PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
96:977-980, December 1984

DDO AND *UBV* PHOTOMETRY OF RED GIANT STARS IN NGC 6791

KENNETH A. JANES°

Department of Astronomy, Boston University, 725 Commonwealth Avenue, Boston, Massachusetts 02215

Received 1984 June 6

Photoelectric DDO and *UBV* observations of red giant stars in the old open cluster NGC 6791 were used to help derive the reddening to the cluster and to find its distance and metallicity. A comparison of the DDO photometry with previous results leads to a reddening estimate of $E(B-V) = 0^{m}.10 \pm 0^{m}.03$. With this reddening, the DDO metallicity index, $\delta CN = 0.026 \pm 0.015$, corresponding approximately to [Fe/H] $= -0.08 \pm 0.07$. There is no evidence for a spread in composition on the cluster giant branch. Although the composition appears to be nearly solar, lingering uncertainty as to the reddening to the cluster and a possible systematic error in *UBV* photometry prevents a definitive statement of its properties. Additional photometry is desirable.

Key words: photometry—abundances—galactic cluster

I. Introduction

The old open cluster NGC 6791 (C1919+377; $l = 70°$, $b = 11°$) is of considerable interest since it is one of the oldest (if not the oldest) of the disk clusters. Kinman (1965), in his important study of the cluster's color-magnitude diagram, found that it is an old system with a distance modulus of $(m-M) = 13.55$ and a reddening of $E(B-V) = 0^{m}.22 \pm 0^{m}.02$. Harris and Canterna (1981) obtained additional photoelectric photometry of stars near the cluster and while they agreed with Kinman on the modulus of the cluster ($(m-M) = 13.58$), they found a lower reddening of $E(B-V) = 0^{m}.13 \pm 0^{m}.03$. They also found evidence for a radially-dependent error in Kinman's photometry. Anthony-Twarog and Twarog (1984) obtained video camera photometry of stars near the main-sequence turnoff, relying on Kinman's photometry, corrected as suggested by Harris and Canterna, to calibrate their photometry. They agreed with Kinman that a higher reddening, of the order of $E(B-V) = 0^{m}.20$ is reasonable, but they also determine a distance modulus between $13^{m}.2$ and $13^{m}.5$.

Because there is still some uncertainty as to the basic properties of the cluster and because of its considerable importance for understanding both galactic and stellar evolution, additional observations are required. This paper reports on the results of a program of DDO and *UBV* photometry of a selection of red giants in the cluster.

II. Observations

During observing runs at Kitt Peak National Observatory in September 1978 and June 1979, observations were obtained on the DDO and *UBV* photometric systems of stars in the field of the cluster, using the 1.3-meter telescope and computer-controlled photometer. Because of crowding in the field, stars were selected for observation if they could be observed with a 10-arc-second diaphragm, as determined from an examination of Kinman's (1965) Figure 1. Similarly, sky measurements were made in regions which showed no stars on the same figure. Since the limiting magnitude of the figure is about $m_v = 20$ and the faintest star observed was $m_v = 15.35$, the results should not be materially affected by uncertainties in the sky measurements. Seeing was generally good during the observing run.

The results of the photometry are shown in Table I. The *UBV* measures were obtained on one night and were transformed to the *UBV* system using standards from Landolt (1973). A total of nine stars was observed; eight of them being cluster red giants. DDO observations were also obtained of the eight red giants and transformed to the standard DDO system using standards from McClure (1976). Between one and four observations were obtained of each star. Based on the dispersion among the observations of the four stars with three or more DDO observations, the rms errors of the three DDO indices are $\pm 0^{m}.029$, $\pm 0^{m}.037$, and $\pm 0^{m}.056$ for the $C(45-48)$, $C(42-45)$, and $C(41-42)$ indices, respectively.

Harris and Canterna (1981) found evidence for system-

Table I

DDO and UBV Photometry in NGC 6791

star	C(45-48)	C(42-45)	C(41-42)	N	V	B-V	U-B
1401	1.316	1.115	0.344	4	15.35	1.36	--
2014	1.334	1.148	0.353	4	14.64	1.39	--
2051	1.360	1.176	0.283	2	14.72	1.47	--
3004	--	--	--	-	12.76	0.61	0.01
3009	1.303	1.140	0.320	1	14.73	1.39	--
3010	1.392	1.385	0.233	3	14.19	1.67	--
3012	1.324	0.982	0.005	2	14.03	1.65	1.47
3016	1.334	1.067	0.342	4	14.57	1.37	1.46
3019	1.316	1.133	0.356	2	14.69	1.34	1.56

°Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by AURA, Inc., under contract with the National Science Foundation.

atic errors in Kinman's photographic $(B-V)$ measurements, and concluded that there was probably a radial trend of errors in the photographic B magnitudes, a possibility also suggested by Kinman. Only two of the stars in Table I are in common with the Harris and Canterna data. The agreement is generally good; they find (V = 14.71, $(B-V)$ = 1.45) for star 2051 and (V = 15.26, $(B-V)$ = 1.39) for star 1401. Only the V magnitudes for star 1401 are somewhat discordant, possibly reflecting the crowding at the very center of the cluster.

The combination of the new photoelectric photometry in Table I plus the Harris and Canterna data permits a reevaluation of the possible radial error in the photographic values. Using Kinman's Figures 1 and 2, the radial distances of the stars from the cluster center were measured and plotted versus differences in the $(B-V)$ values (Janes or Harris and Canterna minus Kinman). Figure 1 shows that there is no clear correlation of radial distance with $(B-V)$ residual. At the most, there is a slight excess of negative residuals between one and two arc minutes of the cluster center. The mean difference is -0.014 with a rms difference of $0^m.08$. Although this is perhaps larger than might be expected, it does not appear to be correlated with position in the cluster.

III. Reddening and Composition

Following the procedures outlined in Janes (1975, 1977) the interstellar reddening to the cluster and the cyanogen strengths of the individual stars can be estimated, given values of the DDO indices and $(B-V)$. The results of these calculations are given in Table II; a mean reddening estimate of $E(B-V) = 0^m.09 \pm 0^m.02$ is found from the DDO photometry.

Kinman (1965) found a substantially larger value of the reddening ($E(B-V) = 0^m.22 \pm 0^m.02$) and Anthony-Twarog and Twarog (1984) found $E(B-V) = 0^m.20$, but Harris and Canterna found $E(B-V) = 0^m.13 \pm 0^m.03$, in reasonable agreement with the present value. Harris and Canterna explained the difference between their value and Kinman's as a consequence of the systematic error they saw in the photographic $(B-V)$ values, but if Figure 1 is correct, there is no systematic error.

Thus, a substantial uncertainty in the reddening remains. There is, however, a total of 26 stars either in Table I or in the Harris and Canterna data which have photoelectric $(U-B)$ and $(B-V)$ color indices; the individual reddenings to these stars and their distances can be estimated, at least approximately. Using the two-color reddening lines from Crawford and Mandwewala (1976), the stars were dereddened to either the luminosity class III two-color relation (FitzGerald 1970) or the luminosity class V line, as appropriate. In several cases, there was an ambiguity between a class V estimate or a class III estimate; the most self-consistent choice was taken in each case. (Fortunately, most of the ambiguous stars were observed spectroscopically by Kinman, so that the

Table II

Reddening and Cyanogen Strengths
Of NGC 6791 Giants

star	E(B-V)	δCN*
1401	0.07	0.054
2014	0.05	0.046
2051	0.12	-0.039
3009	0.11	0.042
3010	0.14	-0.010
3012	--	--
3016	0.14	0.016
3019	0.02	0.063
mean	0.09	0.026
s.d.	0.02	0.015

*Assuming E(B-V) = 0.10

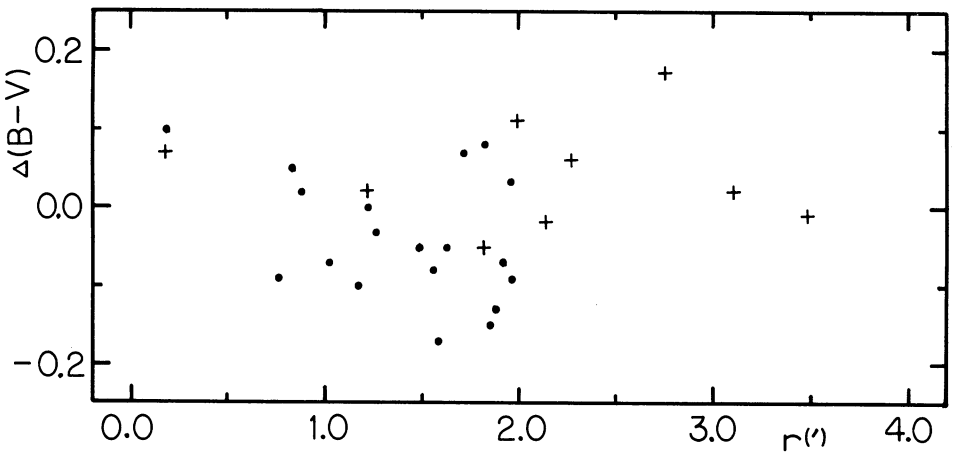

FIG. 1—Differences between $(B-V)$ values from Table I minus Kinman's values (+) and the Harris and Canterna values minus Kinman's (●), plotted as a function of radial distance from the cluster center, r (arc minutes). No definite correlation is evident.

choice could be confirmed.) Using the photometrically determined spectral classes and absolute magnitudes from Allen (1973), the distance moduli of these stars were determined.

The results of this analysis are shown in Table III and Figure 2. The reddening lines for two stars "missed" the two-color relations at spectral type F and intersected at a color indicative of early-B spectral type and very high reddening. A small error in the colors would account for this and give a more modest reddening value. Two other stars fell to the left of the two-color lines, again presumably because of photometric errors. Finally, star 3012 has DDO colors characteristic of a Population II star (see next section). For the remaining stars, Figure 2 shows the estimated distance modulus plotted against reddening. The Harris and Canterna stars are shown as filled circles, the stars from Table I as open circles, and the average DDO reddening is indicated by a filled circle with error bars at an assumed distance modulus of $13^{m}.5$.

All but three of the 23 stars in Figure 2 have reddenings less than $0^{m}.20$, and, as should be expected, the more nearby stars tend to be less reddened. Considering only those stars with distance moduli greater than 11, the average reddening of 0.12 ± 0.02 results. Thus, the DDO and *UBV* methods are in good agreement, with a value of $0^{m}.10 \pm 0^{m}.03$ being a reasonable compromise estimate.

Table III

Reddening and Distance Modulus Estimates for Photoelectric Standards

star	E(B-V)	Sp. type	$(m-M)_o$
D	0.00	A4 V	8.05
S1	0.18	B9 V	9.55
S2	0.13	G9 III	10.50
S3	0.09	F0 V	7.15
1401	0.09	K3 III	15.00
1414	0.00	K3 III	15.85
1425	---	---	---
2001	0.21	K4 III	13.20
2002	0.24	G5 III	15.50
2008	0.14	K5 III	12.65
2015	0.12	F2 V	13.00
2017	0.17	A7 V	12.20
2019	0.04	G7 V	10.00
2023	0.07	G5 V	9.75
2027	0.11	G8 V	10.20
2028	0.05	G5 V	10.15
2031	0.02	K5 V	7.70
2035	---	---	---
2038	0.21	K4 III	13.60
2044	0.10	K0 III	14.20
2048	< 0	K4 III	16.15
2051	0.19	K3 III	14.10
3004	0.10	F7 V	8.70
3012	0.64	Pop II	---
3016	0.09	K3 III	14.40
3019	< 0	K4 III	14.75

IV. Composition, Distance, and Age

The DDO cyanogen strength index, δCN, was computed for each star following the procedure in Janes (1975). Star 3012 falls outside the range of the calibration tables and has DDO colors indicative of a Population II red giant; it presumably is not a cluster member but a background halo giant. The mean value for the remaining stars (see Table II) is $\delta CN = 0.026 \pm 0.015$ which is very close to the CN strength in M67 (Janes and Smith 1984) and indicates a solar metallicity for the cluster (that is, $[Fe/H] = -0.08 \pm 0.07$).

It has become apparent that there is a wide range of surface compositions among stars within individual globular clusters (see, for example, Kraft 1979), but on the other hand, among open clusters, only a few stars with anomalous compositions are found (Smith 1982; Janes and Smith 1984). NGC 6791 as one of the oldest, if not the oldest, of the open clusters, might, therefore, be more likely to have anomalous stars than other open clusters. There is, however, no evidence for such a situation. Although the scatter in δCN values is fairly large ($\delta CN = \pm 0.042$), all of it can be accounted for by the photometric errors. Furthermore there are no individual stars with unusually large δCN values such as is seen in some of the other open clusters. NGC 6791, like the other open clusters, is essentially homogeneous in composition rather than heterogeneous like the globular clusters.

Since NGC 6791 appears to be almost identical to M67 in composition, its distance could be found by matching its color-magnitude diagram to that of M67, whose distance is known accurately (Janes 1984). Unfortunately, the uncertainty about possible systematic errors in the photometry prevent this from being done at the present time. The low value of the reddening that seems to be required by Figure 2 would result in a decrease in the estimated distance modulus and an increase in its age. It is likely, then, that NGC 6791 is the oldest known open cluster. Additional photometry will be necessary to resolve these issues.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities*, 3rd Edition (London: Athlone Press), p. 206.
Anthony-Twarog, B. J., and Twarog, B. A. 1984 (preprint, University of Kansas).
Crawford, D. L., and Mandwewala, N. 1976, *Pub. A.S.P.* 88, 917.
FitzGerald, M. P. 1970, *Astr. and Ap.* 4, 234.

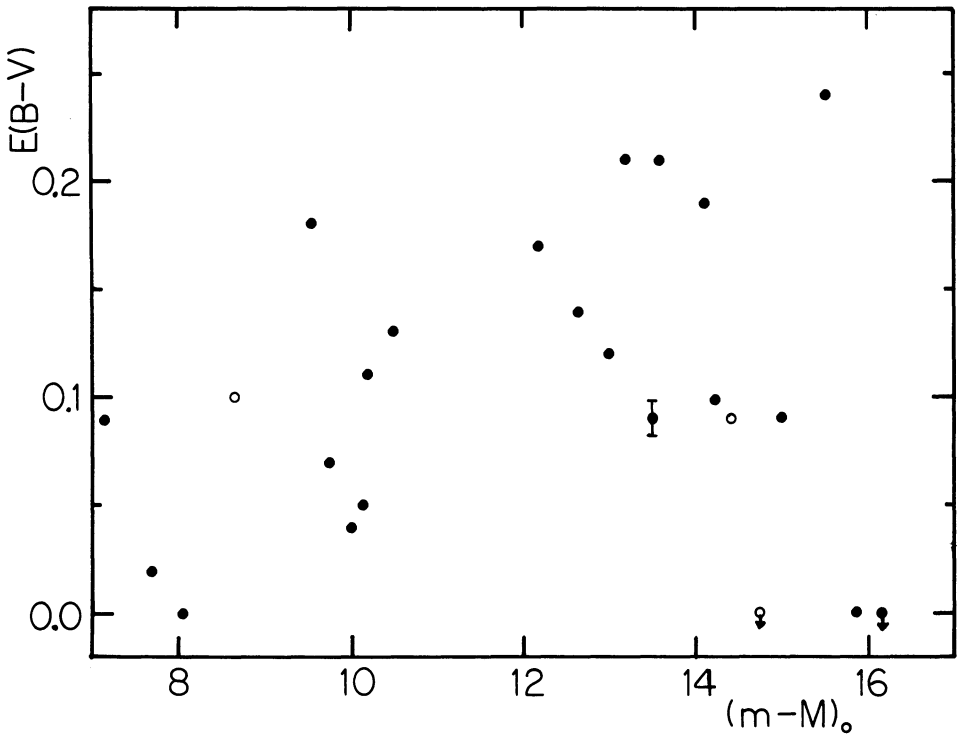

FIG. 2—Reddening estimates for photoelectrically measured stars, as a function of estimated distance modulus (see Table III). Filled circles: data from Harris and Canterna (1981). Open circles: data from Table I. Symbol with error bars: DDO mean reddening estimate at an assumed cluster distance modulus of 13.5.

Harris, W. E., and Canterna, R. 1981, *A.J.* **86**, 1332.
Janes, K. A. 1975, *Ap. J. Suppl.* **29**, 161.
Janes, K. A. 1977, *Pub. A.S.P.* **89**, 576.
Janes, K. A. 1984, in *Calibration of Fundamental Stellar Quantities, I.A.U. Symposium No. 111*, D. S. Hayes and A. G. D. Philip, eds. (Dordrecht: D. Reidel) (in press).
Janes, K. A., and Smith, G. A. 1984, *A.J.* **89**, 487.
Kinman, T. D. 1965, *Ap. J.* **142**, 655.
Kraft, R. P. 1979, *Ann. Rev. Astr. and Ap.* **17**, 309.
Landolt, A. U. 1973, *A.J.* **78**, 959.
McClure, R. D. 1976, *A.J.* **81**, 182.
Smith, G. H. 1982, *A.J.* **87**, 360.