

UBVI CCD PHOTOMETRY OF THE OLD OPEN CLUSTER NGC 1193

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ABSTRACT

We present *UBVI* photometry of the old open cluster NGC 1193. Color-magnitude diagrams (CMDs) of this cluster show a well defined main sequence and a sparse red giant branch. For the inner region of $r < 50''$, three blue straggler candidates are newly found in addition to the objects Kaluzny (1988) already found. The color-color diagrams show that the reddening value toward NGC 1193 is $E(B - V) = 0.19 \pm 0.04$. From the ultraviolet excess measurement, we derived the metallicity to be $[Fe/H] = -0.45 \pm 0.12$. A distance modulus of $(m - M)_0 = 13.3 \pm 0.15$ is obtained from zero age main sequence fitting with the empirically calibrated Hyades isochrone of Pinsonneault et al. (2004). CMD comparison with the Padova isochrones by Bertelli et al. (1994) gives an age of $\log t = 9.7 \pm 0.1$.

Key words : open clusters and associations: individual (NGC 1193) – Galaxy: stellar content

I. INTRODUCTION

Since the open clusters are composed of stars with almost the same age and metallicity, they can be used in testing the theoretical models for stellar evolution. The relatively close open clusters can be good targets for even small telescopes to get a good enough quality photometric data (e.g.: Kyeong, Byun, & Sung 2001; Kim & Sung 2003). In particular, the old open clusters are very useful in testing the stellar isochrones because they show clear evolutionary sequences.

There have been a few observational studies on NGC 1193, which has a condensed central region. One is the *BV* photometry of Kaluzny (1988) which is used to derive the basic parameters. The other is Friel & Janes (1993)'s spectroscopic study of several stars of NGC 1193 to determine its metallicity.

In this paper, we describe the *UBVI* CCD observations of the old open cluster NGC 1193, which is located at $\alpha=3^h 05^m$, $\delta=+44^\circ 23'$ (J2000). Although the bright star in the western side hamper the wide field observation, we present accurate *UBVI* photometry for this cluster and derive the basic parameters such as reddening, metallicity, distance modulus and age from the photometric data. The robust determination of reddening is significant for the estimation of distance, and subsequently age and metallicity. So, we estimate the reddening through two-color diagram method ($U - B, B - V$) and other cluster parameters

are then derived by various conventional methods.

Section II describes the observations and data reduction processes. The comparison with the previous photometric data is presented in Section III. Color-magnitude diagrams (CMDs) and blue straggler candidates are explained in Section IV. Cluster parameters such as the reddening, metallicity, distance modulus and age are derived in Section V. Section VI summarizes our results.

II. OBSERVATIONS AND DATA REDUCTION

UBVI CCD images of the open cluster NGC 1193 were obtained on a photometric night, 2006 August 30, using the 1.5m telescope (f/13.5) and SITe 1K CCD at the Observatorio Astronómico Nacional in the Siera San Pedro Mártir (OAN-SPM) in Baja California, Mexico. The pixel scale is $0''.25/\text{pixel}$ with a total field of view of $4'.3 \times 4'.3$. The gain and readout noise of the CCD camera are $1.2 e^-/\text{ADU}$ and $7.8 e^-$, respectively. The median seeing was around $1''$. Specially, in order to get the long exposures, we excluded the bright star ($V = 11.23$ mag, $K = 6.1$ mag) on the west of NGC 1193. The journal of the observation of NGC 1193 is given in Table 1.

Standard procedures using the IRAF* CCDRED

*IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatory, which are operated by the Association of Universities for Research in Astron-

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TABLE 1.
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Date	UT(Start)	Filter	$T_{\text{exp}}(\text{sec})$	Airmass
2006 August 30	11:06	<i>U</i>	600×3	1.06
	10:50	<i>B</i>	300×3	1.07
	11:38	<i>V</i>	200×3	1.04
	10:37	<i>I</i>	60×3	1.09

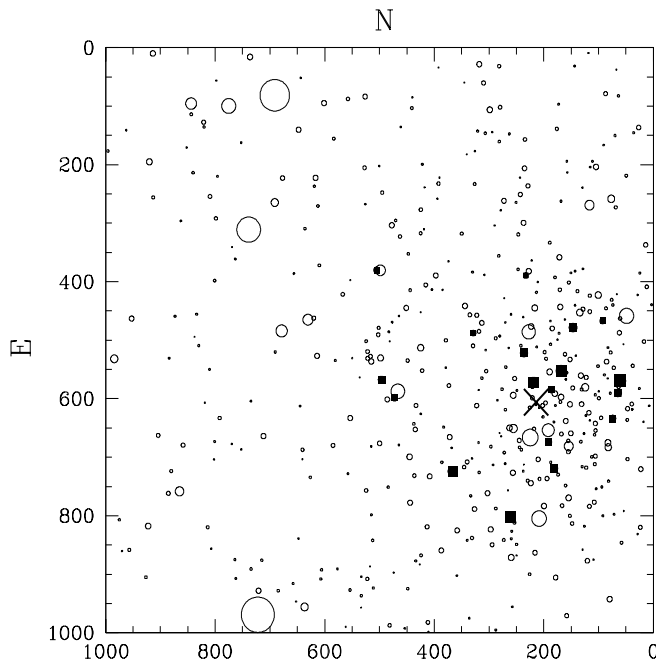


Fig. 1.—Synthetic field ($4'3 \times 4'3$) of NGC 1193 as observed in *V* frame. North is at the top and east is to the left. All the detected stars are plotted. The X- and Y-axes are in pixels and 1 pixel corresponds to $0''.25$. Circle and square sizes are proportional to the brightnesses. The large cross means the cluster center determined by Kaluzny (1988). The filled squares represent the blue straggler candidates (See the text), while their sizes are also proportional to their brightnesses.

package were followed. Object CCD frames were flattened using twilight sky flats after overscan correction and bias subtraction. For each filter, the three frames were median-combined to remove the cosmic rays and to get the high signal-to-noise ratio. Instrumental magnitudes of stars were obtained by the point-spread function (PSF) fitting packages of DAOPHOT II and ALLSTAR (Stetson 1990) and stars of different frames were matched by DAOMATCH/DAOMASTER routines (Stetson 1992). For each frame, a representative model PSF was constructed by using a number of unsaturated and relatively isolated stars. Due to the small field of view of the CCD, it was not necessary to allow the shape of the model PSF to vary quadrat-

ically with position in each frame. Finally, aperture corrections were made using the DAOGROW program (Stetson 1990), for which we used the same stars used in the PSF construction.

The observed CCD field of the cluster is shown in Fig. 1. Each star is represented by an open circle, whose size is proportional to the brightnesses. We use the value $(X_C, Y_C) = (605, 214)$ determined by Kaluzny (1988) as the center of the cluster. Of course their coordinates are converted by the transformation equation between two coordinate systems.

Additionally, we observed 14 standard stars of four Landolt (1992) regions (PG2113, SA112, SA92 \times 2). The color range of these standard stars is $-0.2 < (B - V) < 1.4$ which fully covers the color range of the stars in NGC 1193. Standard stars were observed

TABLE 2.
DERIVED STANDARDIZATION COEFFICIENTS AND ITS ERRORS

Filter	k_1	C_1	Zero point
U	0.664 ± 0.028	$+0.035 \pm 0.014$	-2.708 ± 0.009
B	0.313 ± 0.005	$+0.094 \pm 0.024$	-1.579 ± 0.019
V	0.283 ± 0.021	-0.008 ± 0.019	-1.075 ± 0.015
I	0.162 ± 0.030	$+0.039 \pm 0.020$	-1.271 ± 0.019

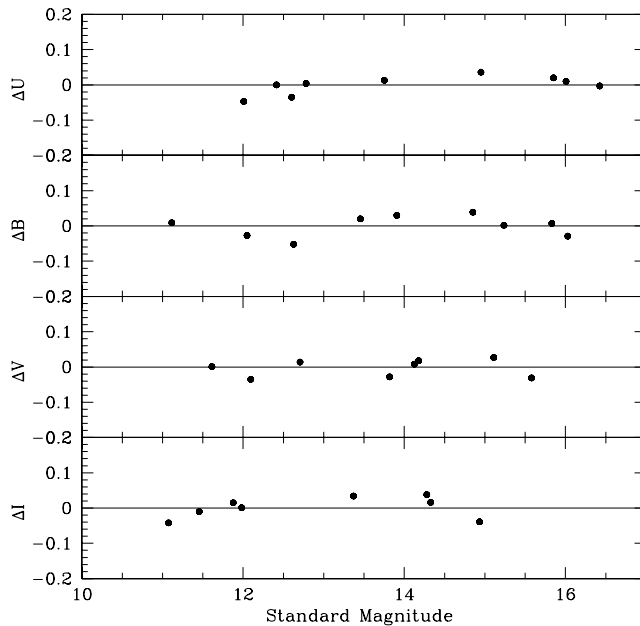


Fig. 2.—Residuals between standard and transformed magnitudes of standard stars, plotted against standard magnitudes. Δ means standard magnitude minus transformed magnitude.

at airmasses between 1.1 and 2.4.

With these standard star observations, the transformation equations between standard and instrumental magnitudes are as follows:

$$\begin{aligned}
 U &= u - k_{1U} X_U + C_U (U - B) + Z_U \\
 B &= b - k_{1B} X_B + C_B (B - V) + Z_B \\
 V &= v - k_{1V} X_V + C_V (B - V) + Z_V \\
 I &= i - k_{1I} X_I + C_I (V - I) + Z_I
 \end{aligned}$$

where small letters represent instrumental magnitudes and the capital letters indicate standard magnitudes. X is the airmass of each filter. All coefficients and its errors are derived from our own standard star observations are also given in Table 2.

Fig. 2 shows the standardization residuals for $UBVI$

filters. We inspected the particular trends like UT term but didn't find any trends in the residuals. In particular, there was no dependency on the secondary extinction coefficient in U and B band, so only the primary extinction coefficients are used in the standardization.

III. COMPARISON WITH THE PREVIOUS PHOTOMETRY

Fig. 3 shows the comparison of the photometries between this study and the BV photometry Kaluzny (1988). For the comparison, we have transformed the X- and Y-coordinates between ours and Kaluzny's using the position of several bright stars.

Fig. 3 shows that the differences of B and V magnitudes of stars with $V < 17$ between the two datasets are negligible within the standardization residuals. On the other hand, for the case of $\Delta(B - V)$ (upper panel),

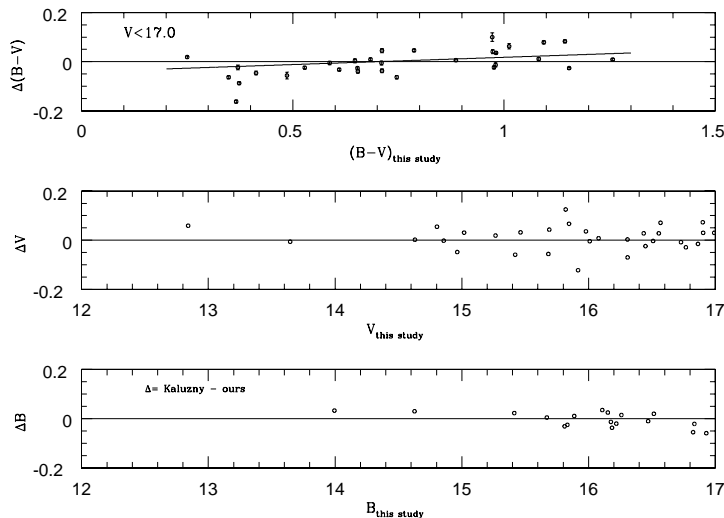


Fig. 3.—Comparison of our photometry with that of Kaluzny (1988), where Δ means Kaluzny minus this study. For the case of $\Delta(B - V)$ (*upper panel*), a linear fitting is overlaid to show the trend clearly.

a trend is shown. In particular, there are two maximum differences of $\Delta(B - V) = -0.02$ at the blue color ($B - V = 0.30$) and $\Delta(B - V) = +0.040$ at the red color ($B - V = 1.3$). This trend means that these color differences make the bluer (than the turn-off) stars bluer and make the red giant stars redder in Kaluzny (1988)’s CMDs. Therefore, the age of NGC 1193 derived by Kaluzny (1988) using the morphological age index (MAI) method or isochrone fitting method appears to be somewhat young.

The photometric data of Kaluzny (1988) are slightly undersampled (with the relatively large pixel scale of $0''.86/\text{px}$ compared to the seeing of $\sim 1''.5$), and the systematic errors of their data are as large as 0.06 mag which is resulted from the uncertainties in their standard transformations and those in their aperture corrections. Nevertheless, the source of this trend in $\Delta(B - V)$ is not clear.

IV. COLOR MAGNITUDE DIAGRAMS AND BLUE STRAGGLER CANDIDATES

331 stars are detected in all the *UBVI* optical bands. This small number of stars is mainly due to the scarcity of detected stars in the *U* filter. In Fig. 4 we present CMDs in various passbands. But the CMDs of NGC 1193 show the distinguishable features usually seen in the CMDs of old open clusters (e.g., NGC 2243, NGC 188, etc): well defined main sequence (MS), sub giant branch and red giant branch.

Ahumada & Lapasset (1995) define the blue straggler region as $0.0 < (B - V)_0 < 0.8$ and $1.0 < M_V < 5.0$, located above the zero age main sequence (ZAMS) line. They pointed out that the blue stragglers seems to be concentrated in the central region of the clusters

and the degree of concentration is stronger in the case of old open clusters. Adopting the distance to NGC 1193 derived in this study (see §V), $(m - M)_0 = 13.32$, M_V range for the blue stragglers in NGC 1193 becomes 14.3 – 18.3. We identified the 15 blue straggler candidates already known in literatures[†] including the five stars discovered by Kaluzny (1988) and identified three new objects by applying the Kaluzny (1988) and Ahumada & Lapasset (1995)’s criterion. Fig. 5 shows these blue straggler candidates in CMDs. The *UBVI* magnitudes of these blue stragglers are given in Table 3.

V. PHYSICAL PARAMETERS OF NGC 1193

(a) Reddening

Reddening is an important basic parameter of a star clusters, since it can significantly affect the determination of other physical parameters. Several reddening values for NGC 1193 are reported. Kaluzny (1988) estimated the reddening to be $E(B - V) = 0.12$ by isochrone fitting. Noriega-Mendoza & Ruelas-Mayorga (1997) determined the reddening and metallicity values simultaneously from the $(V, B - V)$ CMD of Kaluzny (1988), which are $E(B - V) = 0.24$ and $[\text{Fe}/\text{H}] = -0.54$, respectively. If deeper *U*-band observations are made, the straightforward method for the reddening determination would be possible using the two-color diagram.

Fig. 6 shows the $(U - B, B - V)$ two-color diagram. The reddening value is estimated, shifting the intrinsic relation of the dwarf stars given by Schmidt-Kaler (1982) along the reddening line of $E(U - B) =$

[†]WEBDA (<http://www.univie.ac.at/webda/>) report 16 blue straggler candidates in NGC 1193, while one is outside of the field of view of our CCD frame.

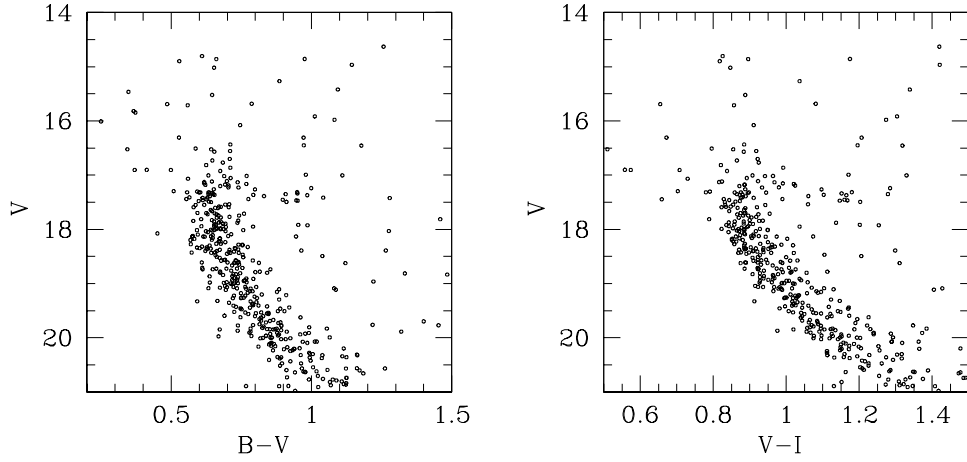


Fig. 4.—Color-magnitude diagrams of NGC 1193.

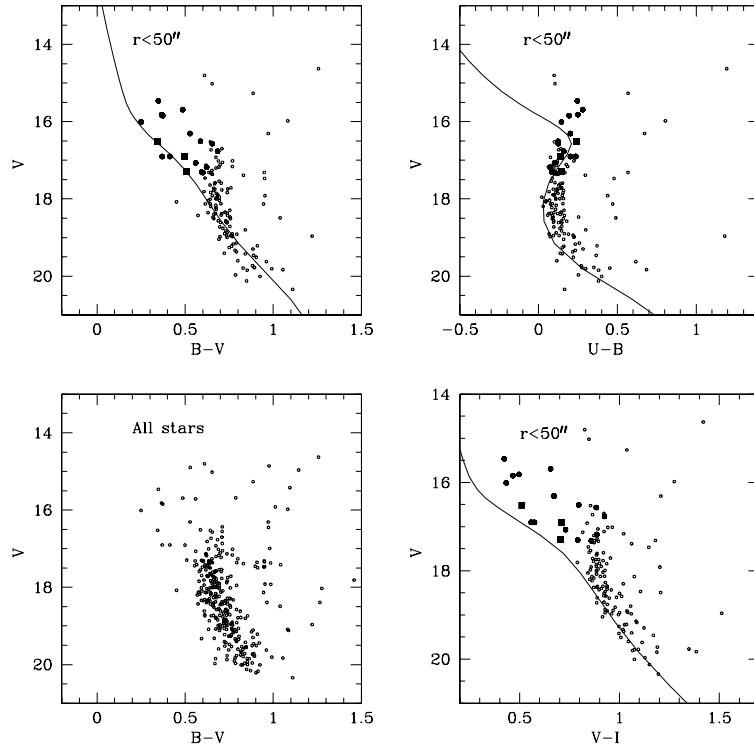


Fig. 5.—Blue straggler candidates of NGC 1193 are denoted as larger filled symbols on the optical-band CMDs. Filled squares are three blue straggler candidates newly found in this study and filled circles are the candidates already known in the literatures, while small open circles are all other stars. Solid lines denote the ZAMS line by Bertelli et al.(1994) with $[Fe/H] = -0.61$, and $\log t = 7.8$.

TABLE 3.
MAGNITUDES OF BLUE STRAGGLER CANDIDATES IN NGC 1193

X	Y	V	B - V	U - B	V - I	Comments [†]
380.052	505.504	17.179	0.622	0.074	0.886	1
567.285	496.319	16.768	0.684	0.160	0.925	1
598.199	472.508	16.890	0.370	0.202	0.574	1
487.763	328.471	17.320	0.600	0.104	0.859	1
389.350	232.755	17.303	0.593	0.085	0.791	1
718.860	181.164	16.568	0.654	0.125	0.884	1
723.588	366.707	16.009	0.250	0.145	0.433	1
801.635	260.945	15.819	0.366	0.250	0.497	1
521.599	236.161	16.509	0.587	0.124	0.796	1
571.651	218.347	15.846	0.373	0.194	0.466	1
584.537	185.907	17.067	0.560	0.101	0.730	1
552.273	168.404	15.690	0.486	0.280	0.655	1
478.316	146.595	16.307	0.528	0.202	0.672	1
633.556	74.153	16.901	0.413	0.236	0.558	1
569.258	60.735	15.463	0.348	0.246	0.423	1
589.976	64.463	16.523	0.344	0.237	0.510	2
673.547	191.393	16.906	0.499	0.136	0.708	2
466.978	92.772	17.295	0.509	0.144	0.703	2

[†] : 1: Identified by Kaluzny(1988), 2: Identified by this paper

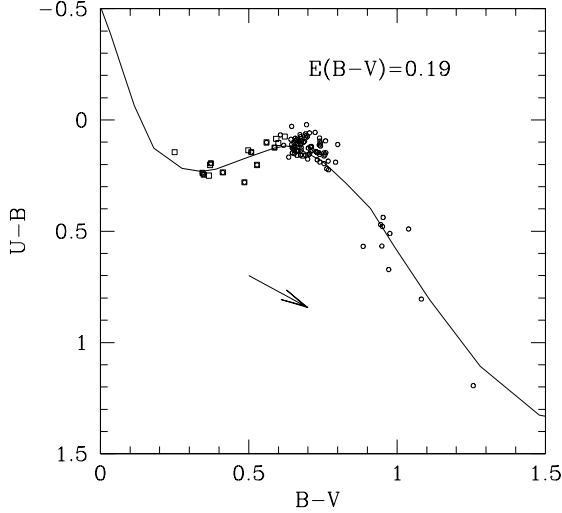


Fig. 6.— $(U - B, B - V)$ two-color diagram for the stars in the inner cluster region ($r < 50''$). The solid lines represent the ZAMS line given by Schmidt-Kaler (1982) reddened by $E(B - V) = 0.19$. The reddening vector with $E(B - V) = 0.20$ is also shown. Open squares denote the blue straggler star candidates.

$0.72 E(B - V)$. In the fitting, only the stars with U, B , and V photometric errors smaller than 0.03 and $r < 50''$ are used. Specially, since the dwarf line moves along the solid line in the diagram, the most sensitive regions to the change of the reddening value are $0.2 < (B - V)_0 < 0.6$, which means A-F stars. So, we used the stars within the blue straggler region. Finally, $E(B - V) = 0.19 \pm 0.04$ is derived from the fitting.

(b) Metallicity

Three values reported in the literature for the metallicity of NGC 1193: using photometric data, Kaluzny (1988) and Noriega-Mendoza & Ruelas-Mayorga (1997) estimated it to be -0.29 and -0.54 , respectively. Friel & Janes (1993) determined $[\text{Fe}/\text{H}] = -0.50$ for NGC 1193 using the spectroscopic data of four stars, which value is less secure as they pointed out already.

The metallicity of an open cluster can be estimated from the difference of the distance moduli measured in $(V, V - I)$ CMD and $(V, B - V)$ CMD, because the distance modulus depends on metallicity. Pinsonneault et al. (2004) illustrated the sensitivity of the MS luminosity to metallicity in three planes of $(V, B - V)$, $(V, V - I)$, and $(V, V - K)$. Among these three planes, the metallicity sensitivity to the distance modulus is less steep at $V - I$. Pinsonneault et al. (2004) also constructed empirically calibrated Hyades isochrone. By using these characteristics, we can approximately estimate the metallicity of NGC 1193. The difference of the distance moduli measured in $(V, V - I)$ and $(V, B - V)$ CMDs after fitting their empirically cali-

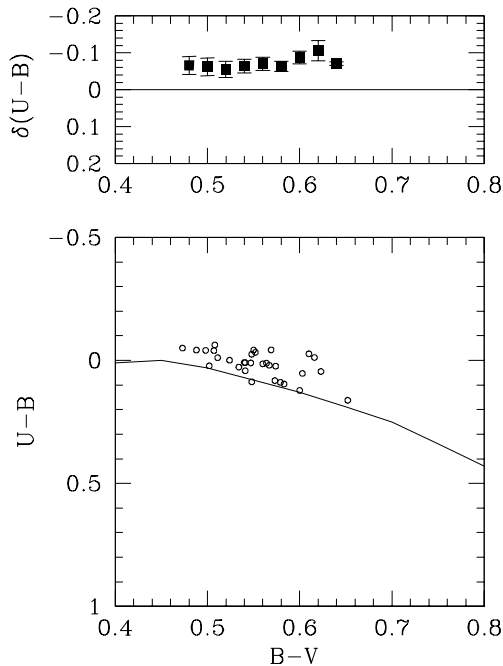


Fig. 7.—Determination of metallicity from the UV excess. Only the stars with magnitude errors < 0.04 mag, $V < 18.5$ mag and $r < 50''$ are used. The solid line of lower panel means the Hyades fiducial line given by Sandage (1969). The upper panel is for the residuals between Hyades fiducial line and the stars of NGC 1193.

brated isochrones to the two CMDs is 0.4 mag, which means the metallicity of NGC 1193 $[\text{Fe}/\text{H}] \sim -0.4$.

More directly, using the reddening value obtained above, the metallicity of NGC 1193 is estimated using the ultraviolet (UV) excess in the $(U - B, B - V)$ diagram. In Fig. 7, the Hyades fiducial line given by Sandage (1969) and the dwarf stars with $V < 18.5$ mag and U, B, V photometric errors smaller than 0.04 mag are plotted. The UV excess is measured to be $\delta(U - B)_{B-V=0.6} = -0.087 \pm 0.017$. The metallicity from the UV excess can be calibrated by Cameron (1985)'s relation, $[\text{Fe}/\text{H}] = 0.08 - 4.93\delta - 13.51\delta^2$. The metallicity of NGC 1193 is thus obtained to be $[\text{Fe}/\text{H}] = -0.45 \pm 0.12$.

(c) Distance Modulus

The distance modulus of NGC 1193 can be measured by using the ZAMS fitting. In this case, a priori known metallicity of the cluster is needed since the distance modulus is systematically shifted by the metallicity of the cluster. Pinsonneault et al. (2004) presented empirically calibrated isochrone of Hyades cluster ($[\text{Fe}/\text{H}] = +0.13$) for the ZAMS fitting. They also gave the amount of correction (ΔM_V) as a function of $[\text{Fe}/\text{H}]$ in several CMD planes in the computation of the cluster distances. Specially, the M_V at fixed $B - V$

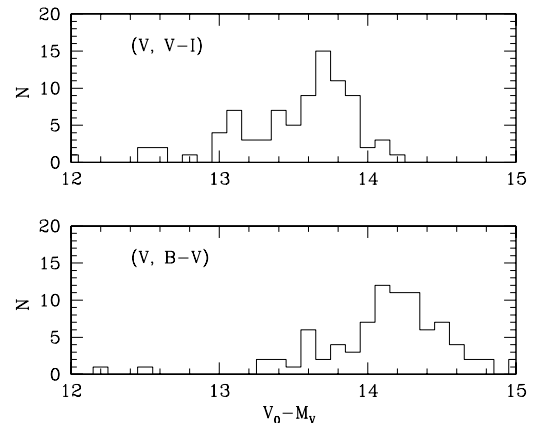


Fig. 8.—Distribution of distance moduli of NGC 1193 with a bin size of 0.1 mag, in $(V, V - I)$ and $(V, B - V)$ CMDs. The stars between $18 < V < 20$ and $r < 50''$ are used. The most probable value of $(m - M)_0$ from the $(V, V - I)$ and $(V, B - V)$ CMDs are 13.7 and 14.1, respectively.

has an average slope of 1.42 mag (0.72 mag in $V - I$ CMD) per dex in metallicity.

Fig. 8 shows the fitting results. In $(V, B - V)$ CMD, the most probable distance modulus is 14.10 ± 0.13 and in $(V, V - I)$ CMD, the value is 13.72 ± 0.15 . Adopting Pinsonneault et al. (2004)'s metallicity sensitivity of isochrone mentioned above and considering $[\text{Fe}/\text{H}] = -0.45$ of NGC 1193 obtained above, the distance modulus of NGC 1193 converge into 13.32 ± 0.15 .

(d) Age and Isochrone Fitting

The age of a star cluster can be determined by comparing the observed CMDs (especially, BVI passbands) with theoretical isochrones. Fig. 9 shows the best matched Padova theoretical isochrone (Bertelli et al. 1994) using the physical parameters obtained above ($E(B - V) = 0.19$, $[\text{Fe}/\text{H}] = -0.45$), which gives the cluster age to be $\log t = 9.7 \pm 0.1$. For the near-IR magnitudes, we sampled the JHK_s data from the 2MASS photometry database (available at <http://irsa.ipac.caltech.edu/applications/Gator/>) and matched them with our BVI magnitude set through coordinate transformation.

In most cases of CMDs in Fig. 9, the isochrone follows the stellar sequence very well. The 2MASS photometry is not deep enough to clearly show the MS turn-off point in the near-IR bands.

VI. SUMMARY

The goal of this paper is to present the $UBVI$ photometric data and derive the basic physical parameters of the old open cluster NGC 1193. The CMDs of NGC 1193 show the characteristics of the old open clusters, such as the sub giant branch and red giant branch.

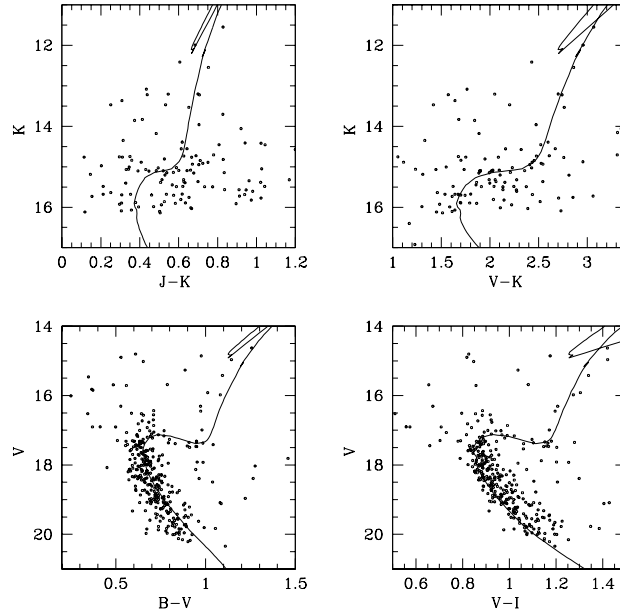


Fig. 9.—Padova isochrone fittings for NGC 1193 for various CMDs. The solid lines represent the Padova isochrones for $[\text{Fe}/\text{H}] = -0.45$ and $\log t = 9.7$.

The blue straggler candidates inside of $r = 50''$ from the center is identified and their magnitudes are also measured.

Using color-color diagrams, the reddening value is determined to be $E(B - V) = 0.19 \pm 0.04$, which is somewhat larger than the Kaluzny (1988)'s value 0.12. The metallicity of NGC 1193 determined by using the UV excess method is $[\text{Fe}/\text{H}] = -0.45 \pm 0.12$, which is in the middle of the two previously values in the literature, -0.50 (spectroscopic data of four stars, Friel & Janes 1993), -0.29 (BV isochrone fitting, Kaluzny 1998). Our derived distance modulus is $(m - M)_0 = 13.3 \pm 0.15$. This value is well matched with the Kaluzny's value of 13.4 within its error. Finally, from the Padova isochrone fitting to the observed CMDs, the age is estimated to be $\log t = 9.7 \pm 0.1$. The summary of the fundamental parameters for NGC 1193 is presented in Table 4.

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TABLE 4.
BASIC INFORMATION OF NGC 1193

Parameter	Information	Reference
R.A. (J2000)	03 ^h 05 ^m 56 ^s	SIMBAD
Decl. (J2000)	+44° 22' 59''	SIMBAD
l, b	146.°81, -12.°16	SIMBAD
Reddening, $E(B - V)$	0.19 ± 0.04 mag	This study
Distance modulus, $(m - M)_0$	13.3 ± 0.15 mag	This study
Distance, d	4.6 ± 0.3 kpc	This study
Metallicity, [Fe/H]	-0.45 ± 0.12	This study
Age, t	5.0 ± 1.2 Gyr (log t = 9.7 ± 0.1)	This study

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