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ON THE EXISTENCE OF STABLE STARS IN THE CEPHEID INSTABILITY STRIP

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ABSTRACT

Forty-eight stars with spectral types near G0 Ib have been examined for light variability. Five stars, HD 191010, 239994, 84441, 213482, and 214847, are suspected of being variable by about 0.1 mag. The remaining forty-three stars appear to be stable to within a few hundredths of a magnitude. HD 194012, with a published spectral type of F8 Ib, was found in fact to be an F7 V star.

Intrinsic colors for many of the nonvariable stars were assembled from published *BVRI* photometry. Absolute magnitudes for a number of them were obtained from cluster membership, K-line widths, etc. Most of these stars appear to lie within the Cepheid instability strip on the H-R diagram; and in a few favorable cases for which the absolute magnitude seems well determined by several independent means, this conclusion appears almost certain.

I. INTRODUCTION

The great majority of known Cepheid variables have light amplitudes of 0.5 mag or more. About a dozen are known to have smaller amplitudes, the extreme case being Polaris, with an amplitude of 0.1 mag. Given the rather haphazard manner in which variable stars are discovered, one suspects that these statistics are in large measure the result of observational selection effects, and that possibly even Polaris would not have been discovered as a variable had it not occupied so singular a position in the sky. It would be of some interest theoretically to know the true frequency of occurrence of low-amplitude Cepheids, and perhaps of even more interest to know whether or not essentially stable stars can exist in the zone of Cepheid instability on the H-R diagram.

We have attempted to answer some of these questions by examining stars having MK spectral classifications very like Cepheids, but which were not known as variables. The basic list of stars was chosen from the compilation of MK spectral classifications by Jaschek, Conde, and de Sierra (1964). Because this catalog is itself quite inhomogeneous, we have not attempted to set any very stringent selection rules. Generally, we have chosen stars with spectral types between F5 and G5, and luminosity classes close to Ib, although even here different classifications by different people make these limits imprecise. In addition, stars were required to be sufficiently far north for us to be able to observe them accurately, they had to be of a brightness suitable for finding comparison stars, and so forth. Ultimately, we have observed the forty-eight stars listed in Table 1. This rather casual selection of stars does not allow any conclusions to be drawn about the true amplitude-frequency function (an almost impossible task anyway), but has permitted a limited search for new Cepheids and an answer to the question on the existence of stable stars in the instability strip.

II. THE OBSERVATIONS

About half the observations were made with a standard *UBV* photometer on the 24-inch telescope of the David Dunlap Observatory, and the remainder with a 16-inch telescope at Kitt Peak. Only the *V*-filter was used throughout. Observations were purely differential between the program star and a comparison star, the latter being a dwarf (in some cases a giant) star of similar color and apparent magnitude. Differential extinction corrections have been applied where the separation of the stars made this significant, although in all cases this was very small.

In order to have a realistic estimate of the observational errors as distinct from any actual variability in the program stars, we have used as a control a pair of G dwarfs, observed in exactly the same way as the other stars. Presumably any apparent variability of these stars would be entirely due to observational errors.

The procedure on any one night was to observe back and forth between a program star and its comparison until each had been observed at least three or four times. This gave several measures of the magnitude difference, the consistency of which permitted an estimate of the sky conditions. This procedure was repeated on at least three different nights for each star, although in some cases where observing time permitted, observations were made on as many as eleven nights. All told, the observations have spanned three years.

III. RESULTS

The results are expressed as follows. The average magnitude difference Δm between a program star and its comparison was found for each night. The night-to-night values were then averaged, and the average residual r between the value on any one night and the average over all nights was found. Thus

$$r = \langle(\Delta m)_i - \langle\Delta m\rangle\rangle .$$

These residuals, together with the number n of nights on which observations were made, are given in Table 1.

The pair of control stars have $r = 0.006$ mag. Also, after the observations were completed it was found that one program star, HD 194012, was in fact not a supergiant but a dwarf (see below). We thus inadvertently had a second pair of control stars, for which $r = 0.009$ mag. It was clear from the reductions, however, that the observational errors were dependent on such things as the separation between program and comparison stars, on hour angle, apparent magnitude, and whether the observations were made principally at Kitt Peak or at Toronto. This explains why favorable cases observed only at Kitt Peak, for instance, show values of r smaller than the control pairs. In general, we accept that values of r smaller than 0.010 mag do not necessarily indicate any significant variation in the program star.

Figure 1 shows the distribution of r-values among the program stars. The general noise level up to about $r = 0.010$ is apparent, as is the fact that the r-values for five stars stand out well above the noise level. These five, listed in Table 2, we suspect of being significantly variable.

What is the relation of r to the probable amplitudes of variation? The known Cepheids of lowest amplitude have light curves which are very nearly sinusoidal. Simple calculation shows that for a sine wave, sampled at random an infinite number of times, the amplitude A is related to r by

$$A/r = \pi \simeq 3.14 .$$

In order to examine the effects of small distortions from a sine wave and only three to eleven samples, synthetic light curves of only roughly sinusoidal shape and amplitudes from 0.1 to 0.5 mag were drawn and sampled at random phases with the aid of a random-number table. A large number of trials showed that the ratio A/r was not at all sensitive to either the number of samples or minor distortions, and that in the range $3 \leq n \leq 11$

$$A/r = 3.7 \pm 0.3 .$$

This value has been used in determining the probable amplitudes listed in Table 2. Our few observations, scattered over three seasons, are not suitable for determining periods or light curves for these stars.

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TABLE 1

BASIC DATA

HD	Other Name	Sp.T.	m_V	r	n	$(B-V)_0$	M_V (1)	(2)	(3)	(4)	Adopted M_V
611	...	G0 Ib	8.2	0.012	3	(0.75)	...	...	...	...	...
4362	HR 207	G0 Ib	6.4	.001	3	0.70	-6.0	-5.9	-5.7	...	-5.9±0.3
11544	...	G2 Ib	6.8	.001	4	(0.85)	...	...	...	...	...
16901	14 Per	G0 Ib	5.4	.004	5	0.66	-5.0	-3.5	-5.0	...	-4.7±0.5
23359	...	F8 Ib	8.4	.002	5	(0.55)	...	...	...	...	...
25056	...	G0 Ib	7.0	.007	4	(0.70)	...	...	...	...	...
26630	μ Per	G0 Ib	4.1	.002	6	0.60	-4.5	-5.7	...	-6.3:	-5.2±0.5
26673/4	52 Per	G2 I+B	4.7	.004	6	0.67	...	...	...	...	...
31910	β Cam	G0 Ib	4.0	.004	5	0.74	-5.3	-5.2	-5.2	...	-5.2±0.2
36891	HR 1884	G0 Ib	6.1	.004	4	(0.60)	...	...	...	...	...
38808	...	G3 Ib-II	8.0	.004	3	0.86	...	...	...	...	...
39949	...	G2 Ib	7.7	.007	3	0.73	...	...	...	...	...
42454	...	G2 Ib	7.4	.002	3	(0.85)	...	...	...	...	...
42456	...	G5 Ib	8.2	.001	3	(1.01)	...	...	...	...	...
44812	...	G5 Ib	7.4	.001	3	(1.01)	...	...	...	...	...
47731	25 Gem	G5 Ib	6.4	.002	3	(1.01)	-4.0	...	...	...	-4.0±1.0
67594	ζ Mon	G2 Ib	4.3	0.002	3	0.81	-4.8	-5.3	-4.8	...	-4.9±0.3
77912	HR 3612	G8 Ib-II	4.6	.004	5	0.87	...	...	...	...	...
84441	ε Leo	G0 I-II	3.0	.025	5	0.61	-2.2	...	-4.4	...	-3.3±1.0
92125	37 LMi	G0 II	4.7	.005	6	0.62	-3.8	...	...	...	-3.8±1.0
159181	β Dra	G2 Ib	2.8	.011	10	0.92	-5.7	...	-5.3	...	-5.5±0.4
171635	45 Dra	F6 Ib	4.8	.005	11	0.51	...	...	-5.0	...	-5.0±1.0
172365	HR 7008	F8 Ib	6.4	.005	3	0.57	...	...	-4.6	-2.5:	-3.9±1.0
179784	...	G5 Ib	6.7	.008	3	(1.01)	...	...	...	...	...
182296	...	G2 Ib	7.1	.010	4	0.82	...	...	...	...	...
183864	...	G0 Ib	8.1	.003	3	0.61	...	...	...	...	...
185758	α Sge	G0 II	4.4	.003	7	0.70	-2.0	-2.9	...	...	-2.3±0.5
187203	HR 7542	F8 Ib-II	6.4	.004	3	0.62	...	...	...	...	...
187299	...	G5 Ib	7.1	.012	3	0.75	...	...	...	-5.4	-5.4±0.4
187505	...	G2 Ib	7.8	.005	4	(0.85)	...	...	...	...	...
191010	...	G3 Ib	8.6	.041	4	0.83	...	...	...	...	...
192713	22 Vul	G2 Ib	5.2	.007	6	0.88	-5.4	-6.0	-5.1	...	-5.4±0.4
194012*	HR 7793	(F8 Ib)	6.2	.009	3	...	...	...	...	...	...
200102	...	G2 Ib	6.6	.006	3	(0.85)	...	...	...	...	...
202314	HR 8126	G2 Ib	6.2	0.004	4	(0.85)	...	...	...	...	...
204022	...	G0 Ib	7.8	.002	3	0.57	...	...	-5.4	...	-5.4±1.0
235518**	...	F8 Ib	8.5	.010	3	0.30:	...	...	-2.3:	-4.1	...
206859	9 Peg	G5 Ib	4.3	.005	7	1.04	-3.6	-4.8	...	...	-4.0±0.8
207647	...	G4 Ib	7.7	.004	3	0.93	...	...	...	...	...
208606	HR 8374	G8 Ib	6.1	.002	3	(1.03)	-4.8	-4.1	...	...	-4.6±0.4
210761	...	G1 Ib-II	8.0	.008	3	(0.75)	...	...	...	...	...
213482	...	F8 Ib	8.6	.021	3	(0.55)	...	...	...	...	...
239994	...	G0 Ib:	9.0	.038	4	(0.80:)	...	...	...	...	...
214847	...	G0 Ib:	8.7	.019	4	(0.80:)	...	...	...	...	...
217476	HR 8752	G0 Ia	5.1	.009	6	0.90	...	...	-5.9	-6.0	-6.0±0.3
219135	...	G0 Ib	7.6	.002	4	0.77	...	...	...	...	...
223047	ψ And	G5 Ib	5.0	.005	4	0.95	-5.7	-5.4	...	...	-5.6±0.2
224165	HR 9053	G8 Ib	6.0	.002	4	(1.03)	...	...	...	...	...

SOURCES of M_V.—(1) Wilson and Bappu (1957); (2) Kraft *et al.* (1964); (3) Parsons and Bouw (1971), Parsons (1971); (4) Schmidt-Kaler (1961).

* Error in spectral type.

** Parsons (1971) suspects error in 6-color photometry.

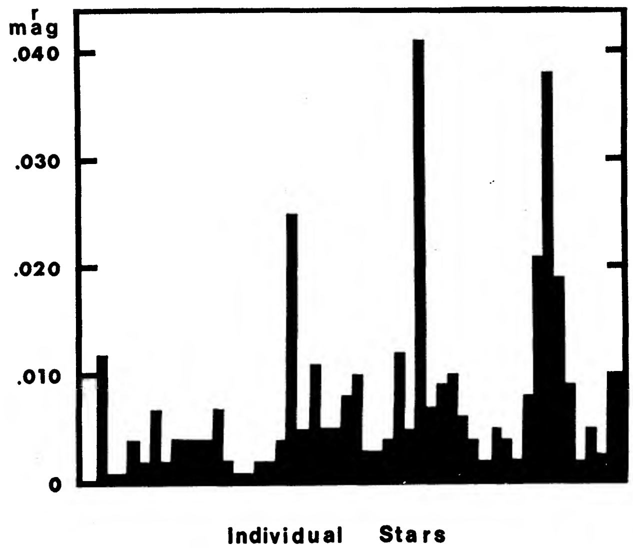

FIG. 1.—Distribution of the photometric residuals r among the individual stars

TABLE 2

STARS SUSPECTED OF VARIABILITY

Star	Amplitude (= 3.7r) (mag)	Star	Amplitude (= 3.7r) (mag)
HD 191010...........	0.15	HD 213482...........	0.08
HDE 239994..........	0.14	HD 214846...........	0.07
HD 84441............	0.09		

If it is variable, then ϵ Leo (HD 84441) becomes the second brightest Cepheid known. Its absolute magnitude of about -3 (see Table 1) indicates a period of only a few days.

IV. ABSOLUTE MAGNITUDES AND COLORS

Having established that many of these stars are nonvariable, in some cases down to a level of about 0.01 mag, we now examine the possibility that some of the nonvariable stars are located in the Cepheid instability strip on the H-R diagram. For this we require absolute visual magnitudes and intrinsic $(B - V)$ colors.

Sources of absolute magnitude that have been used are: width of the K-line emission core (Wilson and Bappu 1957; Kraft, Preston, and Wolff 1964), width of the Hα line (Kraft *et al.* 1964), model-atmosphere fitting to six-color photometry (Parsons and Bouw 1971; Parsons 1971), and membership in clusters or associations (Schmidt-Kaler 1961). The results are listed in Table 1, together with a final adopted absolute magnitude and its uncertainty. This uncertainty is not a formal probable error but rather (it is hoped) a realistic estimate of the overall uncertainty in the absolute magnitude. In forming the adopted absolute magnitude the value derived from the Hα line method was assigned half-weight, since it seems to be a method less accurate than the others.

Intrinsic $(B - V)$ colors are most readily obtained from color-color plots associated with *BVRI* photometry. The data have been taken from Johnson *et al.* (1966) or from the six-color photometry of Kron (1958) transformed to the Johnson *BVRI* system. The color-color plots used were $(B-V)$ versus $(V-R)$ and $(B-V)$ versus $(R-I)$, with intrinsic sequences from Johnson (1966) and color-excess ratios based on the standard Whitford interstellar absorption curve. In general, the intrinsic colors so derived are in quite good agreement with the spectral types, and for the few cases of stars in clusters or associations, the excesses are in reasonable agreement with those derived for the cluster. These colors are probably accurate to within about $\pm$ 0.05 mag.

For nearly half of the stars there is no published *BVRI* photometry. The intrinsic colors for these stars were derived on the basis of their spectral types, and are listed in Table 1 in parentheses. Since $(B-V)$ changes rapidly with spectral type in this range, an error of only one or two subclasses can drastically affect the derived color, so that these results are only of moderate accuracy.

HD 194012 is listed by Jaschek *et al.* (1964) as having spectral type F8 Ib. Near this spectral type, however, the quantity $[(B-V)-(U-B)]$ is a fairly sensitive indicator of luminosity, and the *UBV* colors of this star (Marlborough 1964) quite definitely indicate it to be a dwarf. This is confirmed by its trigonometric parallax of $+0\farcs031$ (giving $M_V = +3.7$) as given in the *Bright Star Catalog*. It is in fact an F7 V star.

V. DISCUSSION

Figure 2 shows the region of the H-R diagram containing the Cepheid instability strip. Three versions of the strip are shown: those due to Kraft (1966), Fernie (1967), and Sandage and Tammann (1969). Also plotted are those stars from Table 1 which have $r \leq 0.010$ mag, and for which photometrically determined intrinsic colors and individually determined absolute magnitudes are available. No star was plotted on the basis of its spectral type and luminosity class alone.

Most of the stars lie well within the instability strip, even when only the narrowest version (Kraft's) of the strip is considered. In a few cases the uncertainties attached to M_V and $(B-V)$ are sufficiently small that entirely unreasonable errors would be required to place them outside the strip. Moreover, if the group is considered as a statistical whole, it would be wholly implausible that they are all in reality clustered outside the

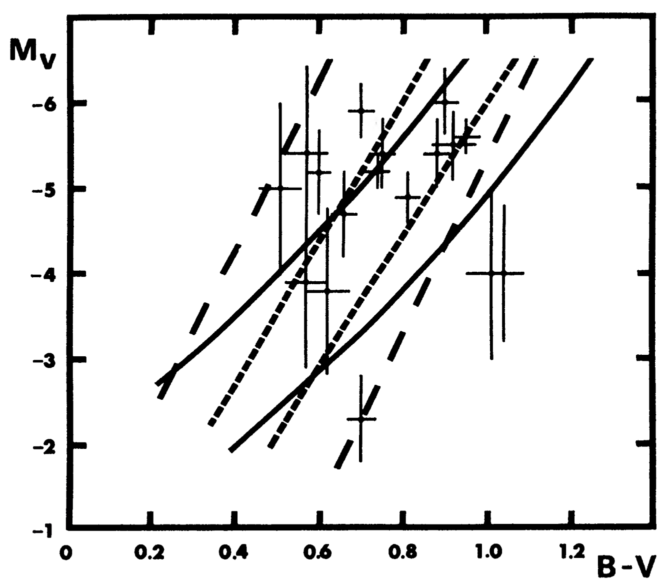

FIG. 2.—Location on the H-R diagram of nonvariable stars in Table 1 having individually determined absolute magnitudes and colors. Also shown is the position of the Cepheid instability strip according to Kraft (*dotted lines*), Fernie (*solid lines*), and Sandage and Tammann (*broken lines*).

strip and have all been scattered into it by observational error alone. We conclude that nonvariable stars are in fact present in the Cepheid instability strip.

It might be argued that the definition of "variable" as against "nonvariable" is arbitrary, imposed by our observational limitations, and that these so-called non-variables might very well be pulsating with amplitudes of only about 0.01 mag. However, although the statistics are insufficient to be conclusive, there is a suggestion in Figure 1 of a real paucity of stars having r between 0.01 and 0.02 mag. In short, there is little difficulty in distinguishing on Figure 1 those stars which are probably variable from those which are not. We very tentatively suggest that there is not a continuous spectrum of pulsational amplitudes, but that if this type of star pulsates at all, it does so with an amplitude of at least about 0.06 mag.

More to the point, perhaps, we consider the distinction between variable and non-variable to be begging the question. What is important is that the stars plotted in Figure 2 are apparently no different from so-called stable stars which definitely lie outside the instability strip. The star α Per, for example, which at $M_V = -4.6$, $(B - V)_0 = 0.39$ lies outside the strip, shows $r = 0.010$ mag on the basis of photometry by Johnson *et al.* (1966). It therefore seems that some stars can evolve into the instability strip without significantly changing the stability they had when outside the strip. Alternatively, it is conceivable that not all stars are continuously variable throughout their *entire* evolutionary traversal of the strip. Possibly one star may become variable only toward the blueward edge of the strip, while another, because of minor differences in rotation, say, may become variable only toward the redward edge of the strip. Such speculations, however, are better evaluated by theory.

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