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CEPHEIDS IN OPEN CLUSTERS AND ASSOCIATIONS

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ABSTRACT

The literature has been surveyed for papers concerning classical Cepheids which are thought to be members of open clusters or associations. The material has been collated and put on a homogeneous basis, using a Hyades distance modulus of 3.29 without metallicity corrections. Twenty-nine cases are listed, of which 27 are considered useful for discussion of the period-luminosity and period-luminosity-color relations.

It is found that these 27 stars define a period-luminosity relation which is

$$M_{\langle V\rangle} = \underset{\pm 0.10}{-1.61} - \underset{\pm 0.084}{2.882} \log P$$

with an rms deviation of 0.16 mag. With so small a dispersion it is found that neither least-squares nor maximum-likelihood techniques serve to evaluate the color term in the period-luminosity-color relation. This is not to deny its existence; it is just that the present selection of stars is inadequate for finding the color term.

Subject headings: clusters: associations — clusters: open — stars: Cepheids — stars: luminosities

I. INTRODUCTION

The calibration of classical Cepheid absolute magnitudes remains a problem of intense interest. The most direct approach to this calibration lies through those Cepheids which are located in open clusters and stellar associations, and as a result numbers of workers have investigated individual cases in detail. This has given rise to papers scattered inconveniently throughout the literature, which are more or less inconsistent in their use of such fundamental parameters as the distance modulus of the Hyades or the calibration of the age-zero main sequence.

This paper does not present any new observations, but sets out to collect these disparate investigations into one data base that is internally consistent.

II. TREATMENT OF THE DATA

Ideally, an investigation of this sort would go back to the original observations of each cluster member as reported in individual papers, and the entire analysis then redone for every cluster in a uniform way. This is a formidable task, so as a first step we decided only to adjust previously determined cluster moduli to a uniform Hyades modulus and to rediscuss the reddening of each cluster Cepheid. We then could examine the period-luminosity relation defined by these data, having in mind that if this relation showed large scatter it would be necessary to return to the basic observations, but if the scatter was small there would be little point in so large an undertaking for what would evidently be minor changes. As will be seen in § III, this first step resulted in a *P-L* relation which showed an rms scatter of only 0.16 mag in M_V. In our view the moduli of clusters and associations are unlikely to be determined with a precision much greater than this, no matter how much care and effort is lavished on the task. Thus we have not gone back to the original observations, but have worked with the distance moduli as published by individual workers.

First, however, we discuss the interstellar reddening corrections. We considered whether to use only the reddenings obtained from the cluster members themselves, or whether to also invoke reddenings determined in other ways, say *BVRI* photometry of the Cepheids themselves. We chose the second alternative since it seemed that would strengthen the results, particularly in those cases where clusters or associations show differential reddenings that make the Cepheid reddening relatively uncertain.

Table 1 tabulates reddening from eight sources. By column from left to right these sources are Parsons and Bell (1975), Pel (1978), Dean *et al.* (1978, *BVI* data), Dean *et al.* (1978, *BVRI* data), OB stars in the clusters or associations, Fernie (1982), Parsons and Bouw (1971), Feltz and McNamara (1980). The final column shows

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TABLE 1

THE ADOPTED REDDENINGS

Star	E_{PB}	E_{PT}	E_{KC}	E_J	E_{OB}	E_{Fe}	E_{PBo}	E_{by}	E_A
SU Cas	0.21	...	...	0.26	(0.37)	0.19/0.20	0.23	...	0.22
EV Sct.......	0.61	0.67	...	0.53/0.68	0.54	0.57	0.63	...	0.60
CE Cas b	...	...	...	...	...	...	...	...	0.54[a]
CF Cas	0.48	...	...	0.61	0.55	0.55	0.53	...	0.54
CE Cas a	...	...	...	...	...	...	...	...	0.54[a]
UY Per	...	...	...	0.91	...	0.82	...	...	0.87
CV Mon	0.75	0.74	...	...	0.74	...	0.81	...	0.76
V Cen	...	0.30	0.36	...	0.29	...	...	...	0.32
VY Per	...	...	...	1.00	...	0.91	...	...	0.96
CS Vel.......	...	...	...	...	0.69/0.75	...	...	...	0.72
V367 Sct	...	...	...	...	1.27/1.27	...	...	...	1.27
U Sgr........	0.36	0.43	0.46	0.44	0.47	0.40/0.41	0.41	0.44	0.42
DL Cas......	0.48	...	...	0.51	0.48	0.49	0.54	...	0.50
S Nor........	...	0.21	0.18	...	0.20	...	...	...	0.20
TW Nor	...	1.21	1.22	...	1.20/1.21	...	...	...	1.21
VX Per	...	...	...	0.49	...	0.48	...	...	0.49
SZ Cas.......	...	...	...	0.85	...	0.78	...	...	0.82
VY Car......	...	0.24	0.27	...	0.25	...	...	...	0.25
RU Sct	...	0.99	...	...	0.95	...	...	...	0.97
RZ Vel	...	0.30	0.33	...	...	...	...	...	0.32
SW Vel	...	0.37	0.37	...	...	...	...	...	0.37
T Mon.......	0.21	0.20	0.16	0.17	0.23	0.15	0.25	0.22	0.20
KQ Sco......	...	...	...	...	0.90	...	...	...	0.90
RS Pup	...	0.50	0.50	0.45	...	...	...	...	0.48
SV Vul.......	0.41	...	...	...	0.45	0.39/0.48	0.47	(0.63)	0.45
GY Sge......	...	...	...	...	1.13	...	...	...	1.13
S Vul	...	...	...	0.74	0.76	0.77	...	...	0.76
V810 Cen ...	...	...	...	...	0.24/0.24	...	...	...	0.24

[a]Values from CF Cas in same cluster.

the adopted reddening values. These are the unweighted means of values shown in the other columns, except that bracketed values were excluded on the grounds of seeming excessively different from the other values.

The distance moduli of all clusters and associations have been adjusted where necessary to correspond to a Hyades modulus of 3.29 (Hanson 1975), which seems to be the most widely accepted figure at the present time. Some authors have invoked metallicity corrections of up to several tenths of a magnitude for some clusters, but in our view these are not yet certain and we have omitted them.

The value of $R = A_V/E_{B-V}$ has been taken as the value obtained from a variable extinction analysis if this was done for any particular cluster/association. If not, a value of 3.08 was adopted from the Galactic mean of Turner (see references to Table 2). The value used in each case is listed in Table 2, which also contains our derived distance moduli, absolute magnitudes, intrinsic colors, etc.

Mean values of all photometric data are intensity means.

III. DISCUSSION

Our main purpose in this paper is to compile the data shown in Tables 1 and 2 for application by ourselves and others elsewhere. It is not our intention to enter into an exhaustive discussion of the period-luminosity (*PL*) or period-luminosity-color (*PLC*) relations here. Nevertheless, it is obviously of great interest to see what these data by themselves imply for these relations.

Figure 1 shows a simple *PL* relation from the data in Table 2. The open circles joined by a vertical line represent two determinations for CS Vel, the more luminous one by Harris and van den Bergh (1976), the less luminous one by Moffat and Vogt (1975). (Our result for CS Vel differs somewhat from that of either paper, Hyades modulus apart, because they applied the OB star excess directly to the Cepheid.) It seems to us from Figure 1 that neither value justifies inclusion in a *PL* discussion, and the star has therefore been omitted from the analysis.

V810 Cen ($M_{\langle V \rangle} = -8.18$, $\log P = 2.115$) appears to fit the *PL* relation of Figure 1 reasonably well, but it is

TABLE 2

CALIBRATING DATA

Cepheid	log P	Cluster	$M_{<V>}$	$(<B>-<V>)_o$	Ref	$(m-M)_o$	Ref	$E^{(OB)}_{B-V}$	R	Other Ref
SU Cas	.290	R-assoc.	-2.48	.50	32	7.72	28	.24	3.08	9,17,26,35,38,59
EV Sct	.490	NGC 6664	-2.90	.53	32	11.15	1,19	.67	2.80	6,11,27,35,58
CE Cas b	.651	NGC 7790	-3.68	.58	31	12.85	3,29	.59	3.09	36,58
CF Cas	.688	NGC 7790	-3.57	.68	32	12.85	3,29	.59	3.09	35,36,58
CE Cas a	.711	NGC 7790	-3.75	.66	31	12.85	3,29	.59	3.09	36,58
UY Per	.730	h&χ Per	-3.70	.68	32	12.05	3,33	.96	3.08	35
CV Mon	.731	anon	-3.78	.57	45	11.50	45	.83	3.09	27,39
V Cen	.740	NGC 5662	-3.50	.56	32	9.24	24,53	.35	3.1	6,27,37
VY Per	.743	h&χ Per	-4.10	.66	32	12.05	3,33	1.05	3.08	35
CS Vel	.771	Ru 79	-2.49	.62	15	11.95	15,24	.79	3.08	-
V367 Sct	.799	NGC 6649	-4.07	.56	22,51	11.49	22,41,51	1.38	3.0	6,23
U Sgr	.829	M 25	-4.05	.70	32	9.21	18,30,55	.46	3.08	7,9,26,27,34,35,58,59
DL Cas	.903	NGC 129	-4.10	.69	32	11.35	2,31	.56	3.01	35,39,58
S Nor	.989	NGC 6087	-4.22	.75	32	9.95	19	.22	3.08	5,7,27,34
TW Nor	1.033	Lynga 6	-4.26	.79	21	11.77	4,20	1.35	3.08	6,27
VX Per	1.037	h&χ Per	-4.41	.73	32	12.06	3,33	.54	3.08	35
SZ Cas	1.134	h&χ Per	-4.99	.67	32	12.05	3,33	.90	3.08	35,40,58
VY Car	1.277	Car OB1	-5.24	.92	21	11.86	44	.28	3.05	6,27
RU Sct	1.294	Tr 35	-5.60	.75	32	11.89	49	1.07	3.00	27,58
RZ Vel	1.310	Vel OB1	-5.54	.81	21	11.52	47	.36	2.88	7,27
WZ Sgr	1.339	anon	-4.85	.94	21	11.26	54	.52	3.08	6,27
SW Vel	1.370	anon OB	-5.54	.81	21	12.38	47	.41	3.04	6,27
T Mon	1.432	Mon OB2	-5.70	.99	32	11.10	43	.23	3.2	7,9,26,27,40,58,59
KQ Sco	1.458	anon OB	-5.81	1.04	32,56	12.60	47	1.00	3.04	-
RS Pup	1.617	Pup OB3	-6.21	.96	21	11.55	16,31,57	.54	3.08	7,27
SV Vul	1.653	Vul OB1	-6.38	1.02	13a	12.10	46	.50	3.0	9,26,35,40,58
GY Sge	1.708	anon OB	-6.57	1.12	14	12.99	14	1.30	2.93	-
S Vul	1.830	Vul OB2	-7.15	1.16	10	13.51	48	.88	3.0	35
V810 Cen	2.115	Stock 14	-8.18	.58	8,12,52	12.44	24,52	.26	3.05	13,52

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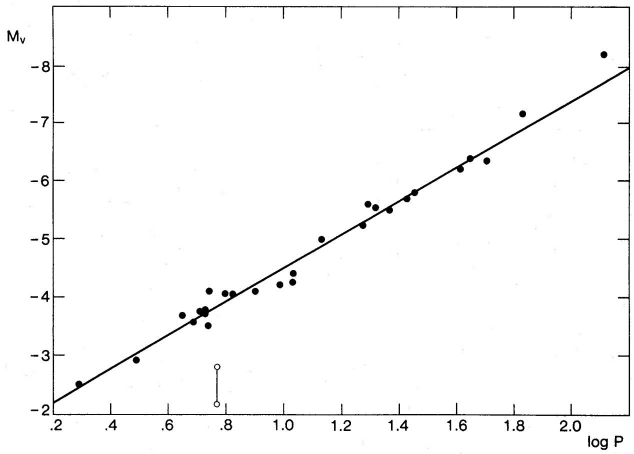

FIG. 1.—The period-luminosity relation defined by the data of Table 2. The straight line represents equation (1). The two open circles joined by a line represent two determinations of the absolute magnitude of CS Vel, and because of its displacement in this diagram it is rejected from further consideration. The star of longest period, V810 Cen, has also been rejected because of its displacement in Figs. 2 and 3.

so far removed from the normal instability strip—witness Figures 2 and 3—that we have preferred to omit it also from the analysis.

With these two stars omitted, a least-squares solution for the *PL* relation gave

$$M_{\langle V\rangle} = \underset{\pm 0.10}{-1.61} - \underset{\pm 0.084}{2.882} \log P \qquad \text{(s. e)} \qquad (1)$$

with an rms deviation in $M_{\langle V\rangle}$ of 0.16 mag. This is a surprisingly small dispersion for data that originate from so many different sources, and observational error aside, suggests a narrower instability strip than has often been assumed. In fact, this can be seen from Figure 1 alone, which suggests a total dispersion in absolute magnitude at constant period of no more than about 0.6 mag, i.e. ± 0.3 mag about the mean relation.

This figure must be regarded only as a lower limit. A problem hovering over any study such as this, and one which cannot be dealt with effectively, is the selection effect arising from circularity of argument. Ideally, each paper dealing with a Cepheid in a cluster or association would address the membership question on the basis of data such as space motions. In practice such data are often unavailable, so the author makes a judgment as to the Cepheid's membership by whether the latter leads to an absolute magnitude that is consistent with a previous *PL* relation. If it is not, the work may never be completed and published.

However, while we accept that some such bias is probably present, we suggest it is not very great. We offer two reasons for this claim: First, we seriously doubt that most workers would totally reject (in the sense of not publishing) a case where the discrepancy was only around 0.4–0.6 mag or even up to 1 mag. Yet such cases are absent. Second, if we apply equation (1) to the seven "classical" cases of EV Sct, CE Cas a, b, CF Cas, U Sgr, DL Cas, and S Nor, for which other evidence of membership has been established, then we obtain residuals $O - C$ between observed and calculated absolute magnitudes of $+0.12$, -0.09, -0.19, $+0.02$, -0.05, $+0.11$, and $+0.24$, respectively, for an rms deviation of 0.14 mag. This indicates that the figure of 0.16 mag for the sample as a whole is not grossly in error; the real dispersion is not likely to be much greater.

For comparison, corresponding Cepheids in the Large Magellanic Cloud observed by Martin, Warren, and Feast (1979) yield a figure of 0.25 mag for a *PL* relation without differential reddening corrections, while Small Magellanic Cloud Cepheids observed by Gascoigne

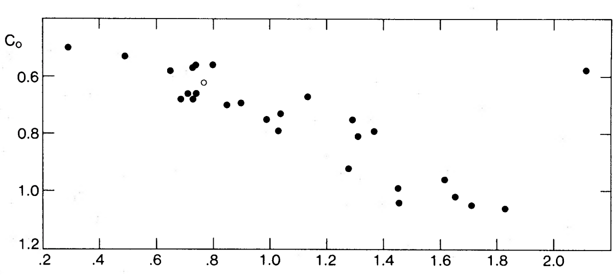

FIG. 2

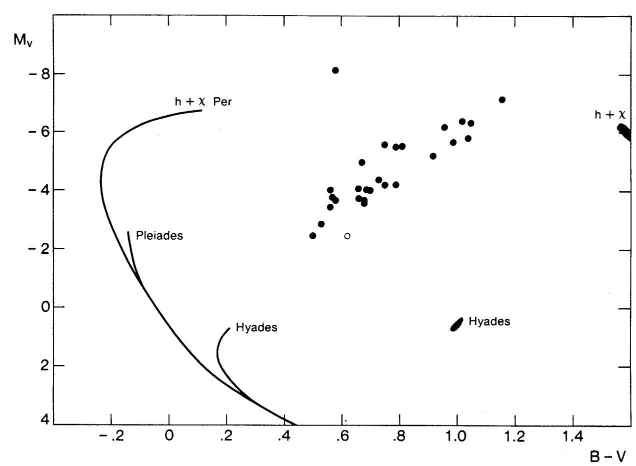

FIG. 3

FIG. 2.—The mean color-period relation for the present data. $C_0 \equiv (\langle B\rangle - \langle V\rangle)_0$. The open circle represents CS Vel.

FIG. 3.—The color-magnitude diagram for the present data, with a number of open clusters shown schematically. The open circle represents CS Vel.

TABLE 3

MAXIMUM LIKELIHOOD SOLUTIONS

$M_{\langle V\rangle} = a + b \log P + c(\langle B\rangle - \langle V\rangle)_0$

σM_V	$\sigma \log P$	σBV	a	b	c
0.15	0.001	0.04	−1.81	−3.14	0.61
		0.05	−1.97	−3.35	1.12
		0.06	−2.69	−4.29	3.37
0.25	0.001	0.05	−1.63	−3.07	0.32
		0.06	−1.72	−3.19	0.61
		0.07	−3.09	−5.00	4.92

(1969) yield 0.21 mag, again for a *PL* relation without differential reddening corrections.

These figures refer, of course, to the dispersion in M_V at a given period. In the instability strip itself, as Figure 3 shows, the range in M_V at a given *color* is more like 2 mag.

A quadratic solution produced no significant second-order term in log P and did not reduce the rms deviation, although inclusion of V810 Cen would result in a small but significant second-order term.

The slope of equation (1) is in good agreement with that derived from LMC Cepheids of similar period range by Martin, Warren, and Feast (1979), who find values between −2.70 and −2.90, depending on choice of data. The ridge-line *PL* relation of Sandage and Tammann (1968), while not quite linear, is closely approximated for $\log P < 1.8$ by

$$M_{\langle V\rangle} = -1.33 - 2.87 \log P .$$

Again the agreement is excellent, apart from the zero-point shift resulting from the newer Hyades distance modulus.

We first investigated the *PLC* relation by means of multilinear regression, obtaining a least-squares solution of

$$M_{\langle V\rangle} = \underset{\pm 0.19}{-1.72} - \underset{\pm 0.23}{3.01} \log P + \underset{\pm 0.53}{0.30}(\langle B\rangle - \langle V\rangle)_0 \quad \text{(s.e.)} \qquad (2)$$

with an rms deviation of 0.16 mag. Clearly the color term is not significant and does not improve the rms deviation.

However, the *PLC* relation is now more usually discussed by means of the maximum likelihood method rather than least-squares, so we have done this as well. This requires estimates of the uncertainties in the three observed quantities. On the basis of the above discussion we believe the uncertainty in M_V cannot be far from 0.2 mag, and we have tried values of 0.15 and 0.25 mag. For the uncertainty in log P we arbitrarily assumed 0.001 as a general upper limit, and for uncertainties in intrinsic color we tried values between 0.04 and 0.07 mag. Results are shown in Table 3. Clearly they are very unstable to the assumed uncertainties; changes of only 0.01 mag in σ_{BV} produce large changes in the results, particularly the color coefficient. We conclude that the method does not yield useful results in this case, and in turn interpret this to mean that by themselves the data in Table 2 are incapable of calibrating the *PLC* relation.

This does not necessarily mean that we reject the existence of a color term altogether; only that the present data define too narrow an instability strip to allow the calibration of a color term. Meanwhile, equation (1) represents our best method for determining absolute magnitude.

Figure 2 shows the period-color relation. A least-squares solution gave

$$(\langle B\rangle - \langle V\rangle)_0 = \underset{\pm 0.04}{0.32} + \underset{\pm 0.032}{0.418} \log P ,$$

This is in satisfactory agreement with that of Dean *et al.* (1978), as of course it should be since their data appear in Table 1. It does, however, demonstrate consistency.

Finally, for general interest, Figure 3 shows the data plotted on a color-magnitude array, along with the schematic positions of a few well-known clusters (Sandage 1958).

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