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Edward G. Schmidt
University of Nebraska at Lincoln, eschmidt1@unl.edu

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FOUR-COLOR AND Hβ PHOTOMETRY OF STARS IN THE GALACTIC CLUSTER NGC 129

EDWARD G. SCHMIDT [a)]

Department of Physics and Astronomy, University of Nebraska, Lincoln, Nebraska 68588

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ABSTRACT

Four-color and Hβ photometry has been obtained for 22 stars in the field of the open cluster NGC 129. Based on this photometry, the membership of these stars in the cluster is discussed and it is found that many are field stars. The color excesses for cluster members obtained here range from $E(b-y) = 0.207$ to 0.513 and are larger than those found from previous *UBV* photometry. It has been suggested that this cluster contains a nonvariable Cepheid strip star. However, the present reddening places this star at the edge of the instability strip. A true distance modulus of 10.93 mag is found for this cluster, which is less than some previous values.

I. INTRODUCTION

The galactic clusters which have Cepheid members are of special interest in connection with the luminosities, intrinsic colors, temperatures, evolutionary status, and pulsational properties of such stars. Previously the distance moduli and color excesses of these clusters have been obtained from broadband three-color photometry. For reasons given previously (Schmidt 1980), it is desirable to determine these quantities using the four-color and Hβ system. This paper presents data for the cluster NGC 129 which contains the Cepheid DL Cas (period = 8.00 days).

II. THE OBSERVATIONS

The stars in the field of NGC 129 which I have observed are listed in Table I. Most of the stars brighter than $V = 13$ with *UBV* colors which place them near the main sequence were included. The designations of Arp *et al.* (1959), Hoag *et al.* (1961), and Lenham and Franz (1961) are listed for each star in the first three columns. Lenham and Franz studied the probabilities of membership from proper motions, and the fourth column indicates those stars which they considered highly probable members (Yes) and those which they considered likely nonmembers (No). Frolov (1975) has also studied the motions of this cluster. However, it does not appear that his data are accurate enough to discriminate members. The spectral types in the fifth column are taken from Kraft (1958) for all the stars except star 48. The spectral type of star 48 came from Hoag and Applequist (1965).

The photometric data for this cluster were obtained during 1975 and 1976 with the 76-cm telescope at Behlen Observatory and during 1977 and 1978 with the 1.3-m telescope at Kitt Peak National Observatory. At Behlen Observatory the automatic photometer was used (Taylor 1980), while at Kitt Peak the observations were made with the two-channel photometer. The V magnitudes in the table were obtained by taking an average of the present determinations (weighted by the number of observations), the photoelectric values of Arp *et al.* (weighted by the number of observations), and the values of Hoag *et al.* (with unit weight).

The observations were reduced to the standard system using standard stars from the lists of Crawford and Mander (1966) and Crawford and Barnes (1970), stars from h Per (Crawford *et al.* 1970), and secondary standards which were previously referred to the Crawford and Mander and Crawford and Barnes standards. In the case of the Hβ index, it has been shown (Muzzio 1978; Schmidt and Taylor 1979) that filter sets in common use can have significant color effects. For the 1975, 1976, and 1977 observations no color terms were required, but a value of −0.079 mag was used with the 1978 observations. This was determined from the transmission curves of the filters, which were measured immediately following the observing run. To check further on the possibility of systematic errors in the Hβ index, I have compared the results from the various observing runs (during which different filter sets were used). The 1975 and 1976 indices are 0.005 ± 0.003 mag smaller than the 1978 values for two stars with many observations, while the mean difference between the 1977 and 1978 values is 0.000 ± 0.003 for six stars which have more than two observations each year. This indicates that no significant systematic error is present between the various sets of photometry included here. One can also check for systematic effects by comparing the Hβ indices measured in 1978 for stars in h Per with the results of Crawford *et al.* (1970). This was an especially important test since h Per was used in the luminosity calibration of the system for B stars and since it has a

[a)]Visiting Astronomer, Kitt Peak National Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

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TABLE I. Photometric data for stars in NGC 129.

Star designation: Arp *et al.*	Hoag *et al.*	Lenham and Franz	Proper motion member	Spectral type	V	$b-y$	m_1	c_1	n	β	n	Spectral range	$E(b-y)$	V_0-M_V	Photometric member
B	7	42	No	F6V	9.27	0.309	0.132	0.312	9	2.629	9	F	−0.014	4.65	No
C	11	44	Yes	B6III–IV	10.91	0.388	−0.057	0.619	6	2.654	11	B	0.444	11.76	Yes
D	14	26			11.13	0.216	0.096	1.059	1	2.882	1	A	0.161	8.78	No
G					12.81	0.444	0.079	0.456:	2	2.698:	2	F	0.196	6.25	No
AC	10	63	Yes	B9V	9.95	0.165	0.032	0.750	6	2.721	6	B	0.207	10.02	Yes?
AE	22	59	Yes		12.37	0.340	−0.020	0.635	3	2.716	4	B	0.393	11.35	Yes
S2	8	60		A0V	9.38	0.143	0.050	0.702	3	2.754	3	B	0.187	8.60	No
S3	6				8.91	0.139	0.103	1.141	2	2.889	2	A0			No
S4		65	Yes	B8.5V	10.77	0.192	0.114	1.040	3	2.877	4	A	0.140	8.56	No
16	21	53	Yes		12.32	0.339	−0.041	1.001	3	2.580	4	e?			?
24	17	51	Yes	B6V	11.77	0.359	−0.041	0.521	4	2.696	4	B	0.425	10.92	Yes
48	9	48	No	F6V	9.65	0.286	0.148	0.422	3	2.675	3	F	0.018	6.60	No
61		45	Yes	B5V	11.72	0.344	0.009	0.441:	4	2.700	4	B	0.420	10.59	Yes
93					12.42	0.449	−0.075	0.567	1	2.731	1	B	0.513	10.23	Yes
96	20	41	Yes		12.26	0.429	−0.039	0.437	3	2.706	4	B	0.507	10.50	Yes
105	13	39	Yes	B9V	11.15	0.350	−0.035	0.511	5	2.676	4	B	0.417	11.01	Yes
111	12	35			10.92	0.342	0.135	0.954	1	2.822	1	A	0.226	7.91	No
115	15	36			11.43	0.455:	0.145:	0.490:	2	2.644	2	F	0.133	7.73	No
118		31	Yes		11.91	0.444	0.069	1.095	3	2.840:	4	A	0.355	9.08	No
123		29	Yes		12.07	0.370	−0.029	0.487	3	2.712	4	B	0.440	10.59	Yes
125	18	30			11.79	0.402	−0.056	0.545	4	2.663	2	B	0.467	11.99	Yes
151		23	Yes		12.15	0.323	0.003	0.457	3	2.696	4	B	0.396	11.30	Yes

reddening similar to that of NGC 129. I find that the mean difference between my indices and the published values is 0.006 ± 0.003 in the sense that my indices are smaller. This indicates that I have matched the standard system accurately.

The four-color and Hβ indices in Table I are averages for the number of nights indicated in the 10th and 12th columns of the table. The internal scatter for stars observed multiple times indicated that the standard deviations are the following for a single observation: $b-y$, 0.016 mag; m_1, 0.026 mag; c_1, 0.029 mag; β, 0.013 mag.

In order to apply the various calibrations to my data, it is necessary to separate the stars into B stars, A stars, and F stars and to exclude any of later type for which no calibrations exist. I have done this by referring to the $[m_1]-[c_1]$ diagram to separate the B stars from the later types. The A and F stars were distinguished by their β indices. The 13th column in Table I gives the inferred type for each star. The star S3 appears to lie between the B and A regions of the diagram, and no calibration exists for stars which are so close to the maximum of the hydrogen absorption. Star 16 has an abnormally small β index, considering its other indices. It is possible that it is an emission line star, and it has been excluded from the analysis for this reason. Of the nine stars for which spectral types are given in the fifth column of Table I, only two, S2 and S4, show minor disagreements between our inferred spectral type and the observed spectral type. This confirms that the separation of the various spectral types by using the $[m_1]-[c_1]$ diagram is quite reliable.

The color excesses and absolute magnitudes were obtained for each of the stars using the calibration appropriate to its spectral range (Crawford 1975b, 1978, 1979). The color excesses are listed in column 14 of Table I, while the true distance moduli are listed in column 15.

III. THE CLUSTER MEMBERSHIP AND THE DISTANCE MODULUS

In order to determine the distance modulus of the cluster, it is necessary to remove nonmembers from the sample. By plotting various diagrams involving the photometric indices and quantities derived from them, it is possible to separate out various types of field stars. In this particular case, it turned out that the three diagrams shown in Fig. 1 were the most useful. In the color excess–distance modulus diagram it is apparent that there is a clustering of stars with color excesses between 0.39 and 0.51 and distance moduli near 11. Stars elsewhere in the diagram are field stars. The c_1-V diagram similarly shows a clustering of stars near $c_1=0.5$ and fainter than $V=11$. In the $V-(b-y)_0$ diagram many of the stars are seen to be too red to be members, compared with the main sequence of the cluster. Those stars which lie within the cluster group in all three of the di-

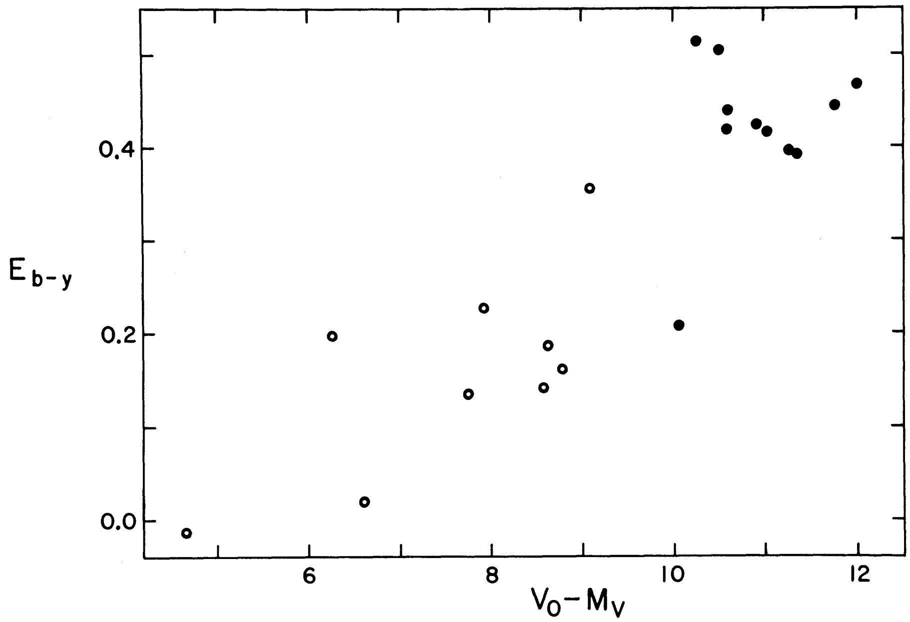

FIG. 1(a). The color excesses of the cluster stars plotted against the distance modulus.

agrams are considered members and this is indicated in the last column of Table I. The members are plotted as closed circles in Figs. 1(a)–1(c). It should be realized that part of the ability of the four-color photometry to separate members results from the ability to sort the stars according to the groups B, A, or F, which was discussed in Sec. II.

For two stars, I have indicated uncertainty regarding membership. Star 16 has indices which do not fit the calibrations and which might be accounted for by assuming it to be an emission line star. Since it is peculiar, I can neither derive its reddening and distance modulus nor determine whether it is a member of the cluster. Star AC has a distance modulus reasonably close to the cluster stars, but the color excess is much smaller. It is located away from the other cluster members. According to Turner (1976) the reddening in this cluster is smaller for stars away from the cluster center. Thus, I have included it as an uncertain member.

The average distance modulus for stars which are photometric members (including star AC) is 10.93 ± 0.19 (standard error of the mean). In Fig. 2, I have plotted the distance moduli of the individual stars against their apparent magnitudes. It can be seen that there is no obvious trend indicating that the calibration has correctly accounted for evolutionary effects. The color excess in this cluster is quite variable. The average of the member stars observed here is $E(b-y) = 0.442$, but there is a range from 0.393 to 0.513 (excluding star AC).

IV. DISCUSSION

Arp *et al.* obtained *UBV* colors for all the cluster members observed here and Hoag *et al.* obtained colors

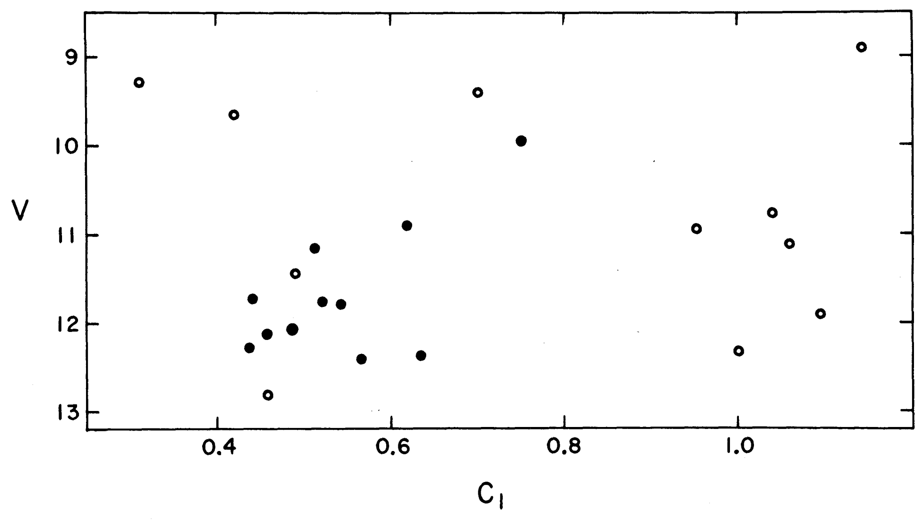

FIG. 1(b). The apparent magnitude plotted against the c_1 index.

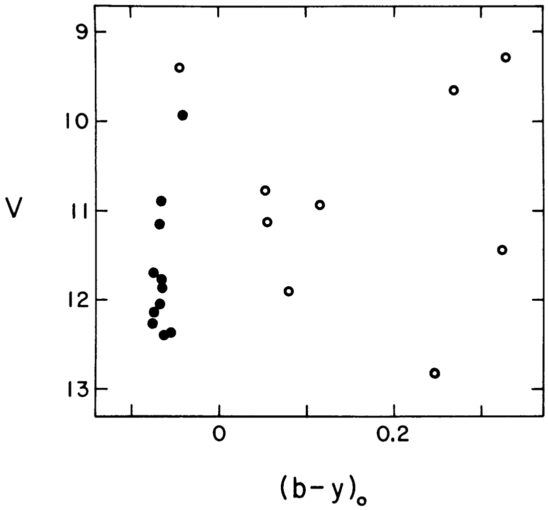

FIG. 1(c). The apparent magnitude plotted against the intrinsic color. The closed circles indicate stars which are considered members on the basis of the photometry, while the open circles represent field stars.

for seven of them. The color excesses from these two sets of data differ in the sense that the Hoag *et al.* excesses are systematically larger by 0.04 mag. I have converted the present excesses using the relation $E(b-y) = 0.74E(B-V)$ (Crawford 1975a) and find that the present values are larger by 0.08 mag than the Arp *et al.* values and are larger by 0.03 mag than the Hoag *et al.* values. The agreement with the latter scale is probably reasonable, and I suggest that the Hoag *et al.* colors may be systematically closer to the *UBV* system than the Arp *et al.* results.

There are two stars of special interest in NGC 129. They are the Cepheid, DL Cas, and the yellow supergiant, star A. We can estimate the reddening of these objects from the stars I have observed near them in the cluster. Unfortunately, in the presence of variable absorption, the accuracy of this method is limited. In the case of DL Cas, stars 105 and 125 yield a color excess of $E(b-y) = 0.442$. Since the color excesses of these two stars differ by 0.05 mag, this value is uncertain by at least several hundredths of a magnitude. For star A, I have

TABLE II. Distance moduli for NGC 129.

Source	$V_0 - M_V$
Arp *et al.* (1959)	11.00
Johnson *et al.* (1961)	11.1
Hoag and Applequist (1965)	10.8
Sandage and Tammann (1969)	11.28
Becker and Fenkart (1971)	11.20
Turner (1976)	10.98
Cogan (1978)	11.46
de Vaucouleurs (1978)	11.42
Cox (1979)	11.54

used stars 93, 96, and C to obtain a mean color excess of $E(b-y) = 0.488$. In this case the range in color excess among the three stars is 0.07 mag and we must again expect several hundredths of a magnitude uncertainty in the color excess of the yellow giant. Converting these color excesses to the *UBV* system and correcting for the difference in color excess between B stars (used in the determination) and G stars (following Fernie 1963), I obtain a color excess of $E(B-V) = 0.56$ for DL Cas and $E(B-V) = 0.62$ for star A. In the case of DL Cas the present color excess is larger than that used in establishing the PLC relation, $E(B-V) = 0.50$ (Sandage and Tammann 1969). It was suggested (Schmidt 1976) that star A is within the Cepheid strip, based on a reddening of $E(B-V) = 0.50$. The present value of the reddening places this star at the hot edge of the instability strip and thus weakens the case for considering this object to be a nonvariable Cepheid strip star.

In Table II, I list a number of estimates of the true distance modulus of NGC 129 collected from various papers. Most of these estimates are based on the same photometric data but are somewhat independent in the sense that the various authors have reanalyzed the data and have used different assumptions regarding the Hyades distance, the effects of metal abundance, and the reddening law. Readers are referred to the original papers for a full discussion of these various assumptions. The paper of Cox does not discuss distances directly but rather shows that the luminosities implied by the adopted distance scale produce pulsational masses in agreement with the evolutionary masses for Cepheids. This gives support to the large distance modulus given in the last

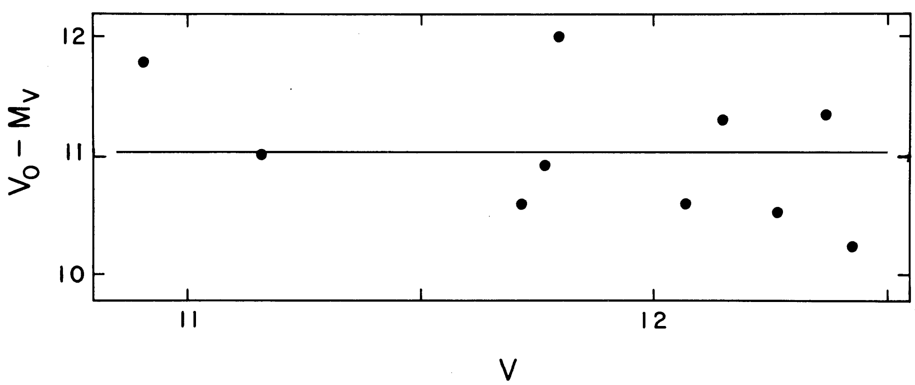

FIG. 2. The true distance modulus plotted against the apparent magnitudes for the stars which are photometric members. The solid line indicates the adopted modulus.

line of Table II. It can be seen that my distance modulus, 10.91, is in agreement with the smaller values in Table II but not with several of the higher values. I will defer a full discussion of the distance scale and the Cepheid luminosities until the observations of other clusters with Cepheid members have been completed.

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