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(R - I) COLORS OF CEPHEIDS AND YELLOW SUPERGIANTS IN OPEN CLUSTERS

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ABSTRACT

$(R - I)$ and $(b - y)$ observations of nine Cepheids which are members of open clusters, 14 field Cepheids, and 34 nonvariable yellow giants in or near open clusters are presented. Color-color relations for the Cepheids are found to differ significantly from star to star. Additionally, the nonvariables may differ from the Cepheid color-color relation. Pulsational masses are determined for the Cepheids using both $(R - I)$ and $(B - V)$ colors as temperature indicators. For some of the shorter period stars the $(R - I)$ masses agree with evolutionary masses, which is not the case for the $(B - V)$ masses. A small increase (about 0.1 mag) in the absolute magnitudes of the short-period Cepheids is sufficient to bring agreement between the $(R - I)$ masses and the evolutionary masses for the bulk of the stars, but the long-period stars still have low masses. However, it is suggested that this may be due to systematic errors in the color excesses. The cluster NGC 129 is found to have a nonvariable star within the instability strip in addition to the Cepheid DL Cas. Because the absolute magnitude and intrinsic color are well determined from the cluster, this is the best established case of a nonvariable in the Cepheid strip. Several other clusters contain a number of yellow giants, and they are compared with evolutionary tracks.

Subject headings: clusters: open — stars: cepheids — stars: supergiants

I. INTRODUCTION

The intrinsic colors of Cepheids are important to a number of problems. Chief among these is the question of the masses of Cepheids calculated from the pulsation theory. For this purpose temperatures derived from the $(B - V)$ colors have been almost universally used. However, it has been shown (Schmidt 1973, hereafter Paper I) that temperatures calculated from $(B - V)$ yield considerably different pulsational masses from those calculated from $(R - I)$.

In view of the large effects of line blanketing in the B and V bands, it is likely that $(R - I)$ is a more reliable temperature indicator than $(B - V)$. In addition, some evidence has been found (Schmidt 1972*b*) that the $(B - V)$-temperature relation is not the same for all Cepheids and that it differs between Cepheids and nonvariable supergiants in the same temperature range. Unfortunately, the widespread use of $(B - V)$ is dictated by the absence of $(R - I)$ colors for more than a few Cepheids. A further source of uncertainty arises from the fact that color excesses of these stars are uncertain except for those which are members of clusters. The main purpose of the present paper is to provide $(R - I)$ data for a number of Cepheids, with special emphasis on those in open clusters, and to provide comparable information for nonvariable supergiants which are or may be cluster members.

* Visiting astronomer at Kitt Peak National Observatory which is operated by the Association of Universities for Research in Astronomy, Inc. under contract from the National Science Foundation.

II. THE OBSERVATIONS

Photometric observations were made of 23 Cepheids using the R and I filters of the Johnson *UBVRI* system and the b and y filters of the Strömgren *uvby* system. The measured colors and the R magnitudes were transformed to the standard system in the usual way. These observations were made at Kitt Peak National Observatory using the 92 cm telescope with a two-channel photometer. One channel was used with a red-sensitive photomultiplier to measure R and I while the other channel had a blue photocell and was used to obtain b and y. Table 1 contains the colors and magnitudes of the Cepheids. The phases were obtained from the ephemerides given in the third edition of the *General Catalogue of Variable Stars*.

Of the 23 Cepheids, eight are members of open clusters. Additionally, Racine (1968) has inferred the color excess and distance modulus of SU Cas from its apparent association with early-type stars near a reflection nebula. These nine stars are listed in Table 2. The distance moduli and color excesses come from the clusters of which these stars are members (Sandage and Tammann 1969). The corresponding data for the remaining 14 stars which are not members of clusters are given in Table 3. The values of E_{B-V} were taken from Parsons and Bouw (1971) for SZ Tau and RT Aur, from Fernie (1970) for S Vul, and from Sandage and Tammann (1968) for the remainder of the stars. The absolute magnitudes of the stars in Table 3 were obtained from the Sandage and Tammann (1969) calibration of the period-luminosity-color relation. In Tables 2 and 3 the magnitude mean of $R - I$, $\langle R - I\rangle$, is also given. The color curves measured here

TABLE 1

Photometric Data for Cepheids

SU Cas

J.D. -2441900	Phase	R	R-I	b-y
59.89	0.16	5.18	0.464	0.388
60.89	0.67	5.44	0.502	0.469
62.92	0.71	5.40	0.534	0.509
63.90	0.22	5.17	0.446	0.453
70.86	0.78	5.51	0.510	0.509
71.87	0.30	5.27	0.467	0.479
72.86	0.81	5.45	0.498	0.501
73.86	0.32	5.31	0.477	0.474
74.85	0.83	5.42	0.494	0.503
75.88	0.36	5.32	0.490	0.482
76.88	0.87	5.36	0.476	0.479
77.85	0.37	5.34	0.486	0.496

EV Sct

J.D. -2441900	Phase	R	R-I	b-y
60.62	0.81	8.97	0.311	0.715
61.63	0.14	9.14	0.854	0.762
62.60	0.45	9.01	0.823	0.777
63.60	0.78	9.00	0.814	0.795
70.60	0.04	9.07	0.852	0.790
71.60	0.36	9.07	0.822	0.791
72.59	0.69	8.94	0.802	0.796
73.58	0.01	9.11	0.827	0.847
74.59	0.33	9.04	0.833	0.806
75.59	0.66	9.00	0.838	0.777
76.58	0.98	9.11	0.851	0.341
77.59	0.30	9.08	0.819	0.821

SZ Tau

J.D. -2441900	Phase	R	R-I	b-y
60.00	0.30	5.87	0.607	0.550
60.96	0.60	5.73	0.542	0.490
62.93	0.23	5.83	0.606	0.598
63.92	0.54	5.73	0.570	0.549
70.93	0.77	5.67	0.527	0.494
71.93	0.09	5.78	0.571	0.557
72.91	0.40	5.86	0.587	0.570
73.89	0.71	5.66	0.523	0.511
74.91	0.04	5.70	0.560	0.554
75.91	0.35	5.89	0.595	0.592
76.89	0.66	5.71	0.538	0.515
77.90	0.99	5.75	0.555	0.543

RT Aur

J.D. -2441900	Phase	R	R-I	b-y
60.00	0.33	4.98	0.411	0.437
61.00	0.60	5.17	0.349	0.454
62.98	0.13	4.80	0.314	0.344
71.00	0.28	4.95	0.387	0.404
72.01	0.55	5.12	0.419	0.465
73.00	0.82	4.97	0.356	0.379
74.00	0.09	4.77	0.325	0.366
75.00	0.36	5.02	0.399	0.450
75.99	0.62	5.18	0.418	0.465
76.99	0.89	4.74	0.293	0.278
77.96	0.15	4.79	0.346	0.351

CF Cas

J.D. -2441900	Phase	R	R-I	b-y
59.78	0.82	10.14	0.843	0.758
60.71	0.01	9.87	0.752	0.663
61.75	0.22	10.00	0.810	0.745
62.72	0.42	10.13	0.840	0.816
63.77	0.64	10.30	0.891	0.833
64.78	0.84	10.04	0.761	0.772
70.74	0.06	9.91	0.763	0.745
71.74	0.27	9.99	0.821	0.820
72.76	0.48	10.16	0.843	0.852
73.76	0.68	10.27	0.860	0.838
74.75	0.89	10.03	0.777	0.744
75.74	0.09	9.98	0.783	0.770
76.72	0.29	10.06	0.817	0.771
77.72	0.50	10.22	0.853	0.850

UY Per

J.D. -2441900	Phase	R	R-I	b-y
59.88	0.46	9.98	1.111	1.069
60.88	0.64	10.18	1.149	1.070
62.92	0.02	9.68	1.027	0.981
63.89	0.20	9.77	1.078	1.007
70.85	0.50	10.05	1.038	1.127
71.86	0.69	10.23	1.133	1.131
72.85	0.87	10.08	1.078	1.033
73.86	0.06	9.73	1.021	0.934
74.85	0.24	9.90	1.073	1.035
75.87	0.44	9.99	1.112	1.075
76.87	0.62	10.14	1.133	1.134
77.85	0.80	10.21	1.122	1.100

VY Per

J.D. -2441900	Phase	R	R-I	b-y
59.88	0.13	9.59	1.118	1.002
60.87	0.31	9.77	1.169	1.038
62.89	0.68	9.97	1.213	1.105
63.89	0.86	9.54	1.084	0.994
64.89	0.04	9.58	1.089	1.041
70.84	0.11	9.68	1.108	1.050
71.85	0.30	9.87	1.193	1.134
72.85	0.48	9.98	1.195	1.175
73.85	0.66	10.08	1.198	1.193
74.84	0.84	9.73	1.084	1.020
75.86	0.02	9.55	1.105	0.993
76.86	0.20	9.68	1.133	1.111
77.84	0.38	9.82	1.173	1.118

U Sgr

J.D. -2441900	Phase	R	R-I	b-y
59.63	0.60	5.87	0.724	0.757
60.61	0.75	6.02	0.749	0.767
61.62	0.90	5.83	0.697	0.642
62.60	0.04	5.52	0.632	0.602
63.60	0.19	5.58	0.660	0.643
70.60	0.23	5.58	0.667	0.617
71.59	0.38	5.64	0.691	0.686
72.59	0.53	5.82	0.723	0.757
73.58	0.67	5.96	0.749	0.794
74.58	0.82	5.97	0.747	0.770
75.59	0.97	5.65	0.652	0.602
76.58	0.12	5.56	0.647	0.654
77.58	0.33	5.64	0.690	0.700

DL Cas

J.D. -2441900	Phase	R	R-I	b-y
59.82	0.50	7.98	0.807	0.820
60.79	0.62	8.09	0.793	0.808
61.78	0.74	8.17	0.809	0.805
62.77	0.87	7.99	0.775	0.770
63.83	0.00	7.79	0.738	0.689
64.78	0.12	7.80	0.740	0.710
70.75	0.86	8.05	0.773	0.794
71.75	0.99	7.78	0.723	0.695
72.77	0.12	7.77	0.743	0.712
73.76	0.24	7.83	0.758	0.728
74.76	0.36	7.90	0.773	0.808
75.74	0.49	8.00	0.803	0.798
76.73	0.61	8.12	0.824	0.834
77.73	0.71	8.20	0.820	0.849

Y Sct

J.D. -2441900	Phase	R	R-I	b-y
61.64	0.28	8.22	1.044	1.009
62.61	0.37	8.31	1.059	1.152
63.61	0.47	8.41	1.084	1.203
70.61	0.15	8.02	0.987	0.979
71.60	0.24	8.16	1.022	1.065
72.60	0.34	8.31	1.050	1.138
73.59	0.44	8.43	1.087	1.147
74.60	0.53	8.47	1.097	1.176
75.60	0.63	8.49	1.063	1.099
76.58	0.73	8.33	1.024	1.085
77.59	0.82	8.26	1.004	1.013

Z Lac

J.D. -2441900	Phase	R	R-I	b-y
59.68	0.30	7.46	0.701	0.791
60.68	0.40	7.59	0.724	0.807
61.69	0.49	7.72	0.769	0.851
62.71	0.58	7.80	0.766	0.818
63.65	0.67	7.74	0.730	0.803
64.77	0.77	7.52	0.868	0.722
70.66	0.31	7.52	0.724	0.800
71.69	0.41	7.67	0.758	0.846
72.71	0.50	7.66	0.766	0.854
73.71	0.59	7.79	0.765	0.821
74.70	0.68	7.69	0.727	0.766
75.69	0.77	7.64	0.678	0.712
76.74	0.87	7.48	0.657	0.652
77.70	0.96	7.23	0.607	0.562

VX Per

J.D. -2441900	Phase	R	R-I	b-y
59.86	0.54	8.20	0.709	0.708
60.85	0.64	8.14	0.723	0.632
63.88	0.91	8.15	0.786	0.775
64.80	0.00	8.22	0.792	0.703
70.83	0.55	8.31	0.726	0.727
71.84	0.64	8.26	0.725	0.722
72.84	0.74	8.20	0.720	0.717
73.84	0.83	8.13	0.724	0.712
74.83	0.92	8.27	0.765	0.779
75.85	0.01	8.24	0.796	0.795
76.86	0.10	8.33	0.813	0.836
77.83	0.19	8.50	0.831	0.859

TABLE 1—*Continued*

SV Per

J.D. -2441900	Phase	R	R-I	b-y
60.96	0.26	7.92	0.697	0.655
62.93	0.43	8.09	0.752	0.775
63.92	0.52	8.18	0.761	0.810
70.94	0.15	7.86	0.652	0.657
71.94	0.24	7.92	0.687	0.702
72.92	0.33	7.98	0.719	0.711
73.90	0.42	8.04	0.734	0.758
74.91	0.51	8.16	0.741	0.787
75.91	0.60	8.30	0.758	0.769
76.92	0.69	8.36	0.738	0.764
77.90	0.78	8.23	0.686	0.722

RY Cas

J.D. -2441900	Phase	R	R-I	b-y
60.78	0.36	8.72	0.927	
61.77	0.44	8.85	0.966	0.944
63.80	0.61	8.97	0.986	0.986
71.72	0.26	8.62	0.915	0.889
72.76	0.34	8.70	0.925	0.961
73.75	0.43	8.83	0.983	0.933
74.75	0.51	8.94	0.997	1.030
75.74	0.59	9.02	1.010	0.999
76.71	0.67	9.04	0.987	0.952
77.71	0.75	8.99	0.948	0.947

RW Cas

J.D. -2441900	Phase	R	R-I	b-y
59.85	0.56	8.44	0.847	0.957
60.84	0.62	8.56	0.825	0.966
62.79	0.75	8.54	0.816	0.866
63.84	0.82	8.38	0.763	0.811
64.80	0.89	8.38	0.764	0.773
70.79	0.29	8.10	0.759	0.819
71.76	0.36	8.13	0.788	0.849
72.78	0.43	8.21	0.806	0.883
73.79	0.50	8.33	0.813	0.937
74.78	0.56	8.43	0.831	0.937
75.75	0.63	8.56	0.846	0.916
76.85	0.70	8.56	0.819	0.944
77.76	0.77	8.59	0.802	0.890

CD Cyg

J.D. -2441900	Phase	R	R-I	b-y
59.65	0.42	7.78	0.836	0.932
60.66	0.48	7.87	0.860	0.949
61.67	0.53	7.98	0.861	0.960
62.63	0.59	8.08	0.901	1.009
63.63	0.65	8.10	0.919	1.023
70.64	0.06	7.49	0.695	0.659
71.62	0.12	7.54	0.736	0.690
72.62	0.18	7.56	0.763	0.747
73.63	0.24	7.61	0.793	0.779
74.63	0.29	7.63	0.809	0.835
75.62	0.35	7.75	0.849	0.870
76.61	0.41	7.78	0.853	0.907
77.61	0.47	7.87	0.870	0.925

SZ Cas

J.D. -2441900	Phase	R	R-I	b-y
59.87	0.84	8.62	1.036	0.938
60.86	0.91	8.58	1.019	0.894
62.87	0.06	8.42	1.004	0.902
63.88	0.13	8.32	1.001	0.906
64.88	0.21	8.45	1.011	0.941
70.84	0.64	8.68	1.059	1.025
71.85	0.72	8.66	1.042	1.013
72.84	0.79	8.72	1.051	1.027
73.84	0.86	8.67	1.020	1.005
74.84	0.94	8.61	1.017	0.968
75.86	0.01	8.45	0.993	0.919
76.86	0.08	8.41	0.988	0.924
77.84	0.16	8.38	0.969	0.930

TT Aql

J.D. -2441900	Phase	R	R-I	b-y
60.64	0.49	6.18	0.836	0.958
61.65	0.56	6.30	0.870	0.981
62.62	0.63	6.39	0.870	1.004
63.62	0.70	6.42	0.861	0.995
70.63	0.21	5.84	0.759	0.810
71.61	0.29	5.92	0.800	0.863
72.61	0.36	5.87	0.815	0.779
73.62	0.43	6.11	0.834	0.951
74.60	0.50	6.19	0.856	0.983
75.61	0.58	6.32	0.870	0.994
76.59	0.65	6.39	0.872	1.000
77.60	0.72	6.42	0.859	0.967

CP Cep

J.D. -2441900	Phase	R	R-I	b-y
60.67	0.90	9.33	1.033	1.018
61.68	0.96	9.33	1.017	1.021
63.64	0.07	9.00	0.906	0.936
70.65	0.46	9.16	1.044	1.142
71.63	0.52	9.26	1.096	1.146
72.63	0.57	9.30	1.104	1.211
73.64	0.63	9.44	1.138	1.197
74.64	0.68	9.44	1.125	1.194
75.63	0.74	9.49	1.107	1.173
76.62	0.80	9.44	1.084	1.158
77.62	0.85	9.40	1.049	1.122

SV Vul

J.D. -2441900	Phase	R	R-I	b-y
59.64	0.95	5.72	0.703	0.720
60.65	0.98	5.77	0.708	0.690
61.66	0.00	5.76	0.737	0.702
62.63	0.02	5.82	0.733	0.782
63.62	0.04	5.82	0.742	0.791
70.64	0.20	5.88	0.821	0.937
71.62	0.22	5.91	0.843	0.942
72.62	0.24	5.90	0.848	0.961
73.63	0.26	5.94	0.855	0.962
74.63	0.29	5.93	0.852	0.983
75.62	0.31	5.98	0.863	0.997
76.60	0.33	5.98	0.870	1.011
77.61	0.35	6.01	0.877	1.012

CY Cas

J.D. -2441900	Phase	R	R-I	b-y
61.76	0.09	9.85	1.197	0.971
62.73	0.16	9.90	1.200	1.049
63.78	0.23	9.91	1.250	1.082
70.72	0.72	10.49	1.305	1.259
71.72	0.78	10.30	1.248	1.163
72.75	0.86	10.34	1.239	1.139
73.74	0.93	9.76	1.105	0.886
74.74	0.00	9.80	1.123	0.958
75.72	0.06	9.82	1.144	0.993
76.71	0.13	9.90	1.199	1.059
77.71	0.20	9.90	1.231	1.074

TX Cyg

J.D. -2441900	Phase	R	R-I	b-y
59.72	0.26	7.54	1.345	1.222
60.66	0.32	7.63	1.340	1.229
61.67	0.39	7.70	1.398	1.010
63.64	0.53	7.87	1.430	1.412
70.65	0.00	7.43	1.246	1.096
71.63	0.07	7.40	1.257	1.105
72.63	0.14	7.49	1.303	1.200
73.64	0.21	7.54	1.328	1.215
74.64	0.28	7.55	1.350	1.263
75.62	0.34	7.65	1.378	1.295
76.61	0.41	7.71	1.403	1.361
77.62	0.48	7.81	1.419	1.340

S Vul

J.D. -2441900	Phase	R	R-I	b-y
60.64	0.89	7.61	1.151	1.226
61.66	0.90	7.57	1.154	1.207
62.63	0.92	7.55	1.138	1.248
63.62	0.93	7.52	1.131	1.231
70.63	0.04	7.31	1.078	1.134
71.62	0.05	7.32	1.090	1.123
72.61	0.06	7.30	1.084	1.136
73.62	0.08	7.31	1.082	1.126
74.63	0.09	7.28	1.085	1.128
75.61	0.11	7.30	1.084	1.110
76.60	0.12	7.29	1.090	1.125
77.61	0.14	7.30	1.093	1.116

TABLE 2

DATA FOR CEPHEIDS IN CLUSTERS

STAR	PERIOD	CLUSTER	TRUE DISTANCE MODULUS	E_{B-V}	$M_{\langle V\rangle}$	$\langle R-I\rangle$	$\frac{\Delta(b-y)}{\Delta(R-I)}$	$\log \frac{L}{L_\odot}$	log $\mathfrak{M}$ from $\langle B-V\rangle$	log $\mathfrak{M}$ from $\langle B\rangle-\langle V\rangle$	log $\mathfrak{M}$ from $\langle R-I\rangle$
SU Cas......	1ᵈ95	Reflection nebula	7.50	0.33	−2.54	0.48	0.98	2.897	0.59	0.58	0.55
EV Sct......	3.09	NGC 6664	11.03	0.58	−2.62	0.83	...	2.950	0.49	0.50	0.69
CF Cas......	4.88	NGC 7790	12.53	0.555	−3.08	0.82	1.37	3.148	0.53	0.45	0.67
UY Per......	5.36	h and χ Per	11.90	0.98	−3.54	1.09	1.31	3.326	0.66	0.62	0.67
VY Per......	5.53	h and χ Per	11.90	1.06	−3.91	1.15	1.58	3.467	0.78	0.76	0.80
U Sgr......	6.74	IC 4725	8.98	0.55	−3.93	0.70	1.67	3.480	0.69	0.65	0.60
DL Cas......	8.00	NGC 129	11.28	0.50	−3.84	0.77	1.63	3.459	0.65	0.63	0.74
VX Per......	10.89	h and χ Per	11.90	0.58	−4.34	0.77	1.15	3.651	0.64	0.62	0.62
SZ Cas......	13.63	h and χ Per	11.90	0.88	−4.71	1.03*	1.91	3.795	0.65	0.64	0.71

are not complete for 13 of the stars. In those cases, published $(B - V)$ data were used to estimate $\langle R - I\rangle$. The procedure was to convert the published $(B - V)$ colors to $(b - y)$ using

$$b - y = 0.654(B - V) - 0.053 . \quad (1)$$

This transformation was determined from the nonvariables measured in the present program and published values of $(B - V)$. The $(b - y)$ curve so determined was then converted to $(R - I)$ using the $(b - y) - (R - I)$ relation for the particular star derived from the present photometry. This relation had to be extrapolated in some cases, and it was assumed to be linear. The resulting $(R - I)$ curve was then used to extend the observations throughout the cycle, and the mean was obtained. When this was necessary, it is indicated by an asterisk following the value of $\langle R - I\rangle$ in Tables 2 and 3.

In addition to the Cepheids, 34 nonvariables which may be members of open clusters and which appear to be near the Cepheid region of the H-R diagram were also measured. The data for these stars are given in Table 4. Some are well-known cluster members while others were included because they appeared to lie in the appropriate region of the color-magnitude diagrams given by Hoag *et al.* (1961). The first column of the table gives the number or letter identifying the star. Except for those stars with HD numbers, the designation comes from the first reference given in the last column of the table. The cluster in or near which the star is located is listed in the second column while the distance modulus and color excess of the cluster are in the third and fourth columns. For NGC 129, the cluster data were taken from Sandage and Tammann (1968) while for the others the compilation by Becker and Fenkart (1971) was used. For some of the clusters radial velocity or proper motion studies have been published which help determine membership. This is indicated in columns (5) and (6), where a P means that the data are inconclusive either way. For those stars with spectral types, we can determine whether the colors and magnitudes, together with the cluster reddening and distance modulus, are consistent with the spectral class. This is indicated in column (7). The V and $(B - V)$ data are from published work while the R, $(R - I)$, and $(b - y)$ data are the measurements made in the present program. Column

TABLE 3

DATA FOR FIELD CEPHEIDS

STAR	PERIOD	E_{B-V}	$M_{\langle V\rangle}$	$\langle R-I\rangle$	$\frac{\Delta(b-y)}{\Delta(R-I)}$	$\log L/L_\odot$	log $\mathfrak{M}$ from $\langle B-V\rangle$	log $\mathfrak{M}$ from $\langle B\rangle-\langle V\rangle$	log $\mathfrak{M}$ from $\langle R-I\rangle$
SZ Tau......	3ᵈ15	0.31	−2.80	0.56	1.32	3.022	0.57	0.55	0.68
RT Aur......	3.73	0.09	−3.13	0.36	1.28	3.154	0.62	0.58	0.69
Y Sct........	10.34	0.80	−4.02	1.03*	1.81	3.546	0.69	0.63	0.71
Z Lac........	10.88	0.48	−4.32	0.70*	1.82	3.649	0.68	0.65	0.67
SV Per.......	11.13	0.44	−4.55	0.68*	1.36	3.732	0.71	0.67	0.78
RY Cas......	12.14	0.78	−4.66	0.89*	1.31:	3.778	0.72	0.68	0.65
TT Aql......	13.75	0.55	−4.47	0.79*	1.76	3.726	0.74	0.66	0.68
CY Cas......	14.38	1.10	−4.91	1.25*	1.95	3.880	0.76	0.70	0.87
TX Cyg......	14.71	1.25	−4.90	1.33*	1.65	3.880	0.77	0.70	0.74
RW Cas.....	14.79	0.41	−4.35	0.76*	1.96	3.690	0.72	0.64	0.74
CD Cyg......	17.07	0.64	−4.96	0.83*	1.86	3.916	0.80	0.70	0.68
CP Cep......	17.86	1.08	−5.34	1.023*	2.04	4.046	0.79	0.74	0.32
SV Vul.......	45.04	0.64	−6.03	0.85*	2.07:	4.360	0.83	0.76	0.69
S Vul........	68.83	0.90	−6.28	1.12*	2.40	4.473	0.78	0.75	0.68

TABLE 4

DATA ON NONVARIABLE STARS IN CLUSTERS

Star	Cluster (1)	True Distance Modulus (2)	E_{B-V} (3)	Membership: V_R (4)	Membership: p.m. (5)	Membership: p.e. (6)	Spectral Type (7)	V (8)	$B-V$ (9)	R (10)	$R-I$ (11)	$b-y$ (12)	n (13)	References and Notes (14)
A	NGC 129	11.28	0.50	Yes	...	Yes	F5 Ib	8.85	0.96	7.96	0.709	0.606	3	1
AA	NGC 129	11.28	0.50	No	...	No	K2 Ib	8.57	1.92	7.07	1.104	1.211	3	1
#5	NGC 225	9.00	0.29	...	...	...	...	9.87	0.97	9.07	0.622	0.634	2	2
HD 10494	NGC 654	12.02	0.89	...	...	Yes	F5 Ia	7.30	1.23	6.18	0.904	0.775	2	...
HD 11544	h and χ Per	11.67	0.56	...	...	No	G2 Ib	6.82	1.15	5.94	0.598	0.694	2	3
208	NGC 752	7.90	0.03	...	Yes	P	K1 IV	8.94	1.08	8.80	0.519	0.567	2	4, 5
213	NGC 752	7.90	0.03	...	Yes	Yes	K0 III	9.01	0.99	8.26	0.536	0.580	2	4, 5
295	NGC 752	7.90	0.03	...	Yes	Yes	G9 III	9.29	0.96	8.56	0.520	0.550	2	4, 5
311	NGC 752	7.90	0.03	...	Yes	Yes	K0 III	9.04	1.03	8.25	0.542	0.613	2	4, 5
HD 14662	h and χ Per	11.67	0.56	No	...	No	F7 Ib	6.34	0.90	5.56	0.524	0.557	2	3
HD 17971	h and χ Per	11.67	0.56	...	...	P	F5 Ia	7.75	1.06	6.68	0.854	0.674	2	3
HD 18391	h and χ Per	11.67	0.56	Yes	...	No	G0 Ia	6.89	1.95	5.30	1.200	1.210	2	3
HD 25498	NGC 1502	9.68	0.74	...	...	NO	K	7.93	1.19	6.94	0.745	0.716	2	...
#4	NGC 1528	9.66	0.30	...	...	...	...	9.97	0.92	9.20	0.608	0.588	2	2
HD 27277	NGC 1545	9.50	0.36	...	...	P	F8	8.09	0.99	7.31	0.568	0.591	2	...
#4	NGC 1647	8.70	0.39	...	...	...	...	9.34	0.90	8.63	0.492	0.510	2	2
#8	NGC 1647	8.70	0.39	...	...	...	...	10.33	0.90	9.57	0.525	0.550	2	2
#2	NGC 1664	10.46	0.20	...	...	...	...	7.50	0.97	6.77	0.537	0.576	2	2
#424	NGC 2168	9.70	0.23	...	Yes	...	...	10.56	0.28	10.35	0.157	0.138	2	6, 7
#2	NGC 2251	10.74	0.24	...	...	...	...	9.65	0.56	9.18	0.320	0.348	2	2
f	NGC 2287	9.60	0.00	Yes	...	P	G8 II–III	7.79	1.07	6.96	0.570	0.646	2	8
21	NGC 2287	9.60	0.00	Yes	...	Yes	K3 II	6.93	1.46	5.77	0.766	0.861	2	8
75	NGC 2287	9.60	0.00	Yes	...	Yes	KIII–III	7.46	1.18	6.53	0.612	0.705	2	8
87	NGC 2287	9.60	0.00	Yes	...	Yes	K4 III	7.87	1.30	6.79	0.720	0.773	2	8
97	NGC 2287	9.60	0.00	Yes	...	Yes	K0 II–III	7.82	1.08	6.97	0.568	0.651	2	8
14	NGC 6633	7.61	0.18	...	No	...	...	8.32	1.08	7.49	0.586	0.648	2	9, 10
56	NGC 6633	7.61	0.18	...	P	...	...	8.21	0.82	7.53	0.509	0.508	2	9, 10
116	NGC 6633	7.61	0.18	...	Yes	...	...	8.31	1.13	7.45	0.602	0.672	2	9, 10
122	NGC 6633	7.61	0.18	...	...	...	...	8.67	1.10	7.80	0.607	0.664	2	1, 10
134	NGC 6633	7.61	0.18	...	Yes	...	...	8.96	1.04	8.13	0.590	0.636	2	9, 10
140	NGC 6633	7.61	0.18	...	Yes	...	...	8.79	1.06	7.94	0.584	0.638	1	9, 10
HD 190113	NGC 6871	10.98	0.40	...	...	Yes	G5 Ib	7.91	1.46	6.75	0.770	0.893	2	...
#3	NGC 7063	9.00	0.08	...	...	...	...	9.71	0.46	9.34	0.246	0.239	3	2
HD 220770	NGC 7654	10.93	0.62	...	...	P	A5 Ia	7.77	0.82	6.99	0.719	0.481	3	...

REFERENCES.—(1) Arp *et al.* 1959. (2) Hoag *et al.* 1961. (3) Schild 1967. (4) Heinemann 1926. (5) Ebbighausen 1939. (6) Cudworth 1971. (7) Hoag *et al.* (1961) give $V = 10.09$, $B - V = 0.57$ for this star. However, the $(b - y)$ color measured here is more consistent with Cudworth's value of $(B - V)$. Thus this is a main-sequence star rather than an evolved star as indicated by the Hoag *et al.* photometry. (8) Cox 1954. (9) Hiltner *et al.* 1958. (10) Vasilevskis *et al.* 1958.

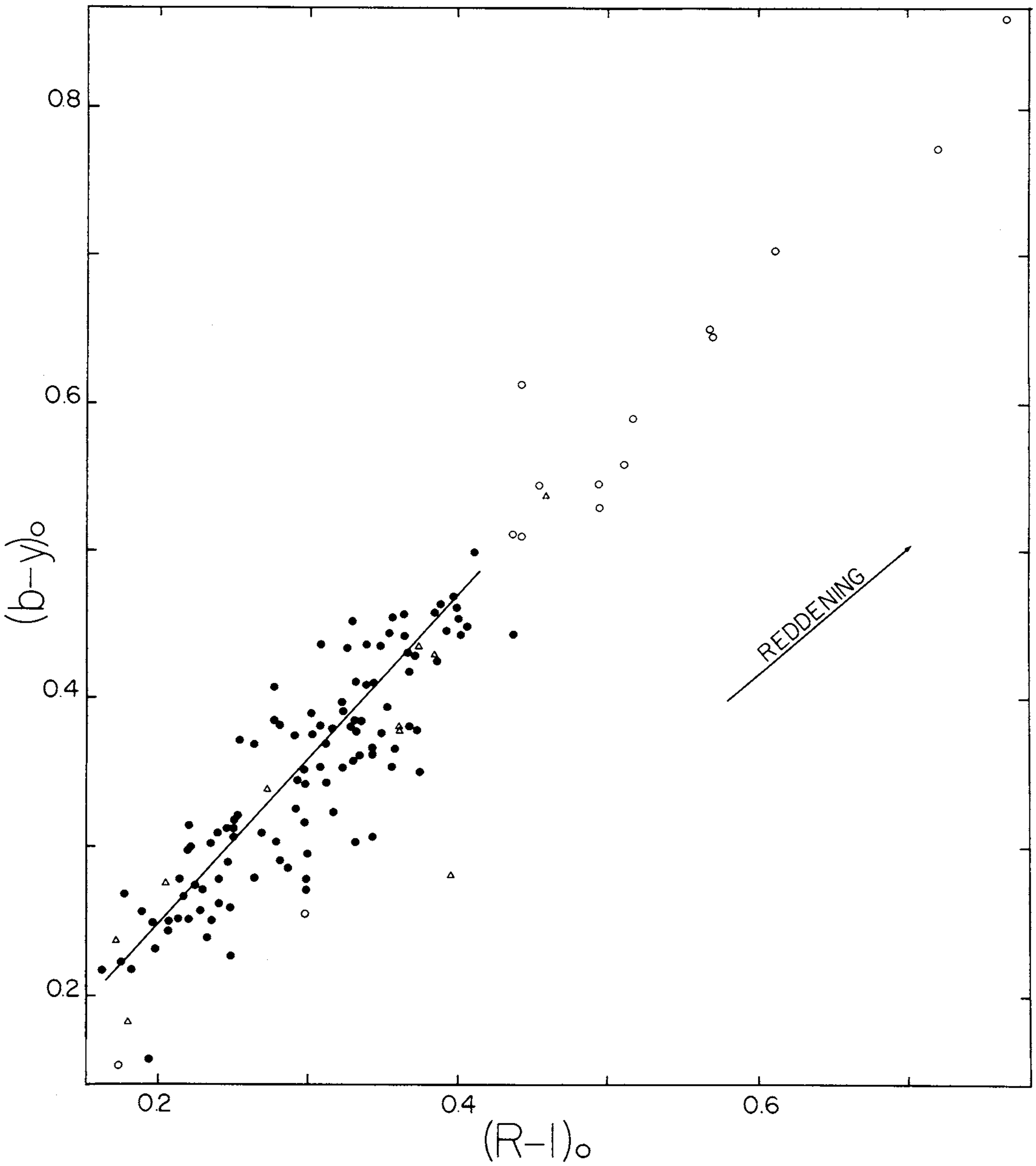

FIG. 1.—A plot of $(b - y)_0$ versus $(R - I)_0$ for the Cepheids and nonvariables in clusters. The solid circles represent the Cepheids, open circles are the nonvariable stars for which cluster membership is positively indicated in Table 4, and the triangles are the stars in Table 4 which may be cluster members. The solid line was fitted by eye to the Cepheids.

(13) contains the number measurements made for each star.

The accuracy of the photometry was determined from the scatter in the measurements of the nonvariable stars and the standards. The standard deviations of a single measurement are 0.023 mag for R, 0.008 mag for $(R - I)$, and 0.012 mag for $(b - y)$.

III. THE COLOR-COLOR RELATIONS

In Figure 1 $(R - I)_0$ is plotted against $(b - y)_0$ for the Cepheids which are members of clusters. The reddening was removed from the observed colors using $E_{b-y} = 0.7E_{B-V}$ and $E_{R-I} = 0.82E_{B-V}$. It can be seen that all the Cepheids tend to lie along one sequence in the plot but that individual points scatter considerably. The solid line is an eye-fitted mean. The breadth of the band of points in the diagram is about 0.17 mag in the $(b - y)$ direction which corresponds to 0.26 mag in $(B - V)$. This can be compared with the scatter in a plot of $(B - V)$ versus temperature previously published (Fig. 2 of Schmidt 1972*b*). In that plot the range of $(B - V)$ at a particular temperature was about 0.34 mag. Considering the errors in the

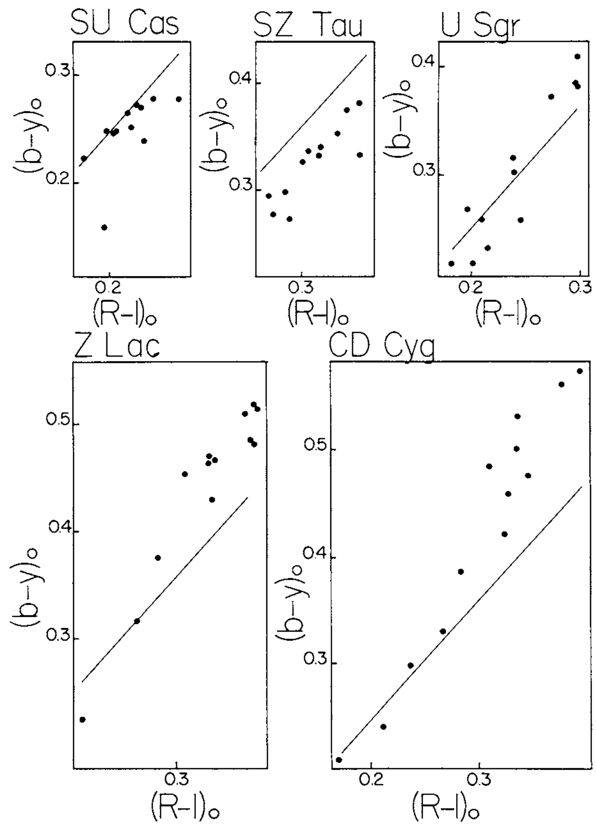

FIG. 2.—Plots of $(b - y)_0$ versus $(R - I)_0$ for various individual Cepheids. The solid line is the mean line from Fig. 1 and is included only for reference.

temperatures, this is reasonably consistent with the present result.

In Figure 2, $(b - y)_0 - (R - I)_0$ diagrams for some individual stars are presented. The solid line in each panel of Figure 2 is the mean line from Figure 1. It can be seen that the individual stars scatter significantly from the mean and that some stars obey a steeper $(b - y) - (R - I)$ relation than others or than the mean. This behavior is further illustrated by the values of the slope of the color-color relation, $\Delta(b - y)/\Delta(R - I)$, which are given in Tables 2 and 3. It can be seen that they range from 0.98 to 2.40 for various stars, compared with a slope of 1.11 for the mean relation. These quantities are plotted in Figure 3 as a function of the period. Except for three stars, SV Per, RY Cas, and VX Per, there is a good correlation between the slope of the color-color relation and the period. On the other hand, no correlation was found with the mean color, the amplitude, or the asymmetry of the light curve. Thus this changing slope is apparently related to the luminosity of the star.

Also of interest in Figure 1 are the points which represent the nonvariable stars. Unfortunately, there are only a few nonvariables which are established members of clusters (*open circles*). It is interesting to note, however, that they lie below the relation for the

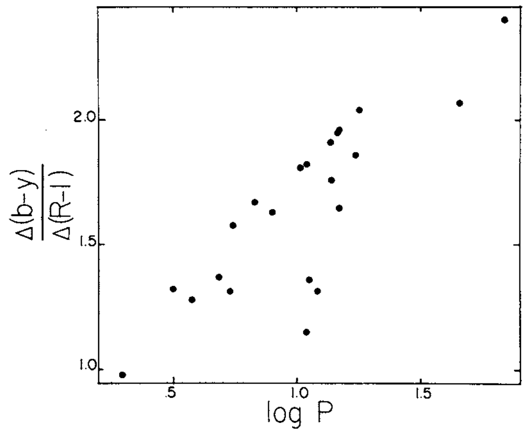

FIG. 3.—The slope of the color-color relation, $\Delta(b - y)/\Delta(R - I)$, as a function of period for the stars in Tables 2 and 3.

Cepheids in the bluer part of the range. This amounts to about 0.07 mag in $(b - y)_0$ at $(R - I)_0 = 0.25$. On the other hand, the coolest of the nonvariables are in good agreement with the extension of the Cepheid curve. Thus the relation between $(b - y)_0$ and $(R - I)_0$ for the nonvariables is steeper than the mean Cepheid relation and has a slope of 1.31. Assuming that $(R - I)_0$ is a better temperature indicator than $(b - y)_0$, we find that this difference should change the slope of the $(B - V)_0$-log T_e relation by about 0.05. This difference in slope is very close to the difference found previously (Schmidt 1972*b*). Thus the present data may support the previous conclusion that significant differences exist between the Cepheids and the nonvariable supergiants in the color-temperature relation. However, there are several stars in Figure 1 which could alter this conclusion if their cluster membership were established (*triangles between* $(b - y)_0 = 0.17$ *and* $(b - y)_0 = 0.28$).

We cannot examine these effects quantitatively without synthetic spectral calculations. However, we note that such calculations by Bell and Rodgers (1969) showed that $(B - V)$ colors in Cepheids are significantly affected by microturbulence and electron pressure. This arises through the strong line blanketing in the blue and visual regions of the spectrum, and presumably $(b - y)$ is similarly affected. Since the line blocking in the red part of the spectrum is considerably smaller than in the visual and blue, we will regard $(R - I)_0$ as a better temperature indicator than $(b - y)_0$ for the remainder of this paper.

IV. PULSATIONAL MASSES

Having shown that there are significant differences between the blue and the red colors, it is now of interest to consider how this affects the pulsational masses. These were calculated from the data in Tables 2 and 3 using the same calibrations and methods as in Paper I. The luminosities and pulsational masses are given in Tables 2 and 3. For $(B - V)$, two masses were calculated. One employed the temperature

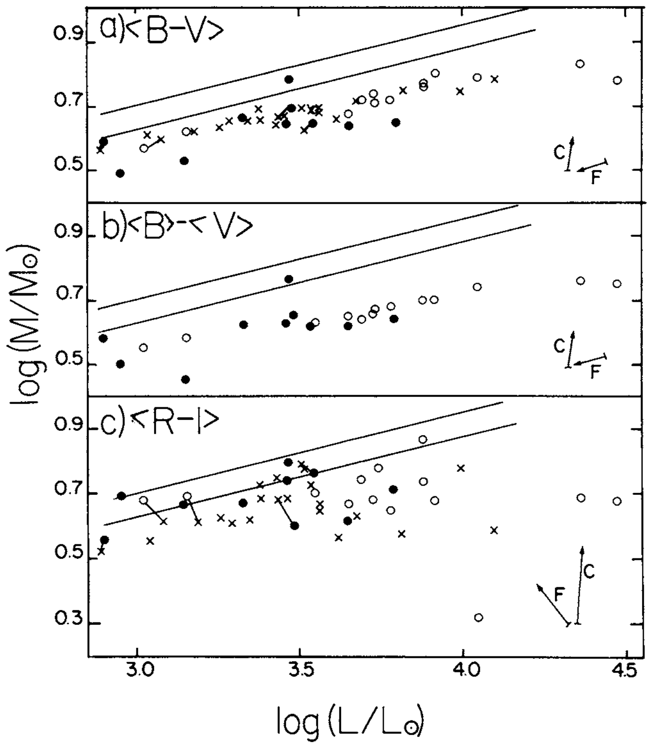

FIG. 4.—The pulsational masses of the Cepheids. In the calculation of the masses in panel *a*, $\langle B - V\rangle_0$ was used as the temperature indicator while in *b* and *c*, $\langle B\rangle_0 - \langle V\rangle_0$ and $\langle R - I\rangle_0$ were used, respectively. *Solid circles*, cluster members; *open circles*, field stars; *crosses*, stars from paper I. The arrows in the lower right-hand corner of each panel indicate the effect of decreasing E_{B-V} by 0.1 mag for the field and cluster Cepheids. The evolutionary masses lie between the pair of solid lines.

derived from $\langle B - V\rangle_0$, the magnitude mean of the color, while the other used the temperature indicated by $\langle B\rangle_0 - \langle V\rangle_0$, the intensity mean. This was done to test the effect on the pulsational masses of the method of averaging over the cycle. Recent calculations by Karp (1975) indicate that the intensity mean, $\langle B\rangle_0 - \langle V\rangle_0$, is more suitable for $(B - V)$ while for $(R - I)$ the method of averaging makes little difference. We do not have sufficient data to calculate $\langle R\rangle_0 - \langle I\rangle_0$ for most of our stars so this was not attempted.

The pulsational masses are plotted against the luminosities in Figure 4. To the nine cluster Cepheids observed here, S Nor (a member of NGC 6087) has been added using the color data from Paper I. These 10 stars are plotted as filled circles. The open circles represent the stars from Table 3 while the stars from Paper I have been plotted as crosses. Points for those stars which are common to the present sample and Paper I are connected (including S Nor) by a line. The differences are almost entirely due to the different adopted color excesses. The two parallel lines in each panel of the diagram show the range of evolutionary masses as given by Iben and Tuggle (1972). In the lower right corner of each panel there are arrows which indicate the effect of errors in the color excess on the plotted points. Each arrow has a length which corresponds to 0.1 in E_{B-V}, and the arrows point in the direction a point would move if the color excess were decreased. The effect of color excess on the field-star masses and luminosities differs from that on the cluster stars because the color enters through the period-luminosity-color relation.

We find, as did Iben and Tuggle (1972), that the pulsational mass of VY Per is greater than the masses of other stars of similar period. In fact, it is the only star in Figures 4*a* and 4*b* which agrees with the evolutionary mass-luminosity relation. Iben and Tuggle suggest that this star is an overtone pulsator on the basis of its high pulsational mass. However, the discussion below seems to point to another explanation.

Looking at the top two panels of Figure 4, we see that the use of $\langle B\rangle_0 - \langle V\rangle_0$ reduces the scatter as compared with the use of $\langle B - V\rangle_0$. However, in both cases the cluster stars scatter more than the field stars. One explanation could be that the color excesses contain errors as large as 0.1 mag. Since the field stars are moved along the sequence by errors in color excess, they will not be scattered by this effect. However, it would be surprising to find such large errors in the cluster reddenings.

Iben and Tuggle (1972) noted that the use of a period-luminosity-color (PLC) relation can act to suppress scatter in the (pulsational mass)-luminosity diagram. There are, however, two situations which must be considered in this connection. If we imagine that the temperature and luminosity of a Cepheid uniquely define its mass, then (following the arguments of Sandage and Gratton 1963) there is a unique PLC relation which all stars obey. On the other hand, scatter in mass at a particular luminosity and temperature will scatter stars about a mean PLC relation. If we consider two stars of equal temperature and luminosity but with masses $\mathfrak{M}_1$ and $\mathfrak{M}_2 = (1 + \delta)\mathfrak{M}_1$, we can see how this works. From the pulsational calculations of Fricke *et al.* (1972) we have the relation

$$\log \mathfrak{M} = 1.27 \log L - 1.5 \log P + \text{const.} \quad (2)$$

Applying this to the two stars we find

$$\log P_2 = \log P_1 - \log (1 + \delta) . \quad (3)$$

Using this period with the Sandage and Tammann (1969) PLC relation gives

$$M_{\langle V \rangle 2}(\text{PLC}) = M_{\langle V \rangle 1}(\text{PLC}) + 3.425 \log (1 + \delta) , \quad (4)$$

or

$$\log L_2(\text{PLC}) = \log L_1(\text{PLC}) - 1.37 \log (1 + \delta) . \quad (5)$$

Finally, entering this luminosity and the period from equation (3) in equation (2) yields

$$\log \mathfrak{M}_{Q2} = \log \mathfrak{M}_{Q1} - 0.24 \log (1 + \delta) . \quad (6)$$

Thus star 2, which should appear directly above star 1 in the pulsational mass-luminosity diagram, will be shifted toward lower luminosity and mass, and the two stars will lie on a line of slope

$$\Delta(\log \mathfrak{M})/\Delta(\log L) = 0.24/1.37 = 0.175 . \quad (7)$$

Since the slope of the evolutionary mass-luminosity relation, about 0.25, is similar to this value, it is apparent that the scatter is greatly suppressed by the use of the PLC relation. As an example consider two stars which are located at the same point in the H-R diagram. If one star is more massive by, say, 25 percent according to equation (5) the PLC relation would indicate a luminosity which is fainter than the less massive star by about 36 percent. This in turn, using equation (6), would result in the pulsational mass of the more massive star being *less* than that of the other star by slightly more than 1 percent. If the mean mass-luminosity has a slope of 0.25, the star which is over-massive by 25 percent will be only about 2 percent above the mean line. Hence nothing can be learned about mass scatter at a particular location in the H-R diagram from pulsational masses based on the PLC relation. However, this does not apply to stars which obey the PLC relation. That is, if any scatter in mass at a given luminosity is related only to the temperature, then the PLC relation should allow a correct determination of the pulsational mass (provided the color dependence of the PLC relation has been correctly calibrated). Thus the width of the band of points for field Cepheids in Figure 4 is an indication of mass spread at constant luminosity across the instability strip. In view of this we might suppose the greater scatter of the points for cluster Cepheids indicates a scatter in mass at a given luminosity and temperature. This could arise from varying amounts of mass loss, but clearly a final conclusion must await further investigation.

Figure 4*c* differs from the other two diagrams in several respects. In the first place, we now find that for luminosities below $\log L/L_\odot = 3.55$, nearly half of the stars fall within the evolutionary mass range. We also see that there is little or no tendency for more luminous stars to have greater pulsational masses than less luminous stars. Thus, there is still a large mass discrepancy among the long-period stars, although much of it has disappeared among the short-period stars. We should note that the greater scatter in the $(R - I)$ diagram is probably due to the stronger dependence of the calculated masses on the color excesses. It is interesting that the mass of VY Per in Figure 4*c* is little changed from that in Figure 4*a* and 4*b* while the other stars of similar luminosity have moved up near it. This suggests that the interpretation of Iben and Tuggle that this star is pulsating in the first overtone is incorrect. It is possible that errors in the color excess have influenced the mass of this star. However, if that is the case it is surprising that $(R - I)$ agrees with $(B - V)$. Rather, it appears that for some reason $(B - V)$ gives the correct temperature only for VY Per.

There are several possible explanations for the results presented in Figure 4. Taking Figure 4*c* at face value, we might conclude that Cepheid masses do not increase with luminosity. This would then suggest that mass loss occurs in such a way that by the time stars reach the Cepheid strip all have nearly the same mass. However, such an extreme conclusion is unwarranted until these results are more firmly established. Another possibility is that the $(R - I)$ photometry contains systematic errors. However, the agreement of the present photometry with that of Wisniewski and Johnson (1968) is excellent for the stars in common, and any difference between the crosses (based mainly on the Wisniewski and Johnson photometry) and the circles in Figure 4*c* is attributable to differences in the selection of color excesses. It is possible that errors in $E_{(B-V)}$ affect the results. There is, however, good agreement between the cluster Cepheids and the field Cepheids for luminosities below $\log L/L_\odot = 3.7$. Since the cluster color excesses should be reliable, this tends to indicate that the trends at lower luminosity are not the result of color-excess errors. Additionally, the fact that there is no dependence of the masses on E_{B-V} indicates that the conversion to E_{R-I} is reasonably correct. In the case of the more luminous stars, however, there may well be systematic errors which contribute to the low masses. For X Cyg and T Mon, observations of field stars (Schmidt 1975) showed that the G band color excesses *may* be too high by as much as 0.15 mag. Parsons and Bell (1975) also found evidence supporting decreased color excesses for the long-period stars. This would move these stars near

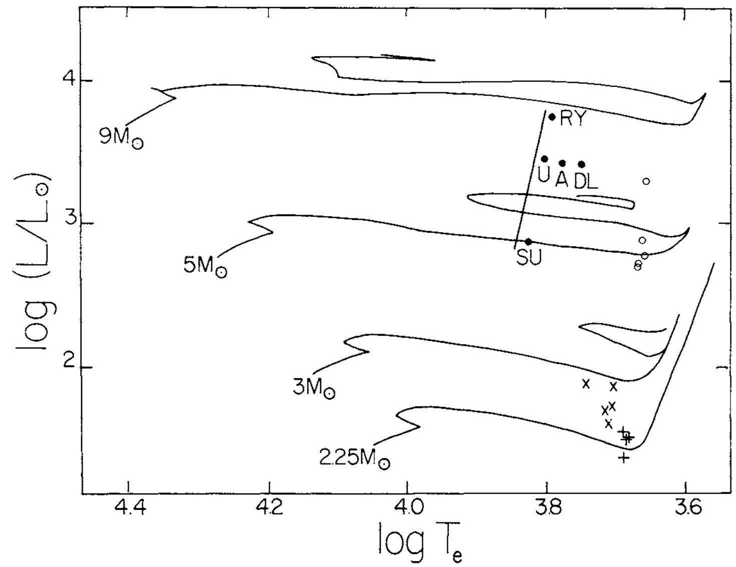

FIG. 5.—The location of some stars from this program in the temperature-luminosity diagram. The evolutionary tracks of Iben (1967) are shown for various masses, and the dark solid line is the edge of the instability strip from a previous paper (Schmidt 1972*a*). The Cepheids RY Cas, U Sgr, SU Cas, and DL Cas, and star A in NGC 129 are indicated by solid circles. Open circles represent the stars in NGC 2287, crosses those in NGC 6633 and plus signs those in NGC 752.

the evolutionary mass-luminosity relation. We also note that errors in the calibration of the PLC relation as suggested by Iben and Tuggle (1972) could play a role. However, until the question of the color excesses is resolved, it seems premature to suggest changing the PLC relation to force agreement. A change in the zero point of the Cepheid luminosity scale might still be considered. Increasing the absolute magnitudes of the Cepheids by about 0.1 mag combined with decreased color excesses for the long period stars would suffice to bring agreement between the pulsational masses and the evolutionary masses in Figure 4*c*. It is clear that much of the burden of resolving this discrepancy lies in better establishing the temperatures and luminosities of the Cepheids. The need for accurate and reliable color excesses is obviously basic to this.

V. THE LOCATIONS OF THE NONVARIABLE YELLOW GIANTS IN THE HR DIAGRAM

The cluster NGC 129 is of special interest because it contains both a Cepheid, DL Cas, and a nonvariable supergiant, star A, which is slightly hotter than the Cepheid. The values of M_V and $(R - I)$ in Tables 2 and 4 have been used to locate these stars in the theoretical H-R diagram. This is shown in Figure 5. The luminosities of the two stars are identical. Also plotted are three other Cepheids, SU Cas, U Sgr, and RY Cas, the blue edge of the instability strip determined previously (Schmidt 1972*a*), and the evolutionary tracks of Iben (1967) for several masses. It can be seen that star A is significantly cooler than the blue edge of the instability strip and is cooler than U Sgr. Additionally, the Cepheids UY Per, VX Per, and VY Per (all cluster members) have absolute magnitudes similar to star A, but are bluer in $(R - I)$. Thus this star is clearly among the Cepheids when $(R - I)$ is used to determine its temperature. If $(B - V)$ had been used, star A would still have been in the Cepheid strip but would have been quite close to the blue edge. However, for the reasons discussed above we consider the temperature determined from $(R - I)$ to be more reliable than that from $(B - V)$. We note that the cluster NGC 129 is not uniformly reddened over its area. The color excesses of several stars near DL Cas and several near star A were determined from the photometric data of Arp *et al.* (1959). It was found that the difference in E_{B-V} between the two regions was only 0.023 ± 0.020 mag (s.e.). Thus the use of the same color excess for both stars is valid and their relative locations in the H-R diagram are well determined. Because the color excess and the absolute magnitude of star A are well established from the cluster, it appears that this is the best established case of a nonvariable star in the Cepheid strip. It therefore lends further strength to the case for the existence of such stars. Additionally, finding such a star in a cluster opens the possibility of understanding the phenomenon of nonvariables in the Cepheid strip through the investigation of other cluster members.

There are three clusters in Table 4 which each contain four or more late giants or supergiants. It is of interest to compare these stars with evolutionary calculations. The requisite information is contained in Table 5 and is plotted in Figure 5. Open circles represent the stars from NGC 2287, the crosses those from NGC 6633, and the plus signs those from NGC 752. In the case of NGC 2287, the stars are too cool for the Schmidt (1973) $(R - I)$-temperature calibration, and the calibration of Johnson (1966) was used. The evolutionary times of various crossings of the yellow giant region differ considerably, and when there are

TABLE 5

MASSES AND AGES OF NONVARIABLE STARS IN THREE CLUSTERS

Cluster	Star	log $L/L_{\odot}$	log T_e	Evolutionary Mass	Age (10^7 yr)
NGC 752.........	208	1.58	3.692	2.4	49.
	213	1.54	3.685	2.3	51.
	295	1.43	3.692	2.2	55.
	311	1.54	3.683	2.3	51.
NGC 2287........	F	2.74	3.666	4.3	11.
	21	3.32	3.660	6.3	4.8
	75	2.92	3.664	4.8	8.6
	87	2.82	3.661	4.6	10.
	97	2.74	3.666	4.3	11.
NGC 6633........	56	1.89	3.749	2.7	36.
	116	1.89	3.710	2.7	36.
	122	1.74	3.707	2.5	43.
	134	1.62	3.714	2.4	48.
	140	1.69	3.717	2.5	45.

multiple crossings the second is the longest. We will therefore assume that all the stars are on the same crossing. The ages and masses in Table 5 were obtained by interpolating among the evolutionary tracks assuming the second crossing. The spread in luminosity in a cluster can be interpreted in terms of a mass spread which in turn implies a range of ages. The stars in NGC 752 and NGC 2287 then have an age spread of about 6×10^7 years while those in NGC 6633 have a spread of about 10^8 years. Iben and Talbot (1966) estimated the time over which stars formed in NGC 2264 to be about 6.5×10^7 years. Unfortunately, their interpretation is uncertain owing to the presence of dust shells around many of the pre–main-sequence stars (Strom *et al.* 1971). Meyer-Hofmeister (1969) found that the scatter of red and yellow giants in NGC 1866 could be accounted for in terms of a range in age of about 1.5×10^7 years. Thus the range found here is somewhat higher than previous estimates.

Clearly, a definitive discussion of the locations of the red and yellow giants in the H-R diagrams of these clusters is not possible at present. Various theoretical uncertainties have been ignored. For example, the location of the red-giant branch and the length of the loops in the evolutionary tracks are sensitive to the mixing length adopted, the composition, and the details of the evolutionary calculation. Thus some of our stars could be on the ascending red-giant branch of the evolutionary tracks. Additionally, the evolution may be affected by rotation, and mass loss may play a significant role. Hence our present conclusions must be tentative. However, as the evolutionary tracks become more certain and various complicating factors are better understood, the clusters with several yellow giants will provide a good check on the theory.

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