.

WR 1: cf. WR 125.

WR 3: Despite the lack of formal evidence for variability, Fig. 16 suggests secular variation of amplitude $\sim 0^{\rm m}015$ over 13 days.

WR 4: cf. WR 125.

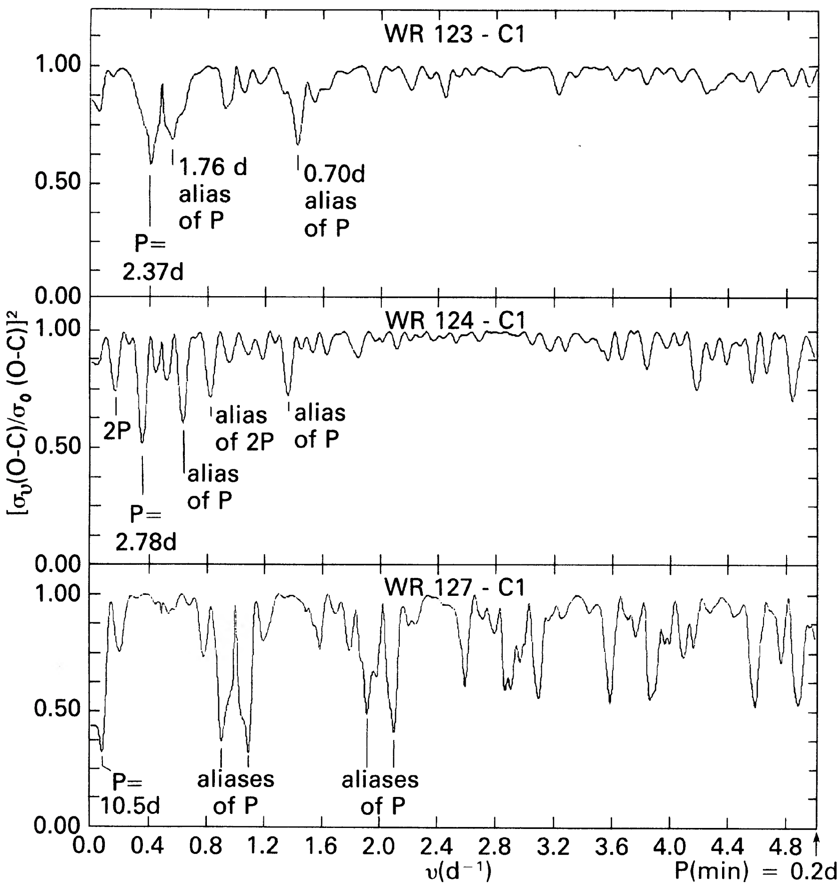


FIG. 20. Normalized variance about an arbitrarily phased sine wave fitted to the data as indicated, versus frequency $\nu = 1/P$, for three examples. The most significant period and the main aliases are indicated.

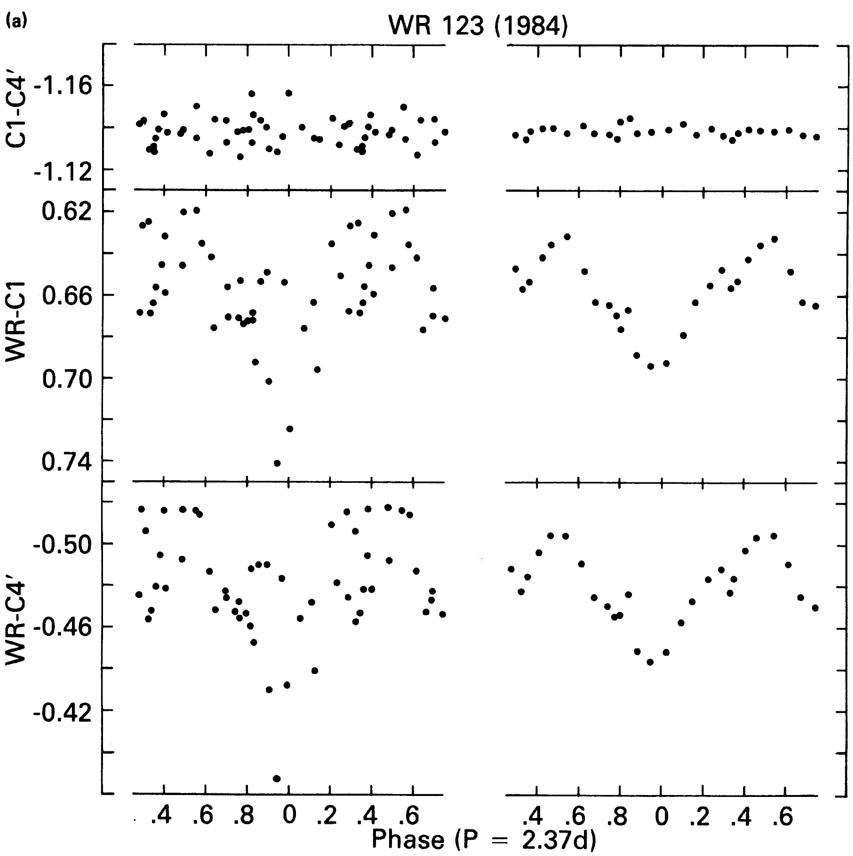
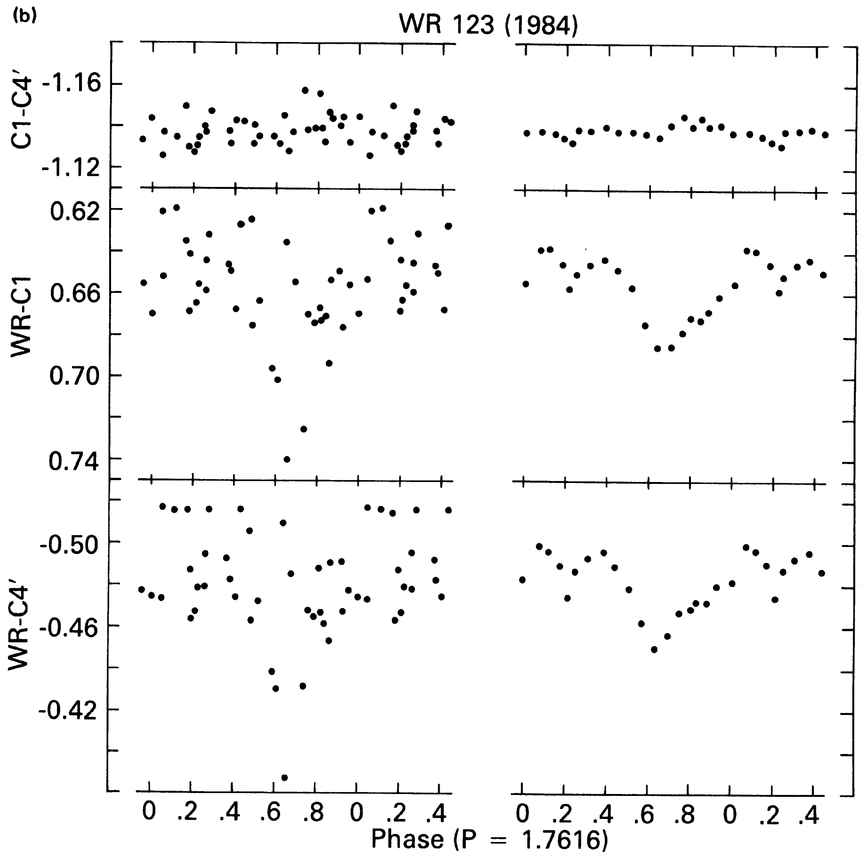


FIG. 21. (a) B magnitude difference versus phase for WR 123 (1984) with $P = 2.37$ days, $E_0 =$ JD 2 445 900 (arbitrary). Raw data appear on the left, five-point binning with two-point overlap on the right. (b) B magnitude difference versus phase for WR 123 (1984) with the previously published ephemeris (Lamontagne, Moffat, and Seggewiss 1983), $P = 1.7616$ days, $E_0 =$ JD 2 443 658.60, the period of which corresponds to the most significant alias in the present photometry. (c) B magnitude difference versus phase for WR 123 (1983) with ephemeris as in (b).



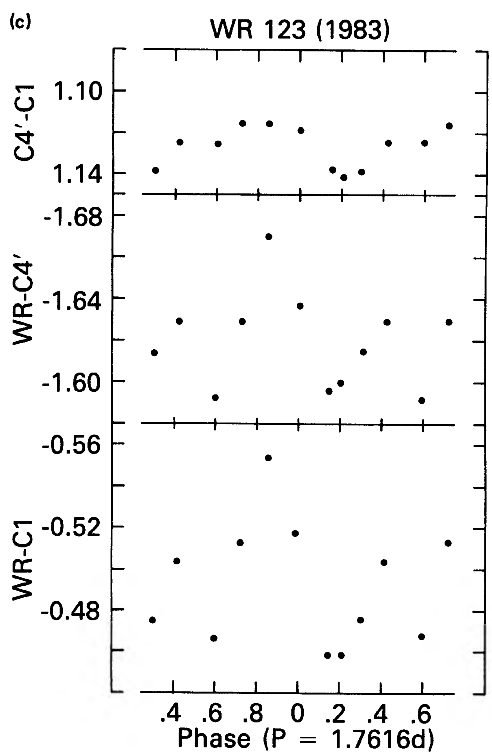


FIG. 21. (continued).

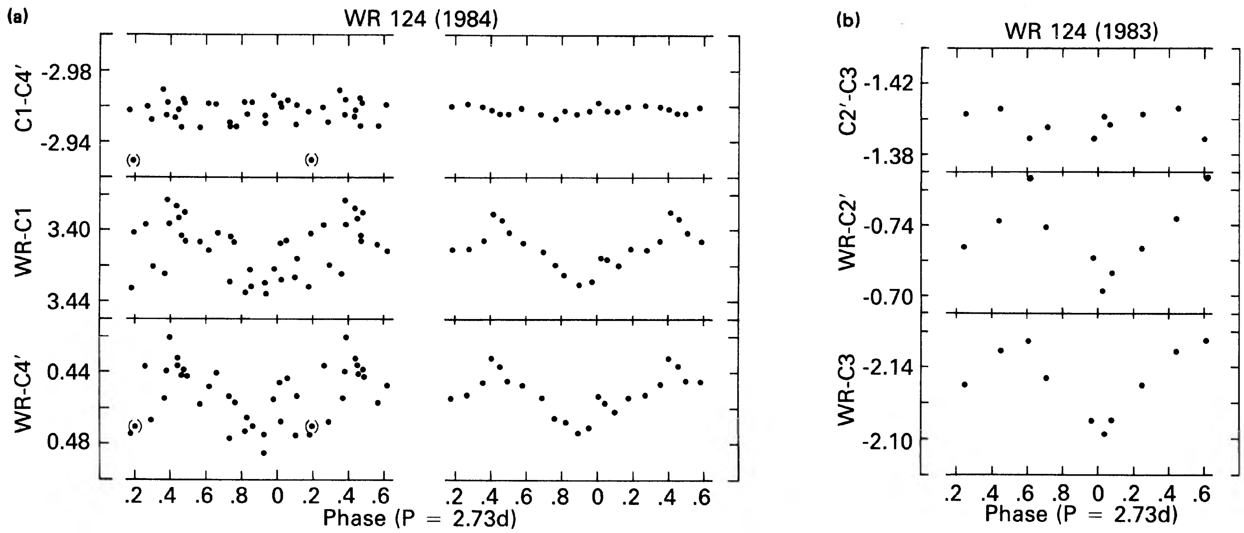


FIG. 22. (a) B magnitude difference versus phase for WR 124 (1984) with $P = 2.73$ days, $E_0 =$ JD 2 445 901 (arbitrary). Raw data are on the left, four-point binning with two-point overlap on the right, omitting the bad data point in parentheses. (b) B magnitude difference versus phase for WR 124 (1983) with $P = 2.73$ days, $E_0 =$ JD 2 445 490 (arbitrary).

24), the first to be obtained for this system, shows a shallow, broad dip of depth 0.03 mag at phase 0.0. This is typical of many W-R binaries and we are confident of the reality of this variation in WR 127. Indeed, its variability was confirmed near the 99% significance level (cf. Table II), also giving confidence in this test method. The O − C scatter about a simple curve drawn through the points is ~0.006 mag (0.007 mag for a sine wave), which is identical to the scatter in c1 − c2. Thus, binary motion *completely* accounts for the light variations at the present level of instrumental precision. Although σ(c1 − c2) is already very low, there is a hint of a 5 day eclipse interval in c1 − c2. This may account for the slightly larger scatter in the phased W-R − c2 than in the W-R − c1 light curve, if c2 is in fact variable. However, the effect is small and needs confirmation; we neglect it here. We note that WR 127 shows no deep eclipses as might be expected on the basis of the observed high value of $M_0 \sin^3 i$, which is close to the expected mass for its spectral type (Massey 1981a). Limited UV observations reveal moderate line and continuum eclipses around phase 0 (Hutchings and Massey 1983).

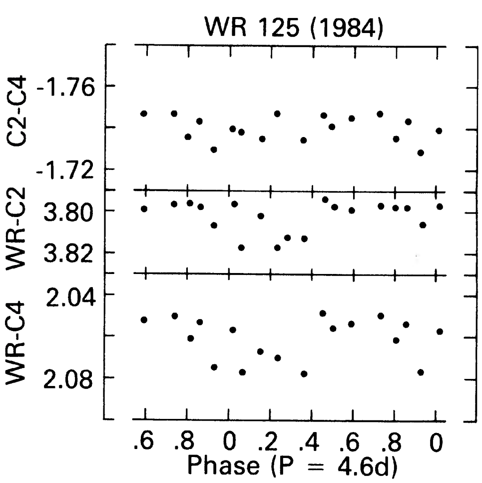


FIG. 23. B magnitude difference versus phase for WR 125 (1984), with $P = 4.6$ days, $E_0 =$ JD 2 445 900 (arbitrary).

5) WR 141 = HD 193928

For WR 141 our data (Figs. 12 and 30) are dominated by light variations in both comparison stars. After eliminating a smooth periodic modulation of each one (cf. Fig. 19), residual noise in the data and a lack of complete phase coverage of this 21.6 day binary prevent us from drawing strong conclusions about its potential variability. However, we can say at least that it is almost certainly not an eclipsing system on the basis of our observations near phase zero.

6) WR 148 = HD 197406

The well-known SB1 system of type WN7, WR 148, is studied for light variability in Figs. 13 and 31. Both the 1983 and 1984 data reveal a shallow, broad 0.04 mag dip centered at phase 0.0 (W-R in front), confirming the previous data of Bracher (1979). In addition to the phase-dependent modulation, there is significant random, nonperiodic noise: a simple curve (not shown) through the unbinned data in Fig. 31(a) would reduce the W-R − c scatter from 0.019 mag before the fit to only ~0.010 mag afterwards. This can be compared to the instrumental scatter in c1 − c2 of 0.004 mag. The time scale for this random component is of the order of days, certainly not hours or less, since multiple, randomly placed observations in the same night with a time difference ranging from 0.13 to 0.24 days do not show significant variations. As we shall see in Fig. 36, this random behavior may be typical of WNL stars, whether in binaries or single. WR 148 is particularly interesting since it is an extreme runaway system and, with its moderately low-mass companion and its non-eclipse type light curve, may harbor a compact (BH) companion (cf. Drissen *et al.* 1986, who present a revised ephemeris and phase-modulated polarization observations).

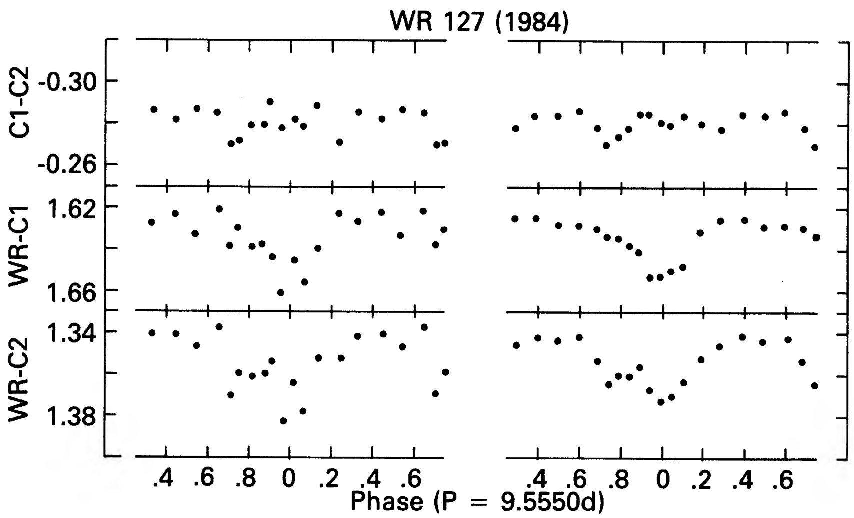


FIG. 24. B magnitude difference versus phase for WR 127 (1984), with the previously published ephemeris (Massey 1981a), $P = 9.5550$ days, $E_0 =$ JD 2 443 789.45. Raw data are on the left, two-point binning with one-point overlap on the right.

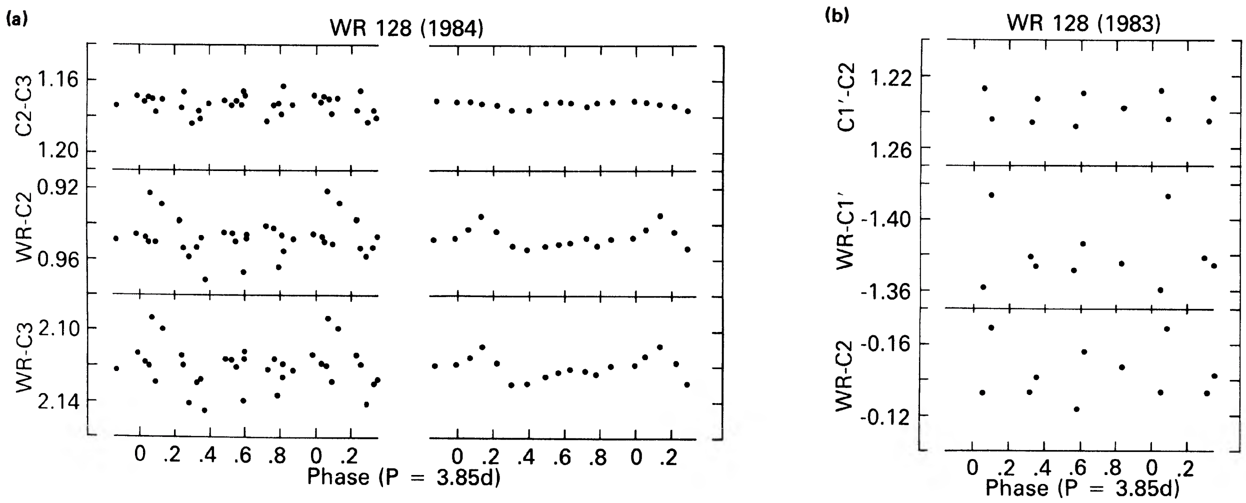


FIG. 25. (a) B magnitude difference versus phase for WR 128 (1984) with the previously published ephemeris (Antokhin, Aslanov, and Cherepashchuk 1982b), $P = 3.85$ days, $E_0 =$ JD 2 444 788.65. Raw data are on the left, four-point binning with two-point overlap on the right. (b) B magnitude difference versus phase for WR 128 (1983) with ephemeris in (a).

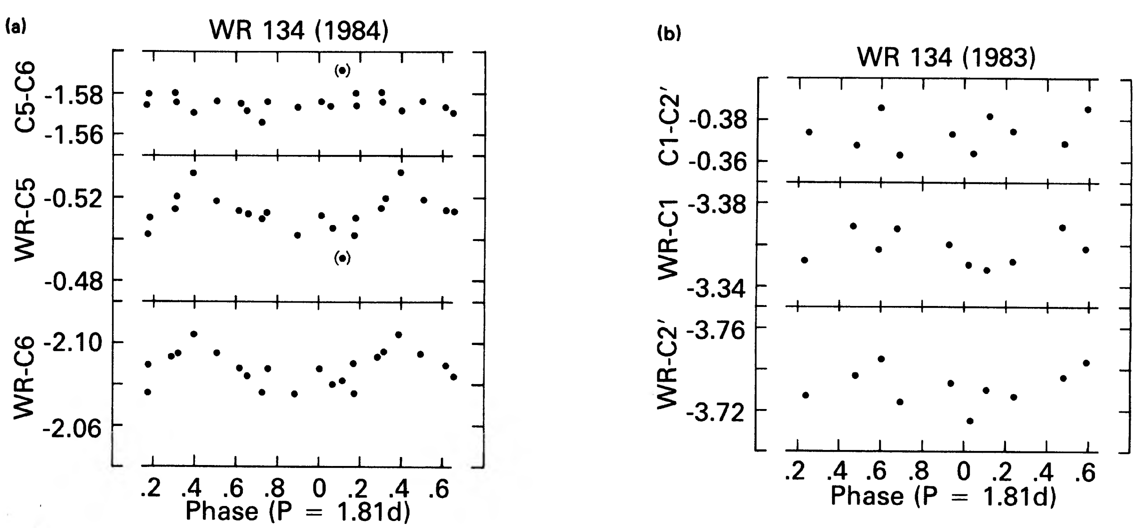


FIG. 26. (a) B magnitude difference versus phase for WR 134 (1984) with $P = 1.81$ days, $E_0 =$ JD 2 445 900 (arbitrary). (b) B magnitude difference versus phase for WR 134 (1983) with $P = 1.81$ days, $E_0 =$ JD 2 445 490 (arbitrary).

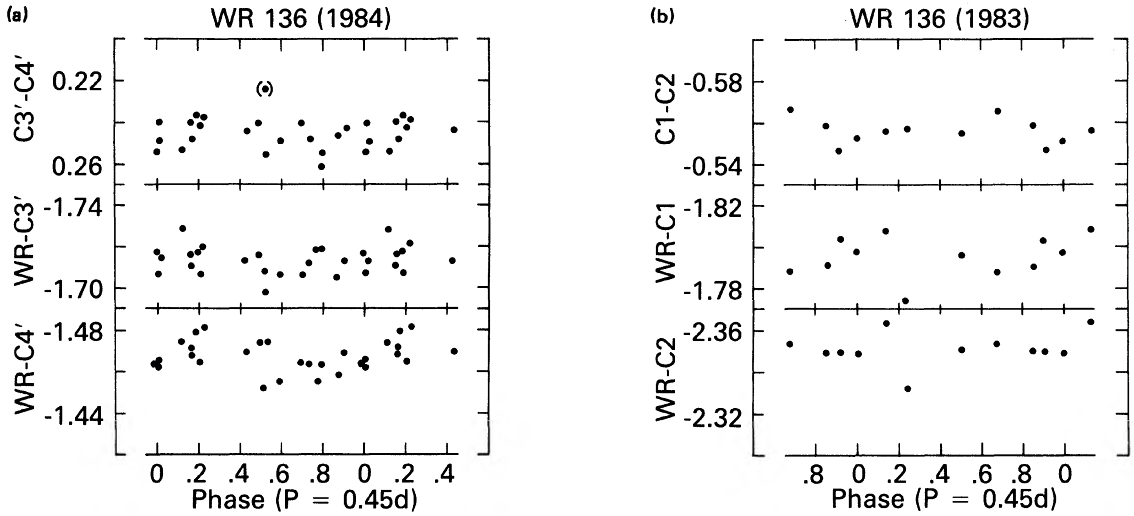


FIG. 27 (a) B magnitude difference versus phase for WR 136 (1984) with $P = 0.45$ days, $E_0 =$ JD 2 445 900 (arbitrary). (b) B magnitude difference versus phase for WR 136 (1983) with $P = 0.45$ days, $E_0 =$ JD 2 445 490 (arbitrary).

b) Suggested Long-Period SB2's: WR 138 = HD 193077 and WR 140 = HD 193793

This group includes only two stars, WR 138 and WR 140, in which O star type absorption lines are seen. This is claimed to be due to wide SB nature (RV orbits of years) for WR 138 by Lamontagne *et al.* (1982), who include the data of Massey (1980) in their analysis, and for WR 140 by Lamontagne, Moffat, and Seggewiss (1984). Lamontagne *et al.* (1982, 1984) give spectral types of O9 and O4 V for the absorption-line components and WN6 and WC7 for the emission components in WR 138 and WR 140, respectively. For WR 138, Massey (1980) claims constant RV, excluding all but a very long-period binary; he prefers the interpretation that the absorption lines are intrinsic to the W-R star. However, it would be unusual for a WN5 star to have strong H absorption lines along with a low H wind as one usually finds among early WN stars. Conti *et al.* (1984) similarly claim non-orbital RV variations for WR 140; they prefer a line-of-sight coincidence between the W-R star and an O star for WR 140 and WR 138. However, on the basis of recent speckle interferometry, Moffat *et al.* (1986) now provide strong evidence that a line-of-sight coincidence is extremely unlikely and that we are dealing with binary systems in both WR 138 and WR 140 with periods shorter than $\sim 10^2$ yr. Higher-angular-resolution observations are needed to tie this down further.

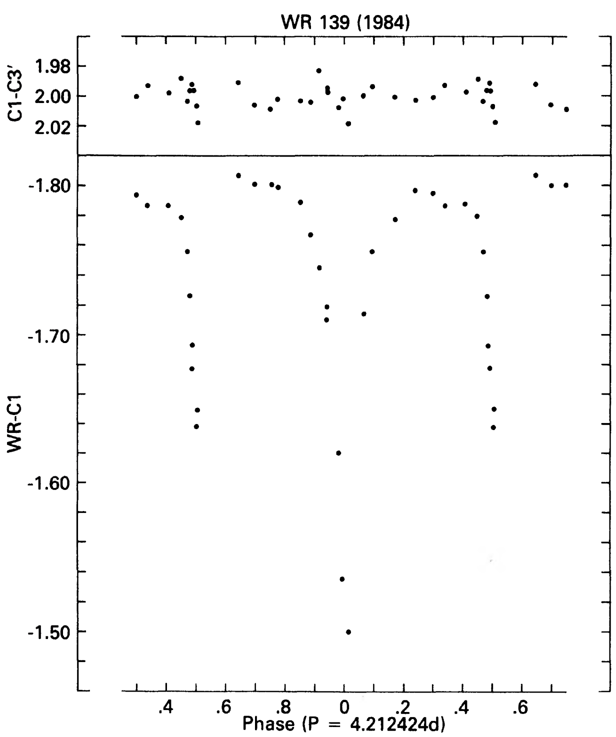


FIG. 28. B magnitude difference versus phase for WR 139 = V444 Cygni (1984) with the previously published phase (Cherepashchuk and Khaliullin 1973), $P = 4.212424$ days, $E_0 =$ JD 2 441 164.332. Note the same magnitude scale but increased phase scale.

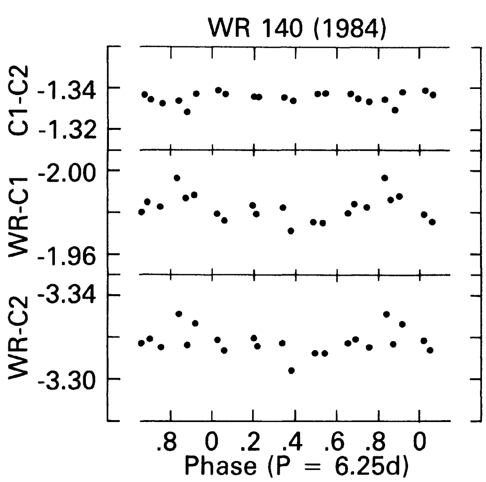


FIG. 29. B magnitude difference versus phase for WR 140 (1984) with $P = 6.25$ days, $E_0 =$ JD 2 445 900 (arbitrary).

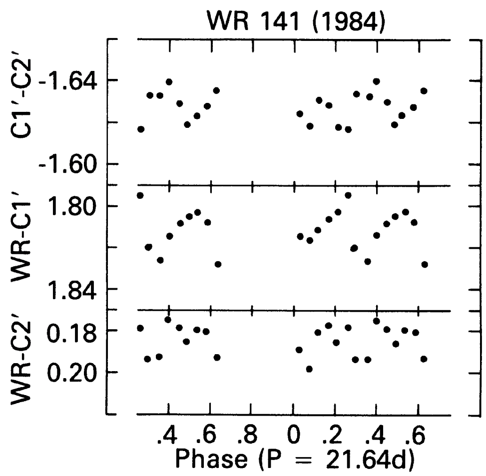


FIG. 30. B magnitude difference versus phase for WR 141 (1984) with the previously published ephemeris (Ganesh and Bappu 1968), $P = 21.64$ days, $E_0 =$ JD 2 434 190.59.

In the meantime, Williams *et al.* (1986) and Moffat *et al.* (1986) have provided further evidence that WR 140 may be a long-period binary system. On the basis of the absorption-line RV's of Lamontagne, Moffat, and Seggewiss (1984), Conti *et al.* (1984) and new data, they find a revised period of $P = 7.9$ yr in a highly elliptical orbit. Furthermore, ever since IR observations have been obtained systematically for this star, outbursts have occurred three times so far, at each periastron passage. While the exact cause of the outbursts is unclear, their recurrence with the same period as the RV variations strongly supports the binary orbit.

Although we do not expect to see any phase-dependent photometric modulation for such wide systems, we observed these stars for the sake of completeness. We note that WR 138 is suspected to harbor a third, close, lowmass (compact?) companion, in addition to the much more distant O companion (Lamontagne *et al.* 1982). Both WR 138 and WR 140 were observed with a very faint visual companion, 4.1 mag fainter at separation 4.4″ for WR 138 and 7.6 mag fainter at 5.8″ for WR 140 (Jefferies *et al.* 1961). Neither of these stars is close or bright enough to affect significantly spectroscopic or photometric observations.

The observations of WR 138 (plotted only versus time in Fig. 10 for 1983 and 1984) show no sign of the 2.32 day period of Lamontagne *et al.* (1982). This is not surprising, as Lamontagne *et al.* also failed to reveal any variation in their less extensive photometry; only the spectroscopic emission-line RVs yielded a 2.32 day sine-wave modulation of low amplitude. It is possible that, if there were any photometric variability at this period, it would be drowned out by the additional O star light. The present light curves do, however, reveal variability at a high level of significance; if this variability is periodic, the most significant period is $P = 11.6$ days, but more data are clearly needed to verify whether the variability is truly periodic or not.

In the case of WR 140 (cf. Figs. 11 and 29) our data show a high probability of intrinsic variability, assuming the value of $\sigma(c1 - c2) = 0.003$ mag not to be fortuitously low. The most significant period to satisfy the W-R variability is $P = 6.25$ days. This variation also needs checking.

c) Suggested SB1's with Possible Low-Mass Companions

Besides the possible triple system WR 138 discussed above, this group includes the five stars WR 123, 124, 128, 134, and 136. The first two stars fall just outside the 11.5 mag limit of our complete sample.

1) WR 123 = HD 177230

WR 123, once claimed to have constant RV (Massey and Conti 1980), was later claimed to be a low RV amplitude, extreme runaway binary (Lamontagne, Moffat, and Seggewiss 1983). The present light curve is the first one ever obtained for this star. In 1983 and 1984, WR 123 was observed with a 5″ companion to the west of and $\Delta B = 3.3$ mag fainter than the W-R star. In 1983 only, a faint, red ($\Delta B = 2.6$, $\Delta(B - V) = 1.2$) 18″ distant companion to the

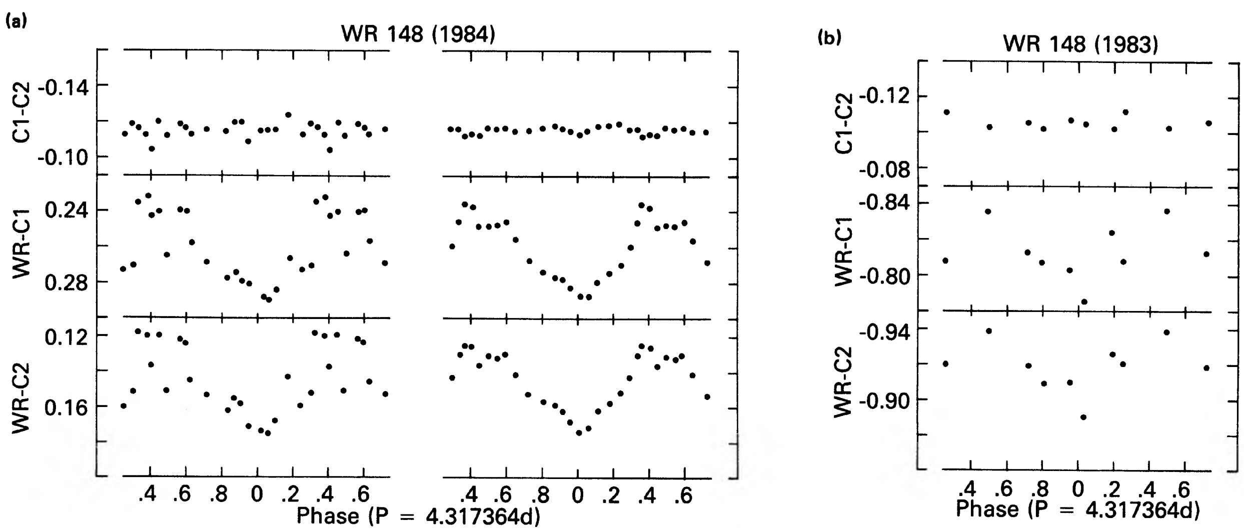


FIG. 31. (a) B magnitude difference versus phase for WR 148 (1984) with the previously published ephemeris (Drissen *et al.* 1986), $P = 4.317364$ days, $E_0 =$ JD 2 432 434.4. Raw data are on the left, three-point binning and one-point overlap on the right. (b) B magnitude difference versus phase for WR 148 (1983) with the same ephemeris as in (a).

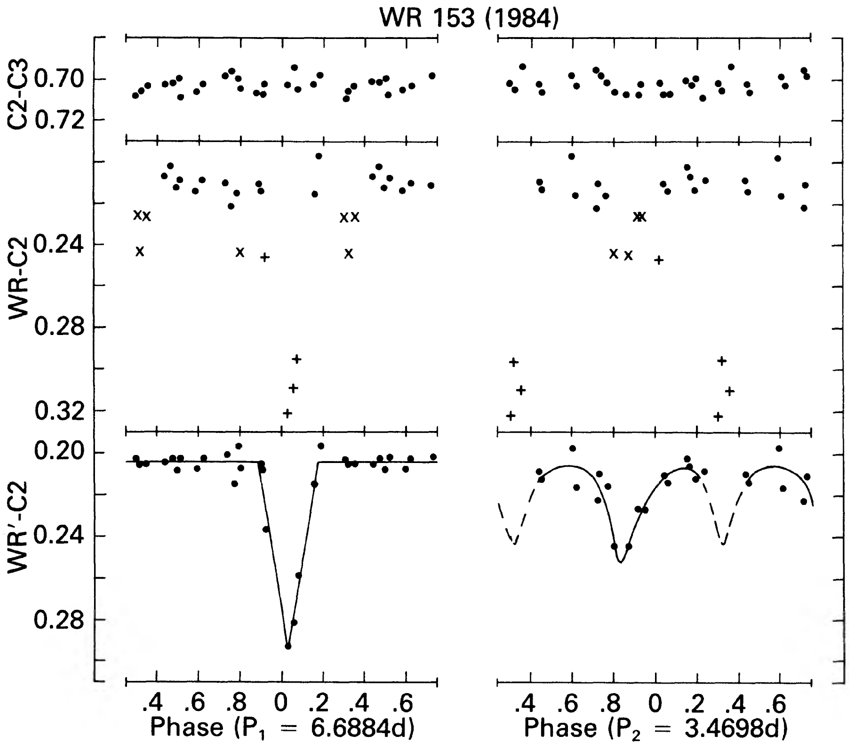


FIG. 32. *B* magnitude difference versus phase for the quadruple system WR 153 = GP Cep (1984) with the previous published ephemeri (Massey 1981a), (left) $P_1 = 6.6884$ days, $E_0 =$ JD 2 443 690.32 for the WR system, and (right) $P_2 = 3.4698$ days, $E_0 =$ JD 2 443 689.59 for the O system. Crosses or pluses refer to eclipses due to the 'other' system and are omitted for clarity in the lower figures, where curves are drawn in order to derive phase-dependent corrections.

northwest was also included in the diaphragm. These stars each contribute only 5% – 10% of the total light. Our photometry, both in 1983 and 1984 (Figs. 1 and 21), shows large variations up to ~0.1 mag.

A period search of the more extensive 1984 observations down to 0.2 days reveals the most significant period $P = 2.37$ days, with aliases of lower relative significance at 1.75 and 0.70 days (cf. Fig. 20). The 1.75 day alias is nearly identical to the most significant period of Lamontagne *et al.* (1983), $P = 1.7616$ days, although their 2.37 day alias is a close second. Thus, the present photometric data are consistent with the RV orbital period suggested for WR 123. Note that the period is not yet known well enough to determine a reliable zero point in phase and thus bridge all the known data together.

In addition to the periodicity, there is a considerable amount of noise which one can beat down by data binning [cf. Figs. 21(a) and (b)]. This high noise level appears to be typical of WN8 stars (Lamontagne and Moffat 1986), which usually show random light variability with or without a periodic component. The well-known WN7 binary system WR 148 also falls in this category (cf. Sec. V and Fig. 36). Alternatively, the increasing amplitude of the light variations with time in Fig. 1(a) suggests that we might be seeing nonradial pulsations with the occurrence of a beat-like phenomenon.

2) WR 124=209 BAC

The WN8 star WR 124 has also been claimed to be a runaway binary system containing a NS companion in a 2.3583 day orbit (Moffat, Lamontagne, and Seggewiss 1982). This was the most significant period found from combining four series of spectroscopic RVs over an interval of 3 yr, and two photometric runs. Due to large windows in these data, other periods are possible out to ~0.2 days from this value, i.e., $P = 2.36 \pm 0.2$ days. The present photometric data (Figs. 2 and 22) yield a most significant overall period $P = 2.73 \pm 0.2$ days. Results of the period search down to $P = 0.2$ days are shown in Fig. 20 for W-R – c1. Other aliases and simple multiples emerge, all with clearly lower significance. No periods shorter than 0.2 days show up either, not surprisingly since multiple observations with Δt ranging randomly from 0.01 to 0.23 days on the same night show little variation. There are still not sufficient data to define an overall accurate period, if the photometric variations are truly periodic. Nevertheless, the 1979 spectroscopic and photometric data are close enough in time to say that minimum light occurs close to phase 0 when the W-R star is in front, in a binary model.

As in the case of WR 123, there is also a random-noise component in addition to the systematic modulation of the light curve, although the noise is of lower relative amplitude in WR 124 (cf. Fig. 36)—in fact it is closer to that seen in the well-known SB1 system WR 148.

Recently, van der Hucht *et al.* (1985) have argued on the basis of its IR energy distribution observed with the *IRAS* satellite that WR 124 belongs to the class of planetary nebulae (PN) nuclei, and is not a Population I object. The two most serious objections to this are:

(1) the high extinction ($A_v = 4.2$ mag), which favors a larger distance* and thus brighter, Pop I absolute magnitude;

*In their closest fields to WR 124, Neckel and Klare (1980) find $A_v = 0.8$ and $d = 400$ pc (close to van der Hucht *et al.*'s 1985 estimate of the distance to WR 124), increasing to $A_v = 3$ mag at $d = 1$ kpc; after that there are too few data. If $A_v = 4.2$ mag is wholly interstellar, this implies at the very least $d > 1$ kpc, compatible with the Population I distance of 4 kpc (Cohen and Barlow 1975). Since PN nuclei do not normally exhibit intrinsic reddening (Pottasch 1984), this is not compatible with the close distance required for a PN nucleus. However, Pottasch did not consider PN with possible WN nuclei, which might show anomalous behavior.

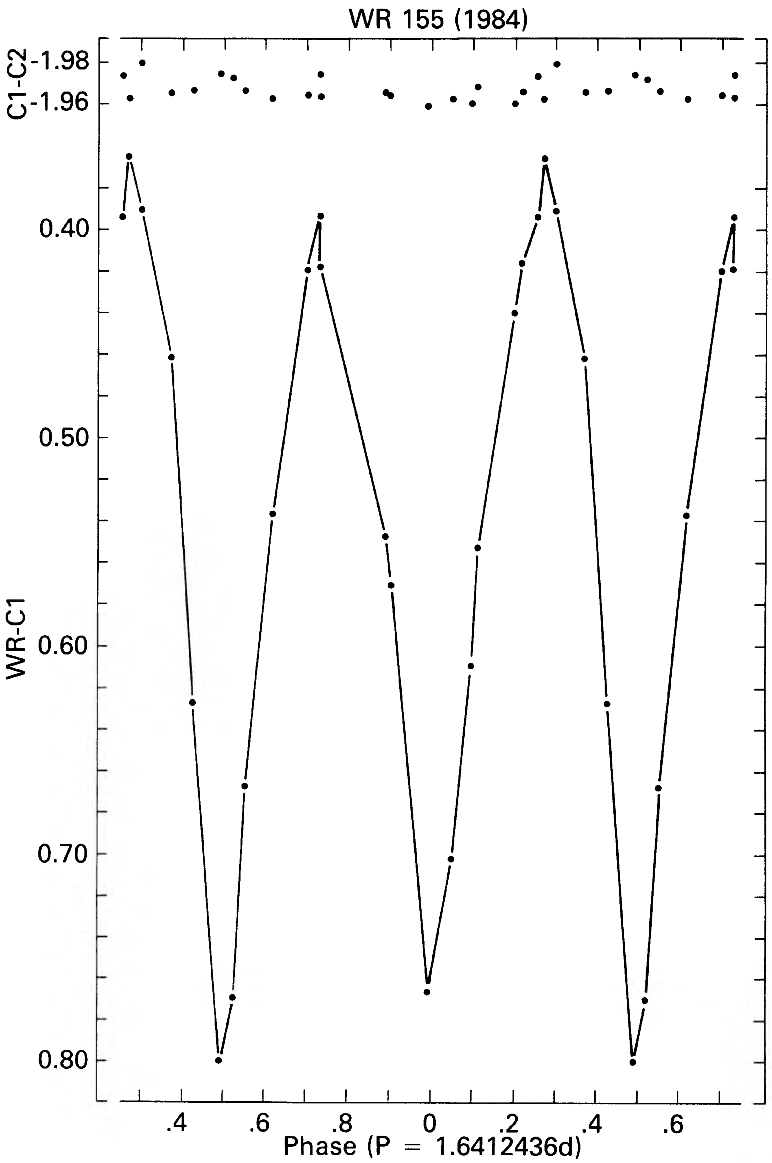


FIG. 33. B magnitude difference versus phase for WR 155 = CQ Cep (1984) with the previously published ephemeris (Walker *et al.* 1983), $P = 1.641\,243\,6$ days, E_0 = JD 2 415 001.231. A straight line arbitrarily joins adjacent points in phase for clarity. Note the increase in scale for the phase axis.

(2) the high systemic RV (~ 190 km s^{-1} heliocentric, at $l = 50.2°$) deviates clearly from the pattern of *all* other galactic PN nuclei with known RVs (cf. Fig. 3 of Schneider *et al.* 1983, and Fig. II-6 of Pottasch 1984).

Assuming WR 124 to be a binary system, a low mass (~0.7 M_0) for the WN8 star as a PN nucleus would yield a mass of ~0.08 M_0 for the unseen star (cf. van der Hucht *et al.* 1985) using the mass function of Moffat *et al.* (1982). Such a low-mass star would be nowhere near luminous enough to explain the observed dip (~0.03 mag) in the visible-light curve if it is caused by phase-dependent transparency effects as the low-mass star circles within the W-R wind (even if one assumed the most favorable case of a total eclipse when the W-R star is in front).* Other mechanisms (e.g., tidal effects, backwarming,...) may be possible to explain the periodic component of the light variations in a low-mass binary model, although it is not obvious how this could occur for such a large mass ratio and moderately large separation. In the Pop I W-R + NS model, the NS could be optically overluminous for its mass due to the emission of down-graded accretion x rays. The very high runaway peculiar RV (~ 150 km s^{-1}) can be explained by a SN explosion preceding the formation of the NS in a very close, massive binary. Since the original primary would have been the less massive star at the time of the explosion due to wind mass loss, the system would remain gravitationally bound. The orbit would become circularized in several million years.

More data are needed to check for the possibility of nonradial pulsations.

*With $10^{[0.4\,(M_v(\mathrm{WR}) - M_{v2}]} = 0.03$ mag in the limit of a total eclipse of the faint unseen star, one has $M_{v2} - M_v(\mathrm{WR}) = 3.6$. Thus, if $M_v(\mathrm{WR}) = -1.2$ as a PN nucleus (cf. van der Hucht *et al.* 1985), one finds $M_{v2} = 2.4$, which is much too bright for a star of mass ~0.1 M_0. If the eclipse is only partial or opacity effects in the W-R wind are responsible for the light variations, M_{v2} must be even brighter.

3) WR 128=HD 187282

WR 128 appears to be variable on the basis of the present data (Figs. 5 and 25) but no periods emerge from a sine-wave period search. A phase plot of our photomeric data

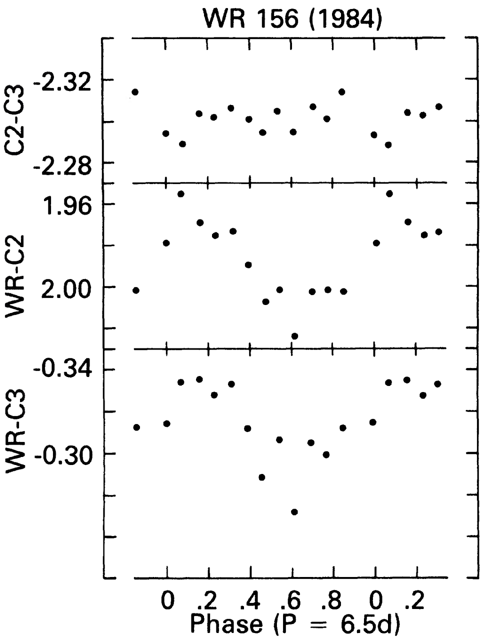


FIG. 34. *B* magnitude difference versus phase for WR 156 (1984) with $P = 6.5$ days, $E_0 =$ JD 2 445 900 (arbitrary).

using Antokhin, Aslanov, and Cherepashchuk's (1982b) claimed binary period of 3.85 ± 0.15 days, shows only a weak, noisy modulation with phase. If the star really is a WN4 + NS binary, it is behaving somewhat differently during our runs from how it behaved before 1983. The spectroscopic data of Lamontagne (1983) yield a most significant period of $P = 3.56$ days and a similar RV amplitude. Further data are needed to check the claims of periodicity or to determine if one of the other mechanisms discussed in Sec. I is operative.

4) *WR 134=HD 191765*

While our 1983 data yield no convincing variability for WR 134 (possibly due to higher residual noise in the comparison stars), our 1984 data (Figs. 6 and 26) do show intrinsic variability at the $> 99\%$ level. The most significant period to emerge for the latter data is $P = 1.81$ days, with inferior-quality periods occurring at the aliases 2.24 days and shorter than 1.8 days. There is no hint of the 7.44 day period of Antokhin, Aslanov, and Cherepashchuk (1982a) or Antokhin and Cherepashchuk (1984), whose observations show an amplitude of 0.04 mag in the optical continuum with that period. The present 1984 photometry yields a sine wave of amplitude 0.02 mag with O − C scatter that is close to the instrumental scatter. If both periods are real and do occur at different times, this may be the first clear case of nonradial pulsations in a W-R star. However, we note that Lamontagne (1983) finds a most significant period in his RV data from 1979–1981 (overlapping in time with the Russian data) of $P = 1.78$ days, with $K = 18$ km s^{-1}. This corresponds to the most significant period found in the present 1984 data and would imply that the Antokhin *et al.* period might be spurious.

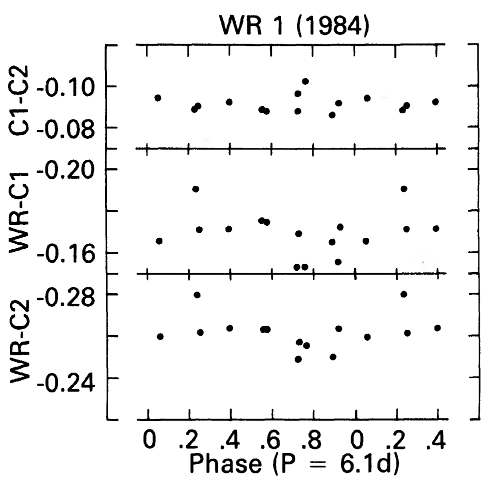


FIG. 35. *B* magnitude difference versus phase for WR 1 (1984) with $P = 6.1$ days, $E_0 =$ JD 2 445 900 (arbitrary).

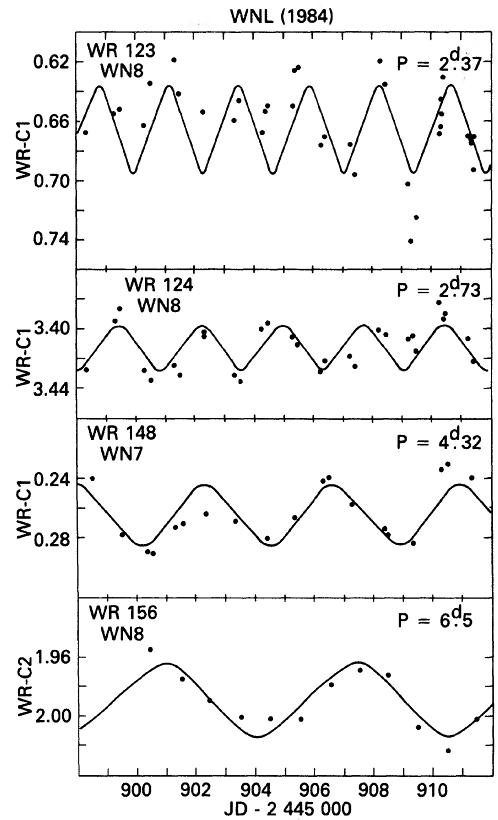


FIG. 36. *B* magnitude difference versus time for the four WNL stars, with mean curves sketched in according to the ephemeri given for each star.

5) *WR 136=HD 192163*

WR 136 has been claimed to be a WN6 + NS binary with a period of 4.5 days (Koenigsberger, Firmani, and Bisiacchi 1980; Aslanov and Cherepashchuk 1981), revised to 4.57 days by Aslanov (1982), or its alias, 0.45 days, by Vreux *et al.* (1984). The latter authors also note the possibility of nonradial pulsations, since this period is relatively short. The present data (Figs. 8 and 27) show only weak evidence for photometric variability in 1983 and virtually none in 1984.

d) Stars with no Previous Known or Suspected Duplicity

This group includes WR 135, 137, 1, 3, and 4, with WR 156 falling just below and WR 125 well below the $b = 11.5$ mag limit. The close visual binary WR 157 has constant RV.

1) WR 125=MR 93

WR 125 may have passed the variability test at the $\lesssim 95\%$ level because it is significantly fainter than any other stars. If it really is variable, a period of 4.6 days fits the data best (Figs. 3 and 23). From IIDS spectroscopy ($\lambda\lambda$ 3800–5000 Å, resolution ~ 6 Å) on four consecutive nights (1984 April 1–4) at KPNO, we find no obvious spectroscopic variability.

2) WR 135=HD 192103 and WR 137=HD 192641

WR 135 (Fig. 7) and WR 137 (Fig. 9) are the only stars in our list that fail the variability test for both years, except for a marginally possible secular variation for both stars in 1983. Neither star shows significant RV variability on a time scale of $\lesssim 2$ yr (Lamontagne 1983; Massey, Conti, and Niemela 1981). Both are of the cool WC sequence (WC8 and WC7 + abs, respectively).

3) WR 1=HD 4004 and WR 4=HD 16543

WR 1 (Figs. 15 and 35) and WR 4 (Fig. 17) show possible intrinsic variability near the 95% confidence level. Periods close to 6 and 10 days, respectively, give the best fit to the data, with shorter aliases also possible. Lamontagne (1983) finds a possible 8 day RV period for WR 1 and no convincing RV period for WR 4.

4) WR 3=HD 9974

WR 3 (Fig. 16) reveals a possibly steady secular increase in brightness during the 13 day interval in 1984. This is compatible with the possible long-period ($P = 47$ day) orbit found by Lamontagne (1983).

5) WR 156=MR 119

WR 156 (Figs. 14 and 34) shows very clear photometric variability. If the star does vary truly periodically, the most significant period is 6.5 days, with shorter aliases also possible due to the daily sampling bias. The light curve covers only two complete cycles. More data are needed to verify whether the variability is truly periodic over longer time scales. Being of peculiar subclass WN8, it is reasonable to suppose that at least some of the variability could be random (cf. Fig. 36). Lamontagne *et al.* (1983) detected no orbital motion for this star.

IV. GENERAL DISCUSSION AND CONCLUSIONS

a) Variability of Wolf-Rayet Stars

Among the complete sample of 18 northern W-R stars with $b \lesssim 11.5$, we find that 9–10 ($\gtrsim 50\%$) are variable with amplitudes $A = 0.02$ mag or greater. This compares with 30% among the 50 non-W-R comparison stars for the same limit of variability. Going down to a less stringent limit of $A = 0.01$ mag, we find that 13–14 ($\gtrsim 70\%$) of these W-R stars are variable. Thus, it appears that W-R stars tend to vary in light more often than randomly chosen stars, but not by a large factor.

With the exception of the well-established binary systems, we can make no definitive claims as to the source of the variability in the remaining stars. Only continued monitoring over very long time intervals will settle this.

b) Photometric Variability of Undisputed Binaries

It appears for our complete sample that all undisputed, short-period ($P \lesssim 20$ days) W-R binaries are photometrically variable at some detectable level, with the following properties:

(1) the light curves are phase dependent, with one minimum falling at phase 0.0 (W-R in front) and, if present, a secondary minimum at or near phase 0.5 (WR 127, 133, 139, 148, 153, 155);

(2) the shorter the period, the deeper the magnitude dip on average;

(3) except for the WN7 binaries WR 148 and 155, the light variations can be fully accounted for by the smooth, phase-dependent light curve.

The basic process operating in W-R binaries is likely phase-dependent obscuration of the light from the companion as it orbits in the W-R wind. This effect has also been clearly seen in UV spectra of WN + O binaries (Koenigsberger and Auer 1985). A narrow eclipse involving the central W-R star as opposed to a broad dip due to variable wind obscuration is seen in some truly eclipsing systems (WR 139, 153, 155). If the light modulation were due to phase-locked rotation of hot spots on the W-R star, one would expect *maximum* light at phase zero (W-R in front). Since *minimum* light always occurs at phase 0, we conclude that rotation effects are not seen, at least in the case of W-R stars in binaries. We would also have little reason to expect them in single W-R stars either.

c) The (Peculiar) Class of WN8 Stars

WN8 stars are distinguishable from other WN stars by their generally narrower emission lines and their strong P Cygni profiles. No WN8 star is known to have an O-type companion. None is known to be a member of a star cluster, while the runaway frequency seems to be relatively high among them (cf. Moffat 1983). Furthermore, the present work shows that WN8 stars (and some of their WN7 cousins) generally show a relatively high photometric noise level. One possible explanation is that we are seeing several beating periods due to nonradial pulsations. Alternatively, these peculiarities could be due to a relatively high frequency of W-R + c binaries among the WN8 stars. Indeed, massive x-ray binaries generally show a high degree of light variability. However, there is still no explanation why no W-R star is known to emit accretion-type x rays, although there are some ways out of this (cf. Vanbeveren, van Rensbergen, and de Loore 1982). On the other hand, WNL stars may be the W-R analogy of normal stars above and to the right of the H-burning main sequence: the brighter and redder they are, the stronger the variability (Maeder 1980). WNL stars generally contain more H than WNE stars and are thus more displaced above and to the right of the He-burning main sequence.

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