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PHOTOMETRY IN THE ANCIENT OPEN CLUSTER NGC 6791

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ABSTRACT

New photoelectric *UBV* photometry in the field of the old open cluster NGC 6791 is reported and discussed. The foreground reddening of the cluster is determined as $E_{B-V} = 0.13$ and the distance modulus $(m-M)_v = 14.0$ ($D_\odot = 5.2$ kpc), by analysis of the color-magnitude (CM) and two-color diagrams along with published spectral types of several cluster stars. For a heavy-element abundance $Z = 0.02$, isochrone fitting to the CM diagram suggests that NGC 6791 is $\sim 7 \times 10^9$ yr old and possibly the oldest known open cluster. Finally, we note an apparent radial field error in B (or $B - V$) to the extent of $\lesssim 0.10$ mag in previously published photographic photometry of the cluster, and discuss its effects on the integral properties of the cluster.

I. INTRODUCTION

The open cluster NGC 6791 (C 1919+377; $l = 70°$, $b = +11°$) was shown, in a classic paper by Kinman (1965), to be an extremely old object in the same general category as NGC 188. Open clusters in this age range have been of continuing interest as keystone tracers of the age, star-formation history, and chemical enrichment history of the Galactic disk as well as observational laboratories for the evolution of low-mass stars (cf. also Hirshfeld *et al.* 1978, Anthony-Twarog *et al.* 1979, and van den Bergh and McClure 1980). However, for NGC 6791 in particular, little has happened to improve our state of knowledge since Kinman's discussion. Although quite populous, NGC 6791 is a distant, compact object situated in a fairly crowded star field; so observations of it require not only a large telescope (main-sequence turnoff at $V \simeq 17.5$) but good ($\lesssim 2$ arcsec) seeing conditions.

During a photometric program on selected open clusters, we were able to obtain new photoelectric *UBV* photometry for stars in NGC 6791 and to use these results to investigate its reddening, composition, and age in comparison with Kinman's very thorough *BV* color-magnitude study. Our data and subsequent analysis are presented in the following sections.

II. PHOTOELECTRIC PHOTOMETRY

During two observing runs at the Wyoming Infrared Observatory (WIRO) in October 1979 and 1980, we used the optical photometer with the 2.3-m telescope to obtain *UBV* measurements for 23 stars in the NGC 6791 field. Because of the crowding in the cluster field we used photometer aperture sizes ranging from 6 to 10 arcsec in diameter, depending on the seeing conditions; even so, it was possible to measure reliably only a handful of the cluster stars in the innermost ring (see below). Local sky measurements were taken for every program star, in representative sky areas usually 10 to 20 arcsec distant from the star. Integration times ranged from ~ 10 s for bright ($V \lesssim 12$) stars up to ~ 5 min in each filter for the faintest ones.

The photometry in the cluster field was done differentially using star S2 (see Table I) as a local standard. On each of the four total nights involved, S2 was in turn calibrated with the Landolt (1973) *UBV* standard star network. Reductions of the program stars were made both from the Landolt standards directly, and also dif-

TABLE I. Photoelectric photometry in NGC 6791.

Star	V	$B-V$	$U-B$	n	Sp.
D	9.86	0.11	0.06	2	
S1[a]	10.63	0.13	0.02	2	
S2[a]	11.51	1.09	0.85	4	
S3[a]	10.07	0.40	0.11	4	
1401	15.26	1.39	1.50	1	
1414	15.85	1.18	1.37	1	
1425	18.03	0.85	0.19:	2	
1459	17.25	1.21		1	
2001	13.71	1.60	1.83	4	K5III
2002	17.00	1.10	0.71	4	
2008	13.84	1.64	1.96	3	K4III
2015	16.11	0.48	0.10	1	F2IV
2017	15.04	0.42	0.20	1	F2IV
2019	15.52	0.76	0.30	1	G2V
2023	15.07	0.76	0.26	1	G0V
2027	16.21	0.90	0.49	1	G0V
2028	15.41	0.74	0.25	1	G0V
2031	15.04	1.12	1.00	1	G8IV
2035	15.78	0.81	0.17	1	G5IV
2038	14.12	1.62	1.86	3	K5III
2044	15.01	1.14	0.99	1	K1IV
2048	16.25	1.27	1.44	2	
2051	14.71	1.45	1.52	2	

[a]Positions of these three stars with respect to Kinman's (1965) cluster center location are as follows: S1, 3'.69 N, 0'.86 W; S2, 1'.13 N, 1'.42 E; S3, 5'.58 S, 1'.79 E.

ferentially with respect to S2; but the latter approach was adopted for the final results since on some of the nights a gradual change in the extinction over the period of observation had to be removed.

The results are summarized in Table I. Here, star D is one of Kinman's (1965) primary photoelectric standards in the field; stars S1–S3 are additional bright stars near the cluster not measured by Kinman; and the remaining numbered stars are ones measured photographically by Kinman which we selected from his two innermost rings centered on the cluster. The numbering system is that of Kinman with the following modification: the first digit of the 4-digit number denotes the ring (1 or 2, with ring 1 innermost), the second digit (in ring 1 only) is the quadrant number (1 = NW, 2 = SW, 3 = SE, 4 = NE), and the last two digits are the Kinman star number in that quadrant. (In ring 2, no quadrants are defined so the second digit was just set at zero.) The last two columns in Table I give the number of independent observations, n, and the spectral classification of the star (where available) as given by Kinman. The internal random errors to be applied to our data are no better than $\sigma_V = 0.02$, $\sigma_{B-V} = 0.03$, $\sigma_{U-B} = 0.03$ for a *single* measurement because of the field crowding and the occasional extinction reduction problems mentioned previously, although we made every effort to ensure that the data are *systematically* true to the *UBV* scale.

Our first step in the subsequent analysis was to compare our photoelectric results with the Kinman *photographic* ($V, B-V$), data for the same stars. The mean differences ΔV, $\Delta(B-V)$, in the sense HC − Kinman, are as follows (no comparison in $U-B$ can, of course, be made):

$$\text{Ring 1 (4 stars):} \quad \langle \Delta V \rangle = +0.023 \pm 0.050, \quad \langle \Delta (B-V) \rangle = +0.068 \pm 0.020,$$

$$\text{Ring 2 (15 stars):} \quad \langle \Delta V \rangle = +0.004 \pm 0.016, \quad \langle \Delta (B-V) \rangle = -0.054 \pm 0.019.$$

The given errors are the standard errors of the mean in each case. The residuals do not appear to correlate strongly with either magnitude or $B-V$, and our V-magnitude scale agrees well with that of Kinman for both groups of stars. But the mean residuals in $B-V$ are significantly larger, in the sense that the Kinman data are slightly *bluer* than ours in ring 1 but *redder* than ours in ring 2 by about the same amount. Given the agreement in V, this would imply that the Kinman B magnitudes are slightly too bright in ring 1 and too faint in ring 2 relative to the photoelectric scale. Since we measured local sky patches for all the stars in our program, we are unable to suggest any way in which the photoelectric data should contain a systematic error in B dependent on position, small though it is. On the other hand, a radial trend of this type with respect to the cluster center is not uncommon in photographic photometry, in the sense that the central stars are the most crowded and thus appear artificially brighter on the photographic plate. In Kinman's photographic data itself, this trend would be expected to show up as a color difference of $\Delta(B-V) \sim 0.1$ in the mean location of the giant branch ($V \lesssim 17$) defined by the stars in ring 1, as compared with ring 2. We have looked for such an effect (cf. also Kinman's Fig. 3), but the relatively small number of clearly defined giant-branch stars and the individual star-to-star differences add enough scatter that only a very marginal suggestion of the systematic radial trend can be found.

For the present, we are forced to conclude that the main source of the systematic differences lies in the B photographic data; however, the presumed explanation is not entirely satisfying and a more thorough photometric investigation would plainly be welcome to settle the question. The only other direct check that we have on our own photometry is Kinman's *photoelectric* published ($V, B-V, U-B$) values for the single reference star D, for which the differences HC − K are $\Delta V = 0.02$, $\Delta(B-V) = -0.01$, $\Delta(U-B) = -0.04$. Although comparisons using only a single star are not too informative, the V and $B-V$ differences are satisfactorily near zero.

III. REDDENING AND COMPOSITION

During our observations, we deliberately selected several stars in ring 2 with classified spectra (last column of Table I) to facilitate estimates of the foreground reddening for NGC 6791. Several of these are F and G stars *above* the cluster turnoff, though Kinman discusses their membership status and concludes that most of them are cluster members. We used the standard intrinsic color versus spectral type calibrations of Fitzgerald (1970) to calculate the reddenings in $B-V$ and $U-B$ for the 12 stars with spectral types that we measured photoelectrically. In addition, we used the M_v vs spectral type calibrations of Keenan (1973), Fitzgerald (1967), and Blaauw (1963) to calculate the apparent visual distance moduli $(m-M)_v$ from our measured V magnitudes, modified appropriately where necessary to correct for the new Hyades distance scale $m-M = 3.30$ (Hanson 1980). The results for these spectroscopic reddenings and parallaxes are collected in Table II.

The individual stellar reddenings group satisfactorily around mean values $\langle E_{B-V} \rangle = 0.126 \pm 0.014$ and $\langle E_{U-B} \rangle = 0.112 \pm 0.033$, excluding stars 2027 and 2031, which lie more than 3σ above these averages in both colors. (Kinman also rejected 2027 as being a cluster nonmember on the basis of its discordant radial velocity.) The ratio

$$\langle E_{U-B} \rangle / \langle E_{B-V} \rangle = 0.89 \pm 0.28$$

agrees well with the expected ratio $\simeq 0.85$ for F- and G-type stars (e.g., Crawford and Mandwewala 1976). Giving double weight to the $B-V$ reddenings because of their lower internal scatter, we adopt a final estimate of $E_{B-V} = 0.13 \pm 0.03$ for the cluster. This is significantly smaller than Kinman's adopted value $E_{B-V} = 0.22$,

TABLE II. Spectroscopic reddenings and parallaxes.

Star	Sp.	E_{B-V}	E_{U-B}	M_v	$(m-M)_v$
2001	K5III	0.09	0.00	−1.0	14.7
2008	K4III	0.21	0.27	−0.7	14.5
2015	F2IV	0.11	0.06	1.9	14.2
2017	F2IV	0.05	0.16	1.9	13.1
2019	G2V	0.13	0.21	4.7	10.8[a]
2023	G0V	0.16	0.20	4.4	10.7
2027	G0V	0.30	0.43	4.4	11.8[a]
2028	G0V	0.14	0.19	4.4	11.0
2031	G8IV	0.30	0.53	3.0	12.0[a]
2035	G5IV	0.11	−0.04	3.0	12.8
2038	K5III	0.11	0.03	−1.0	15.1
2044	K1IV	0.15	0.04	2.7	12.3[a]

[a]Doubtful cluster member on basis of radial velocity.

but most of the difference is clearly due to the systematic change of about 0.06 mag in $B-V$ for the stars in ring 2, as discussed in Sec. II. The remaining ~0.03-mag residual is well within the combined scatter of the individual stars sampled, the uncertainties in the spectral types, and the slight differences in the adopted calibrations. Nevertheless, if our present photometry is correct, then the foreground absorption of NGC 6791 must be quite a bit smaller than was previously thought.

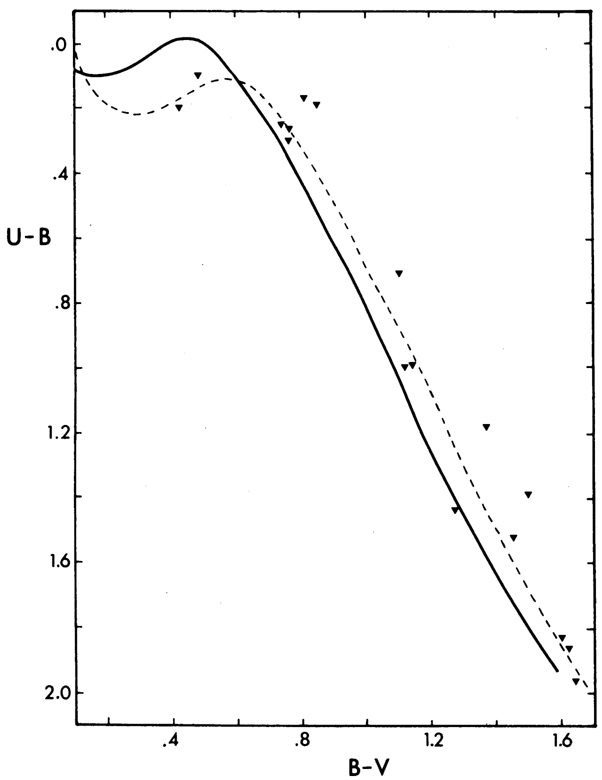

FIG. 1. Two-color diagram for the photoelectrically measured stars in NGC 6791. The solid line is the standard $U-B$ vs $B-V$ curve, and the dashed line is the same curve reddened by $E_{B-V}=0.13$.

Given the spectroscopically determined reddening, the $(U-B,\ B-V)$ diagram (shown in Fig. 1) can be used to provide a crude estimate of the ultraviolet excess $\delta(U-B)$ for the redder stars in the cluster and hence the heavy-element composition. From the stars in Fig. 1 redder than $B-V=1.0$ measured with respect to the reddened two-color line, we find $\langle\delta(U-B)\rangle = 0.04 \pm 0.05$, and hence [Fe/H] $= -0.2 \pm 0.3$ (Wallerstein and Helfer 1966). Within the large uncertainty, we therefore find no evidence that NGC 6791 is strongly different in chemical composition from the Sun. This conclusion is what would be expected from the finding of van den Bergh and McClure (1980)—that [Fe/H] for old open clusters correlates primarily with galactocentric distance, since (as will be seen in Sec. IV) 6791 is at very nearly the solar distance from the galactic center. But an additional independent measurement of the cluster metallicity, such as by DDO photometry of the giants, would clearly be more valuable. (For example, in using the spectral types to determine E_{B-V}, we implicitly *assumed* the stars to have solar-type compositions so that the normal color versus spectral type calibrations could be adopted. What we have derived here is therefore only a self-consistent picture and not a direct confirmation of its "normal" composition.)

IV. DISTANCE AND AGE

We may estimate the distance to NGC 6791 in three, not entirely independent, ways: (a) use of the spectroscopic parallaxes in Table I; (b) identification of the red "horizontal branch" (RHB) in the CM diagram along with its assumed absolute magnitude; and (c) fitting of the observed main sequence to model isochrones. The first method gives widely different results depending on which stars are assumed to be cluster members, since the spectroscopic $(m-M)_v$ values range from 10.7 to 15.1. This probably reflects the presence of a certain fraction of nonmembers, but also the uncertainties in the spectral classifications, since adjacent luminosity classes for late-type stars have large differences in absolute magnitude. If we restrict ourselves *only* to stars lying on or near the giant branch, for which cluster membership is *most* likely, we are left with just three stars (2001, 2008, 2038), for which the mean $\langle m-M\rangle_v = 14.8 \pm 0.2$. The mean of *all* stars, excluding just radial velocity nonmembers (see Kinman), is $\langle m-M\rangle_v = 13.3 \pm 0.6$. It seems necessary to conclude that the available photometry and spectral types yield only a rough idea of the cluster distance.

The second method employs the result shown by Cannon (1970), which is that the RHB occupies a well defined and consistent location, at $M_v = 0.9 \pm 0.3$ and $(B-V)_0 \simeq 1.0$, for open clusters older than $\sim 10^9$ yr. This absolute magnitude value was, however, based on the older Hyades distance modulus of 3.0 and should be corrected upward for the newer value of ~3.3 (Hanson 1980). However, most of the old clusters in Cannon's sample are not as metal rich as the Hyades and it ap-

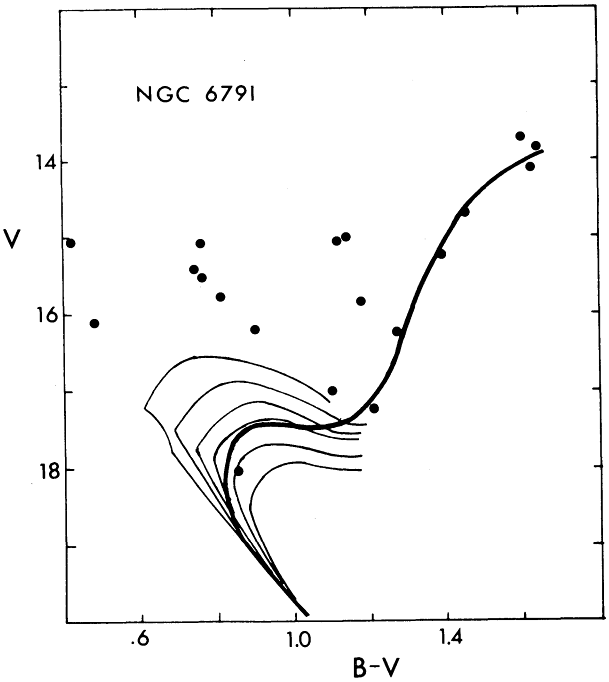

FIG. 2. Isochrone and main-sequence fit to the color-magnitude diagram of NGC 6791. The *dots* are the photoelectrically observed stars from Table I, and the thick curve is Kinman's (1965) mean locus adjusted to our adopted reddening of $E_{B-V} = 0.13$. The fitted isochrones (thin curves) are for our adopted choice of $Z = 0.02$, $Y \simeq 0.25$, $(m - M)_V = 14.0$. An age of 6–7 billion years for NGC 6791 is suggested by comparing it with the isochrone lines, which are for ages of $(3, 4, 5, 6, 8$, and $10) \times 10^9$ yr.

pears reasonable to assume that they are, like NGC 6791, near solar metallicity on average. Taking this into account, we should therefore apply a correction of ~ 0.15 mag to the effective Hyades modulus for solar-metallicity objects (e.g., Turner 1979; van den Bergh 1977), or $M_v(\text{RHB}) = 0.75 \pm 0.3$. Kinman's composite CM diagram for NGC 6791 (see his Figs. 3 and 9) reveals a well defined clump of about 15 stars at $V = 14.65 \pm 0.05$ just off the red giant branch, which we can identify as the RHB; so this method yields $(m - M)_v = 13.9 \pm 0.35$.

The third approach requires a simultaneous solution for the cluster distance and age, by fitting model isochrones for an assumed chemical composition to the observed cluster CM diagram. To do this we used the Yale isochrones of Ciardullo and Demarque (1977), transformed to the $(M_v, B - V)$ plane, for compositions of $Y = 0.2$ and 0.3 and heavy-element abundances interpolated from a minimum $Z = 0.01$ to maximum $Z = 0.04$. The best fits we were able to obtain, for the two choices of helium abundance, were (a) $(m - M)_v = 13.90$ and age $T = (7 \pm 1) \times 10^9$ yr for $Y = 0.3$ and $Z = 0.02$, and (b) $(m - M)_v = 14.20$ and $T = (6 \pm 1) \times 10^9$ yr for $Y = 0.2$ and $Z = 0.02$. What we believe to be our "best compromise" choice is illustrated in Fig. 2: giving high weight to the RHB method for determining the distance modulus, we adopt $(m - M)_v = 14.0 \pm 0.2$, $Z \simeq 0.02$, and an interpolated helium abundance $Y \simeq 0.25$, for a final age estimate of roughly $(6\text{–}7) \times 10^9$ yr.

It is gratifying to note that the isochrone fit independently favors a heavy-element abundance ($Z \simeq 0.02$) which is nearly solar, in agreement with our previous estimate. Values higher than $Z \simeq 0.04$ or lower than ~ 0.01 for the isochrones produce subgiant branches (i.e., the region between the turnoff and the vertical giant branch) which either turn downward too much or rise too steeply with color to match the observed CM diagram.

It is important to note that the mean lines shown in Fig. 2, which we used to superimpose over the isochrones, are the fiducial lines given by Kinman (cf. his Table 5), but dereddened by our value $E_{B-V} = 0.13$. In this figure we have *not* applied the systematic color corrections discussed in Sec. II. The turnoff and main-sequence regions of Kinman's CM diagram depend entirely on stars within ring 1 (innermost) for which we found the photographic photometry to be too blue by ~ 0.07 mag. However, we measured only three photoelectric stars fainter than $V = 17$ (two in ring 1) which fall on or near the subgiant branch and turnoff, so at present we regard the necessary color correction to be applied to the *main-sequence* stars as still rather uncertain. Because photographic field errors (if they are present) can also depend on magnitude, what we have found as color corrections to the brighter giant stars may not in fact apply in detail for the fainter parts of the CM diagram. A more extensive photometric study, with special attention to the photometric calibration below $V \sim 17$, would be an extremely important contribution to the understanding of NGC 6791. If we *do* apply an adjustment of $\Delta(B - V) = +0.07$ mag to the observed main sequence, the properties of the cluster change significantly: the distance modulus is decreased by ~ 0.3 mag, and the derived age is increased by $\Delta T \sim 2 \times 10^9$ yr.

With our adopted modulus and reddening $[(m - M)_v = 14.0$, $E_{B-V} = 0.13]$ and $A_v/E_{B-V} = 3.2$, the true cluster distance from the Sun is 5.2 ± 0.6 kpc, placing it 1.0 kpc above the Galactic plane and 8.3 kpc from the Galactic center if $R_0 \simeq 8.5$ kpc. Even without the possible $B - V$ correction discussed above, the adopted age of 7×10^9 yr is comparable to the ages derived, through the same set of isochrones, for NGC 188 (5×10^9 yr; Twarog 1978) and Melotte 66 [$(6\text{–}7) \times 10^9$ yr; Anthony-Twarog *et al.* 1979]. NGC 6791 thus holds a legitimate claim to being the oldest known open cluster.

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