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INTERMEDIATE-BAND PHOTOMETRY IN THE OPEN CLUSTER NGC 6664

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ABSTRACT

Four-color and Hβ photometry is given for early-type stars in the open cluster NGC 6664. From these data the true distance modulus is found to be 10.7 and the reddening is found to range from $E(b-y)=0.48$ to 0.63 across the cluster. The distance modulus agrees well with some values from the literature, but the present color excesses are about 0.1 mag larger than published values. There are two or perhaps three blue stragglers in the cluster and its age is estimated to be 46×10^6 yr.

I. INTRODUCTION

This is the fifth in a series of papers giving intermediate-band photometry for B stars in clusters containing classical Cepheids. The motivation for this project is discussed in the first paper (Schmidt 1980). The present paper is concerned with the cluster NGC 6664, which contains the 3-day Cepheid EV Scuti.

Arp (1958) obtained *UBV* photometry of stars in NGC 6664 while Kraft (1958) classified the spectra and measured radial velocities for 13 stars in the cluster field. The photometry showed that this cluster is at a distance of approximately 1.5 kpc and that the foreground reddening is highly variable. The radial velocities indicated that the Cepheid EV Sct is a likely member. Its absolute magnitude, as inferred from the cluster distance modulus, also supports its membership. Arp concluded from his *UBV* photometry that NGC 6664 is slightly older than the Pleiades. However, Harris (1976) places this cluster in her age group II, which makes it significantly younger than the Pleiades.

In addition to the Cepheid, NGC 6664 contains about seven red giants. Of these, two are members according to their radial velocities and spectral types. It is likely that at least some of the other five are also members. Additionally, Arp remarked that there are two stars, F and L in his lettering scheme, that seem to be too close to the main sequence for the evolutionary age of the cluster. Both are possible members on spectral grounds but for neither is the evidence strong. It is possible that these stars are blue stragglers and the present photometry should clarify this point.

II. THE OBSERVATIONS

The photometric study of Arp was used to select stars for the present program. All of the stars he listed with magnitudes brighter than $V=13.2$ and with $B-V$ less than 0.75 have been included with only two exceptions, stars A and K. The magnitude limit was imposed by the availability of large-telescope time and corresponds to an absolute magnitude of about 0.0. The color limit includes all the stars that appear near the cluster main sequence but excludes apparent red giants for which the intermediate-band photometry is less useful. Of the two stars that were omitted, star A is unlikely to be a member on the basis of its spectroscopic parallax and its radial velocity. The spectroscopic parallax of star K indicates that it is a probable member. However, Kraft indicated that it was double lined and thus probably a spectroscopic binary.

There are 15 stars in our sample. Although it would obviously be desirable to have a larger number, this would require observing fainter stars. Given the rather large reddening, the availability of telescope time, and the requirements for accuracy, this was not practicable. However, the sample we have is large enough to yield accurate estimates of the distance modulus and color excess.

The stars that were observed are listed in Table I. The second column gives the spectral type from Kraft (1958). The visual magnitudes are means of those from Arp and from the present photometry weighted by the number of nights on which they were observed. The mean indices from the present observations are listed in columns 4–6 and 8, while columns 7 and 9 list the number of nights on which a star was observed with the four-color filters and with the Hβ filters, respectively.

The observations were made at Cerro Tololo Inter-American Observatory between April 1979 and May 1981. The 0.9-m and the 1.5-m telescopes were used with a two-channel photometer. One channel served as a monitor of the transparency while all the measurements were made through the other channel. Standard four-color and Hβ filters were used. The observations were referred to the *uvbyβ* system through the use of secondary standard stars located along the equator. These have in turn been referred to the primary four-color and Hβ standards (Crawford and Mander 1966; Crawford and Barnes 1970). A complete discussion of these secondary standards is in preparation and will be published elsewhere.

Because this cluster is heavily reddened, we must be concerned about the question of reducing the photo-

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TABLE I. Photometric indices of NGC 6664 stars.

Star	Spectral type	V	$b-y$	m_1	c_1	n	β	n	$E(b-y)$	V_0-M_V
F	B3IV	10.97	0.517	−0.101	0.196	3	2.644	4	0.626	10.51
G	A0III	11.02	0.436	−0.052	0.669	7	2.688	5	0.487	10.56
I		11.79	0.564	+0.043	0.581	3	2.703	3	0.325	6.92
J		11.84	0.472	−0.068	0.466	3	2.692	5	0.548	10.49
L	B3V	11.94	0.495	−0.058	0.202	2	2.648	5	0.603	11.44
M	B9V	11.99	0.466	−0.066	0.724	3	2.734	4	0.512	10.21
N		12.42	0.523	−0.063	0.585	5	2.705	5	0.586	10.76
O		12.44:	0.551	−0.059	0.662	3	2.723	5	0.606	10.35
P		12.65	0.524	−0.052	0.725	3	2.731	4	0.570	10.66
Q		12.98	0.482	−0.045	0.706	3	2.694	4	0.529	12.21
R		13.02	0.507	−0.059	0.709	3	2.727	4	0.554	11.18
S		13.06	0.562	−0.056	0.808	3	2.834	4	0.605	9.09
T		13.18	0.435	−0.034	0.732	3	2.741	4	0.480	11.41
10		12.54	0.552	−0.062	0.612	2	2.696	3	0.613	11.09
19		12.99	0.485	−0.057	0.684	3	2.757	4	0.535	10.46

metry to the standard system. In the case of the Hβ index, Schmidt and Taylor (1979) have discussed the effects of color on the transformations. For the 1979 observations, we included a color term as they recommend, but for the more recent observations the filter set was well matched and this was not necessary. Among our secondary standards there are a number of highly reddened B stars. Those which were used in the course of the present observations are listed in Table II. The mean indices obtained from the nights on which NGC 6664 was observed are also tabulated, together with the number of nights for which each standard was used. These values fit the standard values well and no trends with reddening are apparent. However, the establishment of the standard indices poses some difficulty because the primary standards of the four-color system contain no stars that are reddened nearly as much as most of the stars in Table II. The question of how close the indices for these stars are to the *uvby* system will be discussed fully in the paper describing the standards. However, we can perform a preliminary test by deriving their color excesses and comparing them with independently determined values. In column 6 of the table we give the color excesses from Crawford's calibration. Spectral types and $B-V$ colors can be used to obtain another estimate of the reddening. These values have been multiplied by 0.74 to put them on the scale of the $b-y$ colors that are tabulated in column 8 of the table. It can be seen that the differences (column 9) between the two completely independent estimates of the color excesses of these stars are small and, more importantly show no trend with reddening. We therefore conclude that the four-color photometry of these stars is accurately on the *uvby* system.

Because some of the stars in this cluster are relatively faint for intermediate-band photometry and because the substantial reddening reduces the ultraviolet flux considerably, the internal errors are somewhat higher than has been the case in some other four-color studies. However, the bulk of the stars were observed at least three times so the mean values are accurate enough to be useful. The standard deviations for a single observation are as follows: 0^m013 for $b-y$; 0^m020 for m_1; 0^m030 for c_1; and 0.018 for β.

III. THE DISTANCE AND REDDENING

In order to apply the four-color and Hβ calibrations to the photometric data it is necessary to determine the spectral range in which each star falls. Using the dia-

TABLE II. Reddened standard stars.

Star (SAO)	$b-y$	m_1	c_1	n	$E(b-y)$	Sp.	$0.74E(B-V)$	Δ
113973	−0.050	0.076	0.210	3	0.045	B2V	0.07	0.02
122716	0.050	0.062	0.434	4	0.119	B6V	0.09	−0.03
103439	0.023	0.053	0.036	1	0.138	B1.5III	0.15	0.01
114001	0.171	−0.017	−0.010	3	0.291	B0.5V	0.31	0.02
114112	0.232	−0.033	0.045	3	0.349	B0.5V	0.37	0.02
124467	0.259	−0.035	0.031	4	0.378	B1.5II–III	0.35	−0.03
114058	0.315	−0.052	−0.007	3	0.437	B1V	0.46	0.02
123966	0.522	−0.172	0.289	1	0.621	B3V	0.56	−0.06
142589	0.633	−0.080	−0.066	1	0.766	B0.5Ia	0.78	0.01
161476	0.824	−0.151	0.011	4	0.954	B0.5Ia	0.97	0.02
113125	0.870	−0.110	0.194	2	0.986	B1V	1.10	0.11

gram of $[m_1]$ vs $[c_1]$, it appears that all of the stars in Table I are B stars except one, star I. This agrees with the spectral types given for three of the stars. However, the spectral type given for star G, A0III, is in conflict with the photometric indices. From its value of m_0 and β it appears that star G should have a spectral type between B4 and B6. We will therefore treat it as a B star in applying the photometric calibration.

For all the stars except I in the table the distance moduli and color excesses have been obtained from the B-star calibration of Crawford (1978). For star I, his F-star calibration (Crawford 1975) was used. These quantities are listed in the last two columns of Table I. A value of $A_V/E(b-y) = 4.28$ was used (Crawford and Mandwewela 1976) in correcting the distance moduli for interstellar absorption.

Figures 1 and 2 show several plots of the data from Table I. These diagrams serve to assist in detecting any nonmembers among our sample and to allow the reader to form an impression of the cluster's main characteristics. In Fig. 1(a) the apparent magnitude V is plotted against the c_1, while Fig. 1(b) shows the plot of β against

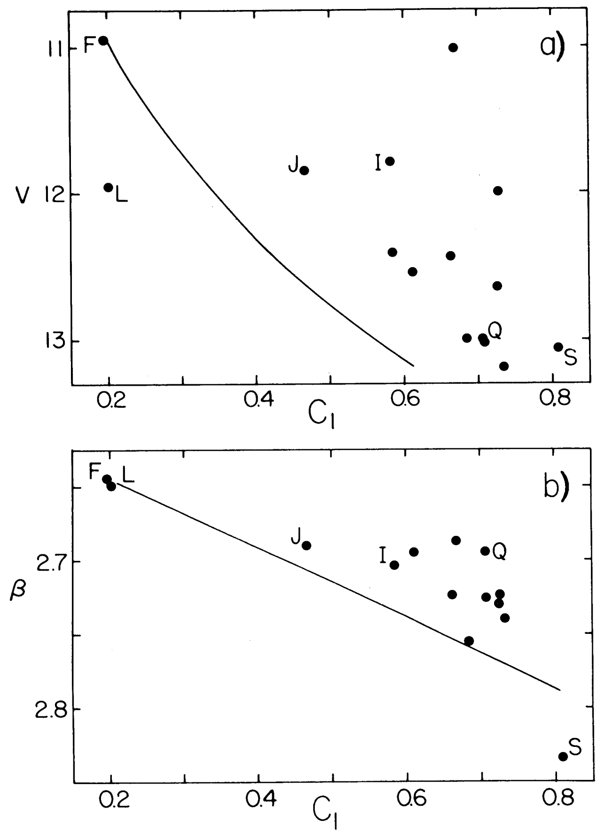

FIG. 1. (a) The diagram of V vs c_1 for stars in the field of NGC 6664. (b) The diagram of β vs c_1. In both diagrams the solid line is the zero-age relation adjusted for a color excess of $E(b-y) = 0.55$ and an apparent distance modulus of 13.1. Points representing stars discussed in the text are labeled.

c_1. Figure 2 is a plot of the color excess against the true distance modulus.

It is quite obvious that star I is a foreground star on the basis of its distance and its reddening (Fig. 2). Stars F and J are nearer the main sequence than should be the case based on the remaining stars in Figs. 1(a) and 1(b). However, they are in locations that are appropriate for blue stragglers. Since such stars appear to give the correct distance modulus from four-color photometry (see Schmidt 1982a for a discussion of this point) we will retain them in our sample. Star L poses some difficulty in that it is nearly a magnitude fainter than star F, even though its other photometric indices match well. The lower apparent magnitude has caused the distance modulus to lie among the largest of those in Fig. 2 that appear to form the cluster group. Since there is no obvious explanation for its lower magnitude, we will reject it from membership. Star S is located away from the other stars in all three samples and is probably a foreground star. Its rather high reddening is not unreasonable in view of the patchiness of obscuration in this field. Finally, star Q appears to be among the cluster stars in both Figs. 1(a) and 1(b) but has a higher distance modulus than the cluster stars. We will therefore regard it as a background star.

The mean distance modulus for NGC 6664, with stars I, L, S, and Q omitted, is $V_0 - M_V = 10.69 \pm 0.38$ (standard deviation of one star). The rejection of stars from the cluster is not crucial in determining the distance modulus. For example, if we include all the stars except star I, the mean distance modulus we obtain is 10.74. Therefore, we will adopt as our mean distance modulus 10.7 ± 0.1 (standard error of the mean).

The mean color excess of the cluster stars is $E(b-y) = 0.556$. However, there is a large range from 0.48 to 0.63. The color excesses are correlated with position in the way found by Arp (1958); the largest color excesses are found in the western part of the cluster and lines of constant color excess run nearly north-south.

IV. DISCUSSION

Previous values of the distance modulus of this cluster have all been based on the same *UBV* data, those of Arp. However, they have covered a large range. Becker and Fenkart (1971) give a true distance modulus of 10.33, while Arp obtained 10.8. Sandage and Tammann (1969) rediscussed the distance of this cluster and quote 11.03. These values were all based on the old value of the Hyades distance. They should perhaps be increased by about 0.3 mag in light of recent studies of the Hyades and thus represent a range from 10.6 to 11.3. In his discussion of Cepheid luminosities, de Vaucouleurs (1978) used a more recent distance for the Hyades and obtained a modulus for NGC 6664 of 10.89. Thus it can be seen that the smaller of these moduli are in reasonable agreement with the present value but the larger ones are not.

Our mean color excess for the cluster, $E(b-y) = 0.556$, corresponds to $E(B-V) = 0.75$.

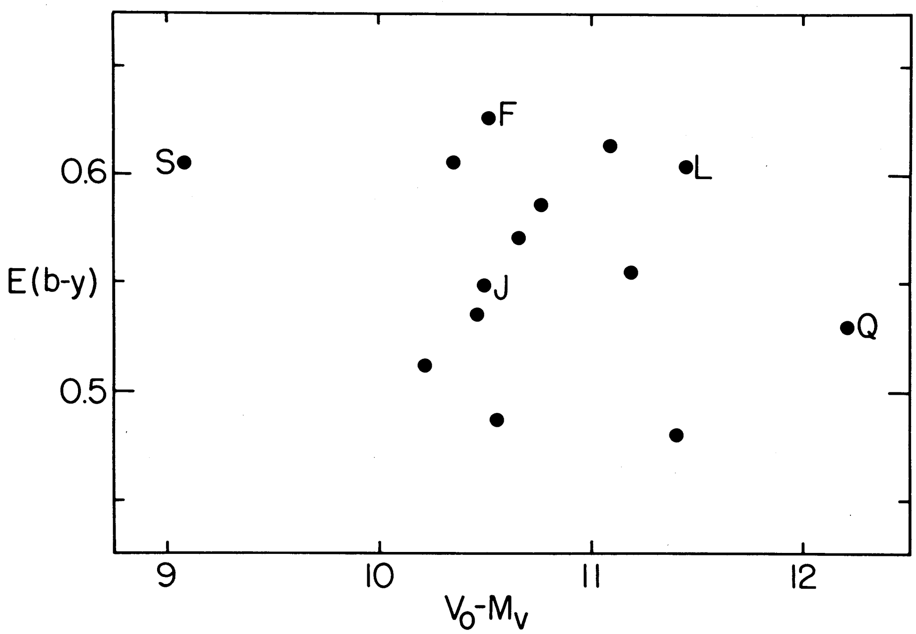

FIG. 2. The color excess plotted against the true distance modulus. Stars discussed in the text are labeled.

This is considerably higher than the value derived by Arp of about 0.60. Some of this discrepancy can be attributed to selection in a small sample with a large range of reddening. However, when the individual color excesses are compared it is found that the present values are larger by an average of 0.12 mag in $E(B-V)$. To further investigate this discrepancy we have plotted the present $b-y$ colors against the $B-V$ colors of Arp and the $u-v$ colors derived from the indices of Table I against the $U-B$ colors of Arp. This is shown in Fig. 3. Also shown for comparison are points representing some of the stars in M25, which has a similar reddening to NGC 6664. The *UBV* data were taken from Wampler *et al.* (1961), while the four-color data came from Schmidt (1982a). It can be seen that both the diagrams exhibit discrepancies from M25 but in opposite senses. Any discrepancy in $U-B$ or $u-v$ will have a relatively small effect on the derived reddenings, but the differences in $B-V$ and $b-y$ between the present values and those for M25 fully account for the different derived color excess.

Unfortunately, there is very little photometry of this cluster beyond that of Arp and the present investigation. Roslund (1963) obtained *UBV* photometry of two of the stars and his results are in reasonable agreement with Arp. However, neither of these stars was observed in the present program so it is not clear how strong this point is.

For the three B stars in Table I with spectral types, we can derive spectroscopic estimates of the color excesses. These are shown in Table III. The standard relations between spectral type ($B-V$ and $U-B$) listed by Johnson (1966) were used to obtain the reddenings given in columns 1 and 2. The mean indices for various spectral types listed by Crawford (1978) were used to obtain the reddening from $b-y$ and c_1 (columns 4 and 5). It can be seen that both $b-y$ and c_1 give spectroscopic color excesses in agreement with the photometric values. On the other hand, while the spectroscopic color excesses from $B-V$ agree with the photometric values, those from $U-B$ show serious discrepancies for two of the stars. In other words, the *UBV* colors are not consistent with the spectral types.

One final point regarding the difference between the *UBV* and the *uvby* photometry is that the *uvby* data were obtained during four different observing seasons and on some of the same nights as the M25 four-color data. A few were also obtained from Behlen Observatory. A search of the original data does not indicate any systematic differences among the data from the various observing runs. It is difficult to see how a systematic error of the order of 0.1 mag could occur between this cluster and M25 under these circumstances.

It is clear that it would be worthwhile to reobserve some of the stars in this cluster in the four-color system, the *UBV* system, or preferably both, to check on these discrepancies. Until such an investigation is carried out, we will have to regard the reddening of this cluster as somewhat uncertain.

As Arp pointed out, although there is a large range in the color excess in this cluster, the variation is rather smooth across the face of the cluster and it is possible to interpolate reasonably well to the location of EV Sct. When we do this we obtain a color excess of $E(b-y)=0.55$, which corresponds to $E(B-V)=0.75$ (for a B star). The scatter about the interpolating line is 0.015 mag and this is likely to be the uncertainty in the color excess of EV Sct.

It appears that this cluster contains two and perhaps three blue stragglers. Stars F and J are clearly hotter

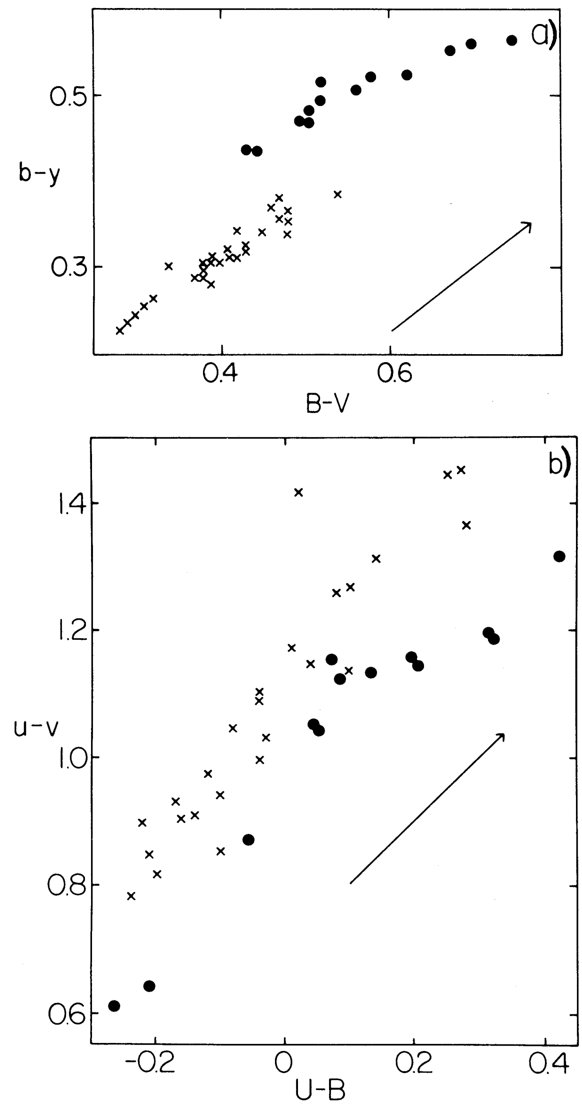

FIG. 3. Plots of colors from the four-color photometry against the corresponding colors from the *UBV* photometry. Solid circles represent the stars in NGC 6664 while the crosses indicate the stars from M25, which are shown for comparison. The arrows show the direction of the reddening trajectory in these diagrams.

TABLE III. Color excesses from spectral types.

	$E(B-V)$			$E(b-y)$		
Star	(1)	(2)	(3)	(4)	(5)	(6)
F	0.73	0.63	0.75	0.60	0.62	0.63
L	0.72	0.69	0.72	0.58	0.59	0.60
M	0.56	0.39	0.57	0.50	0.53	0.51

Explanation of the columns

(1) From spectral type and $B-V$.
(2) From spectral type and $U-B$.
(3) From the $(B-V)$-$(U-B)$ diagram.
(4) From spectral type and $b-y$.
(5) From spectral type and c_1.
(6) From $b-y$ and c_1.

than the turnoff point of the cluster in Figs. 1(a) and 1(b). Additionally, their distance moduli place them within the cluster. Star L is also a blue straggler if it is a cluster member. However, as discussed above, it is possibly a background star. Further studies of this star to more clearly establish its membership might, however, prove useful.

As discussed in a previous paper (Schmidt 1982a) the diagram of β against c_0 is sensitive to age for clusters with the turnoff among the B stars. In Fig. 1(b) it can be seen that the turnoff occurs at about $c_1 = 0.70$, which corresponds to $c_0 = 0.59$. Referring to Fig. 5 of Schmidt (1982a), we see that this makes NGC 6664 slightly younger than the Pleiades but significantly older than the α Per cluster. We can estimate its age (assuming from Harris 1976, that the α Per cluster is about 20×10^6 yr old and the Pleiades is about 60×10^6 yr old) to be about 46×10^6 yr. This conflicts with the data given by Harris for NGC 6664, which imply an age of about 30×10^6 yr. However, she based her estimates on the bluest stars on the main sequence and it is possible that she was misled by the blue stragglers in this case.

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