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BOAO PHOTOMETRIC SURVEY OF GALACTIC OPEN CLUSTERS. I. BERKELEY 14, COLLINDER 74, BIURAKAN 9, and NGC 2355

H. B. ANN[1], M. G. LEE[2], M. Y. CHUN[3], S.-L. KIM[3], Y.-B. JEON[3], B.-G. PARK[3], I.-S. YUK[3], H. SUNG[4], AND S. H. LEE[1]

[1]Department of Earth Sciences, Pusan National University, Pusan 609-735
[2]Department of Astronomy, Seoul National University, Seoul 151-742
[3]Bohyunsan Optical Astronomy Observatory, Yeongcheon 770-820
[4]Department of Earth Science, Kyungpook National University, Taegu 702-742
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ABSTRACT

Open clusters are useful tools to investigate the structure and evolution of the Galactic disk. We have started a long-term project to obtain $UBVI$ CCD photometry of open clusters which were little studied before, using the Doyak 1.8 m telescope of Bohyunsan Optical Astronomy Observatory in Korea. The primary goals of this project are (1) to make a catalog of $UBVI$ photometry of open clusters, (2) to make an atlas of open clusters, and (3) to survey and monitor variable stars in open clusters. Here we describe this project and report the first results based on preliminary analysis of the data on four open clusters in the survey sample: Be 14, Cr 74, Biu 9, and NGC 2355. Isochrone fitting of the color-magnitude diagrams of the clusters shows that all of them are intermediate age to old (0.3 – 1.6 Gyrs) open clusters with moderate metallicity.

Key Words : Open clusters and associations : general – Open clusters and associations : individual (Berkeley 14, Collinder 74, Biurakan 9, and NGC 2355) – photometry : abundances

I. INTRODUCTION

Open clusters are ideal targets with which to investigate the structure and evolution of the Galactic disk as well as the formation and evolution of stars and stellar clusters. Current understanding of the galactic disk has been greatly benefited by the studies of open clusters. Young clusters have been used for investigation of spiral arm structures (Becker & Fenkart 1970; Janes & Adler 1982; Feinstein 1994) and for the study of the star formation processes in the galactic disk (Tarrab 1982; Sagar et al. 1988; Phelps & Janes 1993). Old clusters have provided critical informations about the formation and early evolution of the galactic disk (Janes & Phelps 1994; Friel 1995; Wee & Lee 1996; Twarog, Ashman & Anthony-Twarog 1997; Lee 1997; Park & Lee 1999).

There are about 1,200 known open clusters in the Catalogue of Open Cluster Data (Lynga 1987; hereafter COCD). In spite of many investigations including recent CCD photometries of open clusters, little is known except for the position, angular diameter, and the number of member stars for the majority of the clusters. To date only one third of them have been studied in detail to derive the basic physical parameters such as distance, reddening, age, and metallicity. More than half of them have the Trumpler richness class m and r, while most of the unstudied clusters are classified as p. This shows that the present knowledge of open clusters are heavily biased by the properties of rich open clusters (Ann 1997).

To understand the nature of clusters and the structure of galactic disk as a whole, we have initiated a comprehensive photometric survey of open clusters which were little studied before, using the Doyak 1.8m telescope which was newly installed at Bohyunsan Optical Astronomy Observatory (BOAO) in Korea. The primary goal of the present survey is to obtain accurate color-magnitude diagrams (CMDs) of the clusters with $UBVI$ CCD photometry and to derive the basic physical parameters of the clusters. Secondly we will make a BOAO Photometric Atlas of Open Clusters which will serve as a useful tool to study the structure of the Galactic disk and which will be used as a guide to study the individual open clusters in detail. Along with these main goals, the present survey is designed also to survey and monitor variable stars in open clusters. The primary targets of variable star survey in clusters are short period variable stars such as δ Scuti, γDor, SPB, and β Cephei type stars.

In this paper we describe this survey project in overall and present the first results of the photometric survey on four open clusters made during the observing run of 1998. A brief description of this project was given by Chun (1998). In Section II, we describe the project of the photometric survey of Galactic open clusters. The first results of the present survey are given in Section III and summary and discussion are given in the last section.

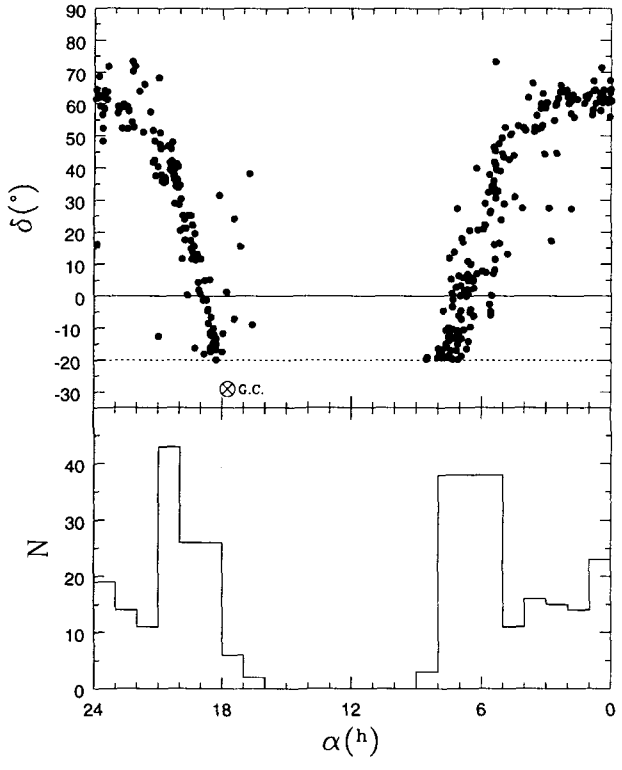

Fig. 1.— Spatial distribution (upper panel) and histogram (lower panel) of the open clusters for the survey project. The open circle with cross in the upper panel represents the position of the Galactic center.

II. THE PHOTOMETRIC SURVEY OF OPEN CLUSTERS

(a) The Survey Sample

First we have selected 343 candidate clusters for the BOAO photometric survey from COCD by the declination criterion of $\delta > -20°$, which are observable at the BOAO. Our sample consists of about half of the clusters with unknown distance and age in COCD. Fig. 1 shows the distribution and histogram of the program clusters. There is almost no cluster in the right ascension of $8^h < \alpha < 16^h$ and most of the program clusters can be observed in the fall and winter season when the weather condition is best at the BOAO. We list the Trumpler class of the program clusters in Table 1. As shown in Table 1, about two thirds of the clusters are classified as richness class p and about a third as m. The clusters of richness class r is less than 5 % of the sample. With regard to the concentration class, about two thirds of the clusters are classified as III or IV. This shows that most of the unstudied clusters are poor clusters with weak central concentration.

Table 1. Data of candidate clusters for the BOAO photometric survey

concentration\richness	p	m	r	total
I	17	18	6	41
II	38	32	4	74
III	51	32	4	95
IV	95	22	1	118
total	201	112	15	328
no data				15

(b) Observational Strategy

The target clusters will be observed using the SITe 2048×2048 CCD camera with Johnson-Cousins $UBVI$ filters attached to the F/8 cassegrain focus of the Doyak 1.8m telescope. The pixel size of the CCD is 24 μm that corresponds to 0.″34 on the sky. The size of the covered field of view is $\sim$ 11.′8 $\times$ 11.′8. The gain and readout noise of the CCD are 1.8 electrons/ADU and 7 electrons, respectively. When the nights are photometric, standard stars (e.g. Landolt 1992) will be observed for calibration of the photometry as well as the target clusters. When the nights are non-photometric, variable stars in the target clusters will be surveyed and monitored.

III. THE FIRST RESULTS

(a) Observations

60 open clusters among the total sample were observed during the fall observing runs in 1998. We report here the first results of this project, based on preliminary analysis of the data of four open clusters in the sample: Be 14, Cr 4, Biu 9, and NGC 2355. These clusters were observed on the photometric night of 1998, Dec. 16. We have obtained images of the central 11.′8 $\times$ 11.′8 regions of each cluster with a pair of exposures, long and short, for each filter. Along with the object observations, we have observed a sufficient number of twilight flat fields before and after the observations of the objects. We observed Landolt standard stars in SA 98 (Landolt 1992) together with standard stars in M67 (Montgomery, Marschall & Janes 1993) and NGC 7790 (Christian 1985) several times during the observations to transform the instrumental magnitudes to the standard system.

Table 2 shows the observational log of the four clusters. Greyscale maps of the V-band images of the clusters taken with long exposures are displayed in Fig. 2.

(b) Data Reduction

We have followed the standard technique of CCD reductions using IRAF/CCDRED for basic reductions of the obtained images. This includes the subtraction of bias frames with overscan correction, trimming, and

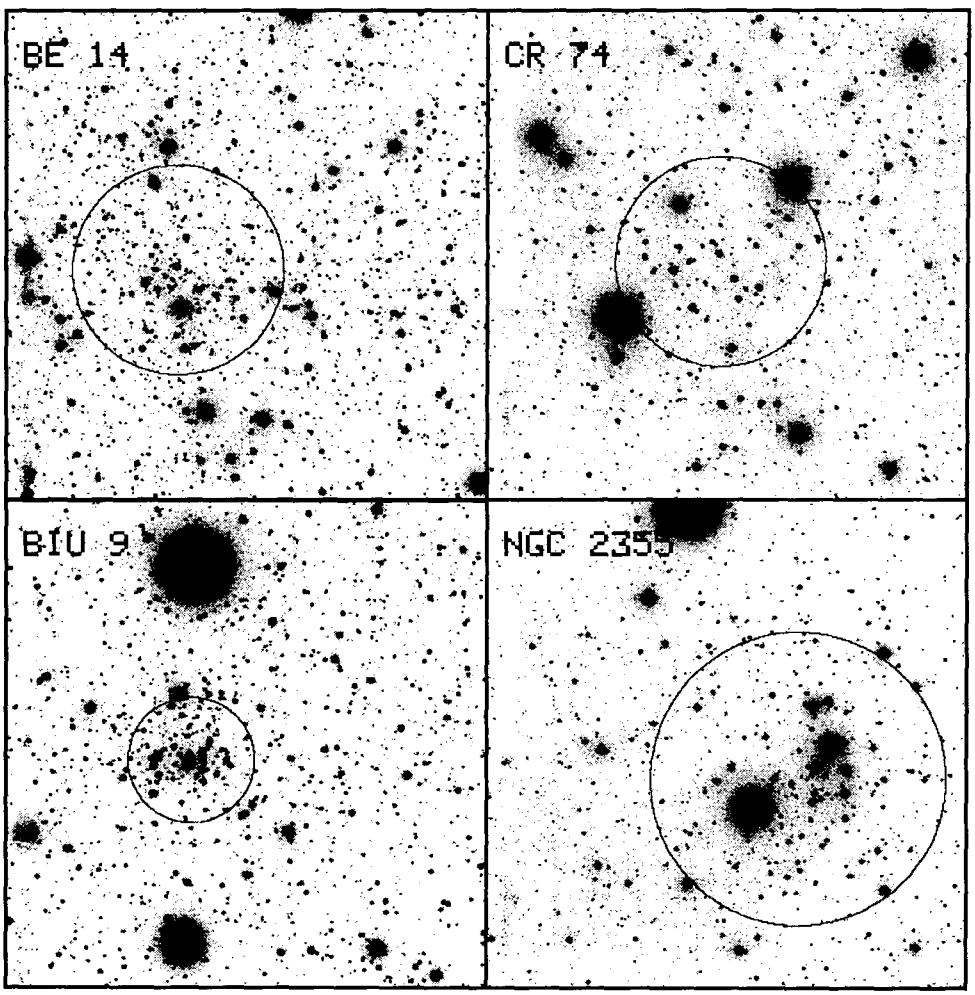

Fig. 2.— Greyscale maps of the V CCD images of four open clusters: Be 14, Cr 74, Biu 9, and NGC 2355. The size of the field of view is $11'.5 \times 11'.5$. North is up and east is to the left. The circles represent the cluster angular diameters given in the COCD (Lynga 1987).

Table 2. Journal of observations

Cluster	Filter	T_{exp}
Be 14	U	900 s
	B	$200s \times 3$, 20 s
	V	$100s \times 3$, 10 s
	I	$50s \times 3$, 5 s
Cr 74	U	$200s \times 3$
Biu 9	B	$200s \times 3$, 20 s
NGC 2355	V	$100s \times 3$, 10 s
	I	$50s \times 3$, 5 s

flatfielding. For stellar photometry, IRAF/DAOPHOT were used to estimate the instrumental magnitudes of the cluster stars and standard stars, respectively. We applied aperture corrections to the instrumental magnitudes of cluster stars obtained from PSF fitting, using the instrumental magnitudes obtained with an aperture radius of $7''$.

The transformation of the instrumental magnitudes to the standard system was made by two steps. First, we applied the atmospheric extinction correction by the primary extinction coefficient derived from the multiple observations of M 67 and NGC 7790. Second, we transform the extinction corrected instrumental magnitudes to the magnitudes in the standard system, by the following transformation equations

$$U = u - z_u - k_u X - a_u(U - B)$$

$$B = b - z_b - k_b X - a_b(B - V)$$

$$V = v - z_v - k_v X - a_v(B - V)$$

$$I = i - z_i - k_i X - a_i(V - I)$$

where the capital letters stand for the magnitudes in the standard system, the lower case letters for the instrumental magnitudes, and X for the airmass. The

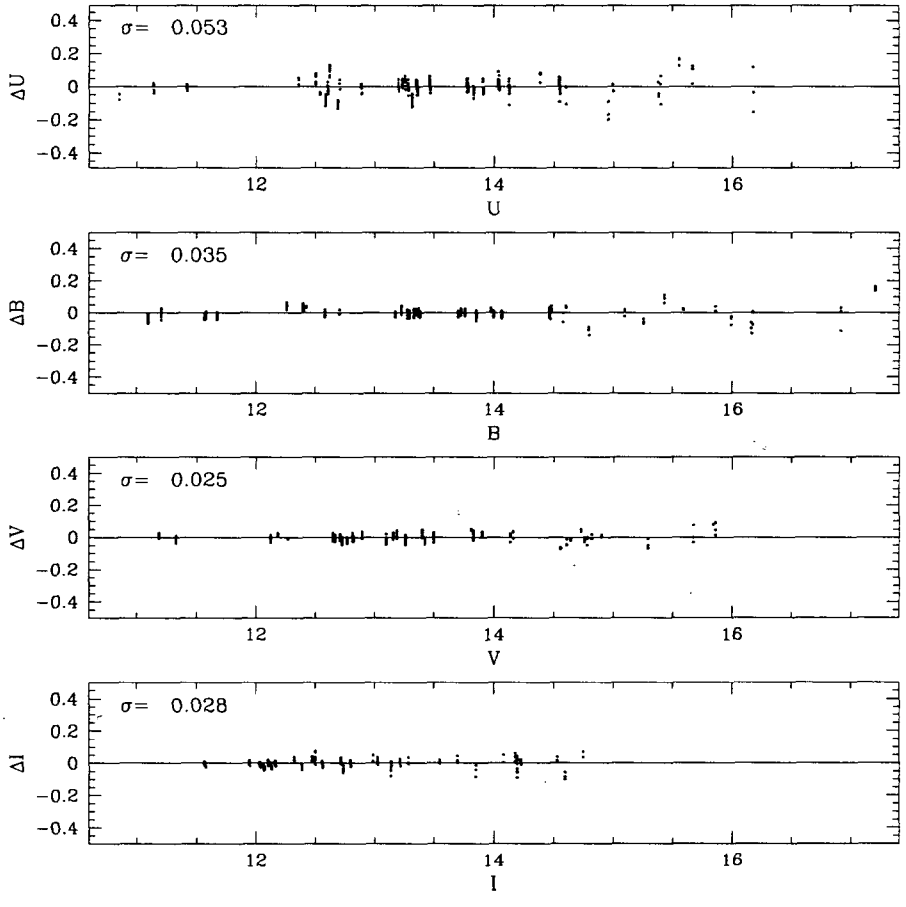

Fig. 3.— Residuals (standard magnitudes minus transformed magnitudes) of the standard transformation for U, B, V and I.

Table 3. Extinction Coefficients and Transformation Coefficients

Filter	k	z	a	σ(fit)
U	-0.520	-4.811	0.347	0.053
B	-0.306	-1.919	0.186	0.035
V	-0.144	-1.624	-0.024	0.025
I	-0.066	-1.707	0.037	0.028

transformation coefficients z's and a's are determined by a least-squares fit of the instrumental magnitudes of the Landolt standard stars to the magnitudes in the standard system (Landolt 1992), after correction of the atmospheric extinction. Fig. 3 displays the residuals of the calibration of the present photometry, showing that the standard deviations of the calibration are less than 0.04 mag except for U which has a standard deviation of 0.05 mag. Table 3 lists the resulting coefficients for the transformation equations.

(c) Results

We have obtained the color-magnitude and color-color diagrams of Be 14, Cr 74, Biu 9, and NGC 2355 from the present photometry. All stars in the cluster images, with photometric errors less than 0.1 mag, are used to construct the cluster CMDs but only the

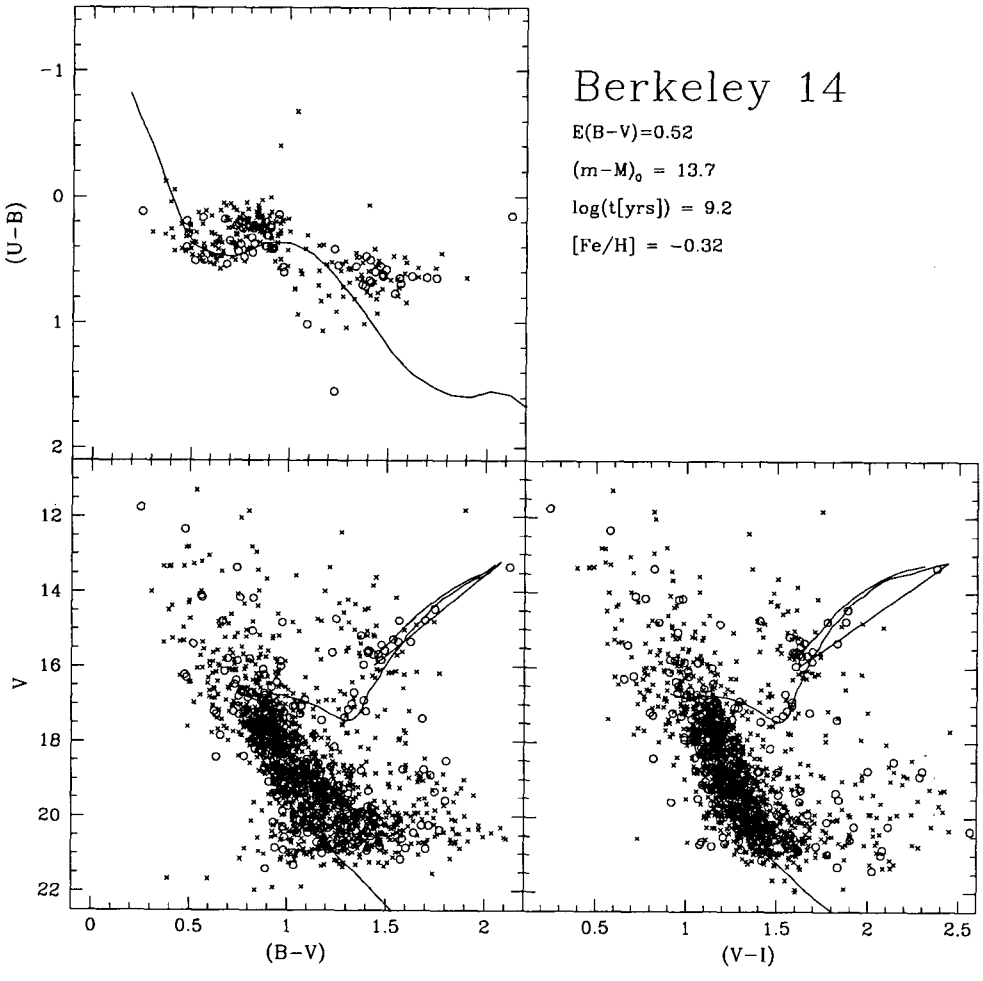

Fig. 4.— Color-color diagram and color-magnitude diagrams of the measured stars in Be 14. Open circles represent the stars within the cluster diameter and crosses indicate the stars outside the cluster diameter. The solid line in the color-color diagram represents the ZAMS, and the lines in the CMDs represent the Padova theoretical isochrones with log(t[yrs]) = 9.2 and [Fe/H] = −0.32 dex, shifted according to the reddening and distance of Be 14.

stars with $V < 17$ are used for the color-color diagrams. The distance, reddening, age, and metallicity of the observed clusters are determined simultaneously by fitting the Padova isochrones (Bertelli et al. 1994) to the observed stellar distributions in CMDs of the clusters. We have also obtained independent estimates of the reddenings of the clusters from the observed stellar distributions in $(U-B)$-$(B-V)$ diagrams (Schmidt-Kaler 1982), which are used as a guide to isochrone fitting. We assumed a slope of $E(B-V)/E(U-B) = 0.72$, the total to selective extinction ratio R_V=3.0, and $E(V-I) = 1.25E(B-V)$ for the analysis of the data in this study (Johnson & Morgan 1953; Dean, Warren & Cousins 1978). In the isochrone fittings, we put the most weight on the stars in the turnoff regions and giant branches, especially the stars located within the cluster diameter, represented by open circles in Figs. 4 – 7. For the main sequence region, we tried to fit the lower envelope of the main sequence, considering the photometric errors.

i) Berkeley 14

Be 14 is located in the constellation Auriga ($\alpha_{2000} = 5^h0^m$, $\delta_{2000} = 43°28.'6$, $l = 162°52'$, $b = 0°43'$). The angular diameter of the cluster in COCD is 5′. The Trumpler class of the cluster is $III1m$, showing that it is detachable from field stars but has little concentration. However, it is difficult to isolate the cluster from the background field stars due to heavy contamination of field stars in the galactic plane. Fig. 4 shows the color-color diagram with fiducial ZAMS lines to-

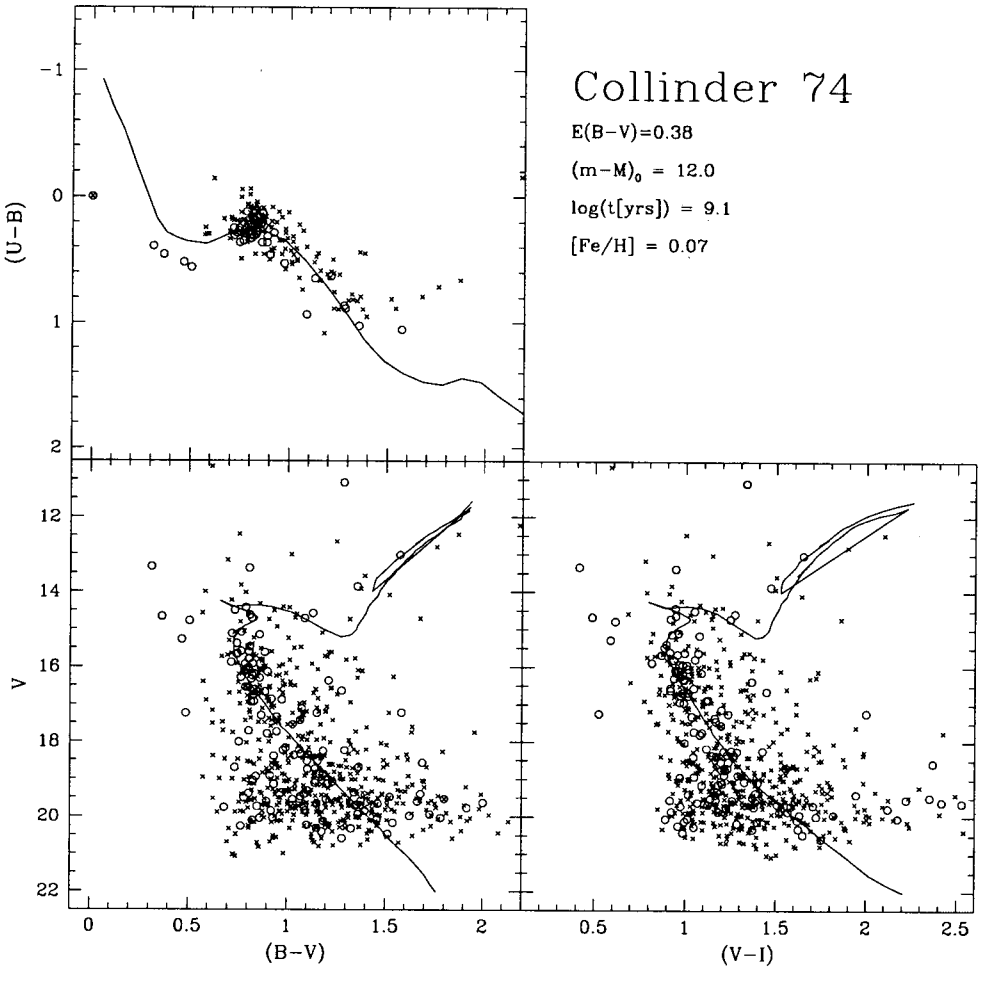

Fig. 5.— Color-color diagram and color-magnitude diagrams of the measured stars in Cr 74. Open circles represent the stars within the cluster diameter and crosses indicate the stars outside the cluster diameter. The solid line in the color-color diagram represents the ZAMS, and the lines in the CMDs represent the Padova theoretical isochrones with log(t[Gyrs]) = 9.1 and [Fe/H] = +0.07 dex, shifted according to the reddening and distance of Cr 74.

gether and the CMDs of the measured stars in Be 14. It is seen in the CMDs that Be 14 shows a typical feature of old open clusters: a red giant branch with well-distinguishable red giant clump at $V \approx 15.5$ mag. A main sequence turnoff of Be 14 is seen at $V \approx 17$ mag. The best fitting isochrone of log(t[yrs]) = 9.2 and [Fe/H] = −0.32 dex, with reddening of $E(B-V) = 0.52$ and a true distance modulus of $(m-M)_0 = 13.7$ is overlayed on the CMDs. As shown in Fig. 4, the fittings of the isochrone to the stellar distributions in the CMDs of Be 14 are quite good, especially for the stellar distributions in the base of giant branch and the clump stars located within the cluster diameter, designated as open circles.

ii) Collinder 74

Cr 74 is located in the west of α Ori ($\alpha_{2000} = 5^h48'30''$, $\delta_{2000} = 7°24.'0$, $l = 198°59'$, $b = -10°24'$), in the direction of the anticenter of our Galaxy. The angular diameter of Cr 74 given in the COCD is about 5′, and the Trumpler class of this cluster is $III1m$. As inferred from the same Trumpler class as Be 14, the appearance of the cluster is similar to that of Be 14, but it is more difficult to isolate Cr 74 from the field stars than Be 14.

Isochrone fittings in Fig. 5 show a pretty good match of the isochrone of log(t[yrs])=9.1 and [Fe/H] = +0.07 dex with $E(B-V) = 0.38$ and $(m-M)_0 = 12.0$ to the observed stellar distributions of Cr 74. Although the lower main sequence is heavily contaminated by field

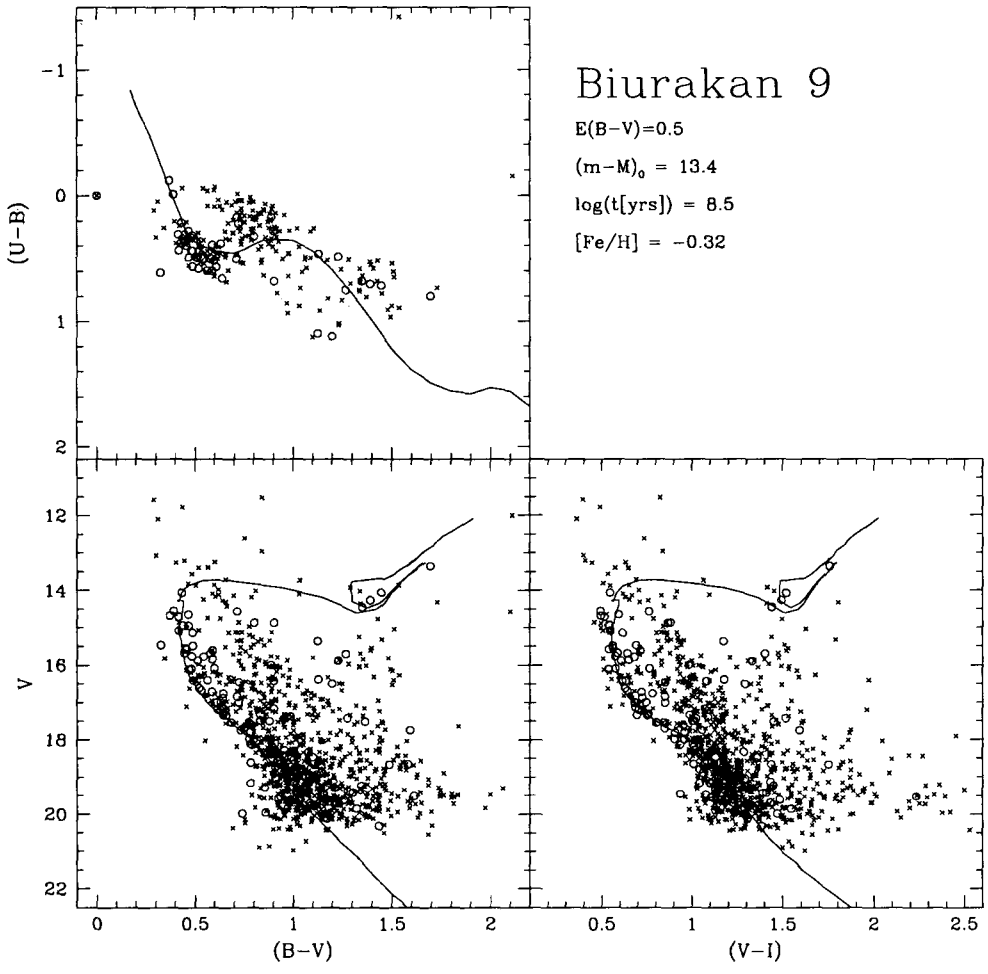

Fig. 6.— Color-color diagram and color-magnitude diagrams of the measured stars in Biu 9. Open circles represent the stars within the cluster diameter and crosses indicate the stars outside the cluster diameter. The solid line in the color-color diagram represents the ZAMS, and the lines in the CMDs represent the Padova theoretical isochrones with log(t[Gyrs]) = 8.5 and [Fe/H] = −0.32 dex, shifted according to the reddening and distance of Biu 9.

stars, the good match of the isochrone to the stars in the turnoff region is remarkable.

iii) Biurakan 9

Biu 9 is located in the constellation Monoceros (α_{2000} = $6^h57'43''$, δ_{2000} = 3°13.′0, l = 210°48′, b = 2°53′). As shown in Fig. 2, it is easy to identify the cluster because of the slight concentration of stars toward the center with moderate number of stars. This property is consistent with the Trumpler class of $II2m$.

Fig. 6 shows the color-color diagrams and CMDs of Biu 9 with ZAMS fitting and isochrone fittings, respectively. The field stars contaminate the photometric diagrams heavily, but they are well separated in the color-color diagrams by two groups of stars: one group with blue $B-V$ colors and red $U-B$ colors, and the other with red $B-V$ colors and blue $U-B$ colors. We have derived the physical parameters of Biu 9 from the stars with blue $B-V$ colors, because the stars with red $B-V$ colors could not be matched by the fiducial ZAMS and isochrones, simultaneously. As shown in Fig. 6, the isochrone of log(t[yrs]) = 8.5 and [Fe/H] = −0.32 dex with $E(B-V)$ = 0.50 and $(V-M_V)_0$ = 13.4 well matches the stellar distributions in CMDs of Biu 9.

iv) NGC 2355

NGC 2355 is located in the constellation of Gemini

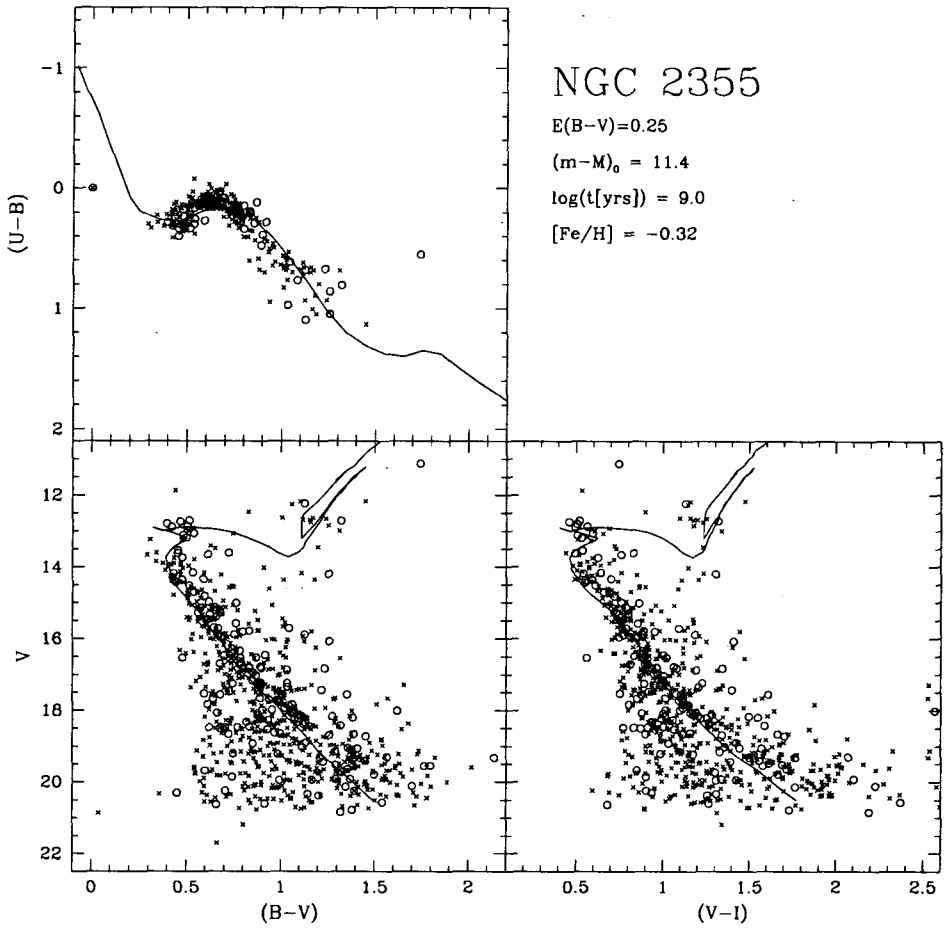

Fig. 7.— Color-color diagram and color-magnitude diagrams of the measured stars in NGC 2355. Open circles represent the stars within the cluster diameter and crosses indicate the stars outside the cluster diameter. The solid line in the color-color diagram represents the ZAMS, and the lines in the CMDs represent the Padova theoretical isochrones with log(t[yrs]) = 9.0 and [Fe/H] = −0.32 dex, shifted according to the reddening and distance of NGC 2355. It appears that there is some error in the calibration of the $(V - I)$ colors of the measured stars in NGC 2355. Therefore the $(V - I)$ colors of the stars have been shifted arbitrarily by 0.1 to match the isochrone.

($\alpha_{2000} = 7^h16'55''$, $\delta_{2000} = 13°46.'7$, $l = 203°22'$, $b = 11°48'$). The Trumpler class of the cluster, $II2m$ is the same as that of Biu 9 but it shows weaker central concentration than Biu 9. However, it is not difficult to identify the cluster in the CCD images.

The color-color diagram and CMDs of NGC 2355 in Fig. 7 show a well defined main sequence with a large number of field stars. We applied isochrone fittings to derive the physical parameters of NGC 2355, together with the ZAMS fitting for reddening determination. As shown in Fig. 6, the isochrone of log(t[yrs]) = 9.0 and [Fe/H] = −0.32 dex with $E(B - V)$=0.25 and $(m - M)_0 = 11.4$ is well fitted to the main sequence of NGC 2355 as well as the stars in the turnoff region in V–$(B-V)$ diagram. However, there are some discrepancies between the isochrone and the stellar distributions in V–$(V - I)$ diagram. The reason for this mismatch is unclear but it might be caused by large photometric errors due to non-photometric condition at the time of observing NGC 2355. There seems to be a main sequence gap similar to that observed in NGC 2420 (Anthony-Twarog et al. 1990; Lee, Ann, & Kang 1998). The present estimate of the age of NGC 2355 is similar to that obtained by Colegrove et al. (1993).

IV. DISCUSSION AND SUMMARY

We have described the BOAO photometric survey of galactic open clusters. The primary goal of this survey is to derive physical parameters of the target open clus-

Table 4. Basic parameters of the four open clusters

Cluster	Angular Diameter	$E(B-V)$	$(m-M)_0$	R_{GC}	[Fe/H]	Age
Be 14	5′	0.52 ± 0.04	13.7 ± 0.2	13.8 kpc	−0.32 dex	1.6 ± 0.2 Gyrs
Cr 74	5′	0.38 ± 0.04	12.0 ± 0.2	10.9 kpc	+0.07 dex	1.3 ± 0.2 Gyrs
Biu 9	3′	0.50 ± 0.04	13.4 ± 0.2	12.8 kpc	−0.32 dex	0.3 ± 0.04 Gyrs
NGC 2355	7′	0.25 ± 0.02	11.4 ± 0.1	10.3 kpc	−0.32 dex	1.0 ± 0.1 Gyrs

ters using *UBVI* CCD photometry obtained at 1.8m telescope of the BOAO. The total sample of the BOAO photomeric survey consists of 343 open clusters with unknown distance and ages, selected from COCD by the declination criteria of $\delta > -20°$. We present the first results of this survey, based on preliminary analysis of the data on four open clusters: Be 14, Cr 74, Biu 9, and NGC 2355, which are subsamples of 60 open clusters that were observed in the first year of the survey.

We have determined the distance, reddening, age, and metallicity of the four clusters by isochrone fittings of the CMDs which are obtained from *UBVI* CCD photometry. Table 4 lists a summary of the basic parameters of the four clusters determined in this study. The reddening estimates of the clusters by matching the fiducial ZAMS to the stellar distributions in color-color diagrams of the clusters are used as constraints for the isochrone fittings. The resulting physical parameters of the clusters show that all of the present sample of clusters are intermediate age to old clusters with moderate metallicity.

The CMDs of the four clusters show morphological properties of intermediate age open clusters, which are characterized by a continuous sequence of stars from main sequence to giant branch with a clump of stars in the red giant branch except for the youngest open cluster Biu 9. The oldest cluster Be 14 shows a large number of clump stars with well developed giant branch. The well defined turnoff regions of Cr 74, Biu 9, and NGC 2355 allow us reliable isochrone fitting. The main sequence gap near turnoff, which is a characteristics of intermediate age open clusters, seems to be present in NGC 2355 at $M_V \sim 2$ mag. Because the gap is thought to be caused by the hydrogen core exhaustion phase (McClure,Forrester, & Gibson 1974; Demarque, Sarajedini, & Guo 1994), we expect a similar gap in Cr 74 whose age is similar to that of NGC 2355. Fig. 5 shows that there is a hint of the gap near the main sequence turnoff of Cr 74, but the presence of the gap in Cr 74 is not as evident as that of NGC 2355.

The analysis of the present photometry indicates that our photometry is accurate enough to derive the physical parameters of open clusters observed on photometric nights at the BOAO. When this survey is completed, the resulting data will serve as a fundamental database for investigation of the structure and evolution of the galactic disk as well as a guide for the study of individual open clusters in detail.

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