2MASS NEAR-IR COLOR-MAGNITUDE DIAGRAM OF THE OLD OPEN CLUSTER KING 11

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ABSTRACT

We study near-infrared properties of the old open cluster King 11, based on the 2MASS photometric data. We determine the location of the red giant clump(RGC) in the $(K, J - K)$ color-magnitude diagram and derive the distance modulus of King 11 to be $(m - M)_0 = 12.50 \pm 0.10$ using the mean K magnitude of RGC. From the red giant branch slope – $[\text{Fe}/\text{H}]$ relation we obtain the metallicity of this cluster, $[\text{Fe}/\text{H}] = -0.17 \pm 0.07$. The age and interstellar reddening of this cluster are estimated to be $\log t = 9.48 \pm 0.05$, $E(B - V) = 0.90 \pm 0.03$, by applying Padova isochrone fits to the data.

Key words : open clusters and associations: individual (King 11) — Galaxy: stellar content

1. INTRODUCTION

Open clusters (OCs) were formed from the same giant molecular cloud, and the member stars are of similar age and chemical composition. Old OCs (age $\gtrsim 1$ Gyr), especially, are important in studying the formation and early evolution of the Galactic disk, since they contain information on the environment of its early evolutionary phase, for example, the Galacto-centric metallicity distribution (Friel 1995; Friel et al. 2002; Chen, Hou, & Wang 2003; Kim 2006). However, the fraction of photometrically well-studied clusters among all the OCs ($N = 2140$; Dias et al. 2002, version 3.1, 2010 November 24) is quite small : three parameters (distances, reddenings, and ages) are known only for 58.5% ($N = 1259$) of OCs and four parameters (distances, reddenings, ages, and abundances) are known even only for 8.5% ($N = 187$) of OCs. It is, therefore, necessary to increase the number of clusters with the physical parameters to study both the clusters themselves and the Galactic disk that contains the clusters inside.

Although there have been various observational works on the old OCs (e.g., Tosi et al. 2004; Kim, Kyeong, & Sung 2009), studying the clusters at low Galactic latitudes is not easy due to heavy interstellar extinction. Near-infrared (near-IR) wavelength is advantageous in this regard, since the interstellar extinction is much less in the optical wavelength ($A_K = 0.11A_V$). Two Micron All Sky Survey (2MASS)¹ project (Skrutskie 2006) imaging data, therefore, obtained in the near-IR wavebands for 99.998% of the celestial sphere are useful to study objects in or near the Galactic plane. King 11 ($\alpha(\text{J2000}) = 23^{\text{h}} 47^{\text{m}} 48^{\text{s}}$,

Fig. 1.— 2MASS K_s image of King 11. The field of view is about $26' \times 26'$. North is up and east is to the left. The inner and outer circles represent $r = 5'$ and $10'$, respectively. The symbol '+' means the center of King 11 given by 2MASS data sampler.

$\delta(\text{J2000}) = 68^\circ 37' 58.8''$, $l = 117.163^\circ$, $b = 6.477^\circ$) is located at low Galactic latitude and naturally have large reddening values ($E(B - V) \gtrsim 1$). In this paper, we have used the 2MASS near-IR imaging data for photometric study of this high extinction, old OC.

Thus far, the highly reddened old OC King 11 has been studied only in the visible wavelength. Kaluzny (1989) found this cluster relatively old (~ 5 Gyr) and highly reddened using BV CCD photometry with

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¹ available at <http://www.ipac.caltech.edu/2mass/releases/allsky>

Fig. 2.— $(K_s, J - K_s)$ (left panel) and $(J, J - H)$ (right panel) CMDs for the stars in the field ($r < 5'$ and $r < 10'$) of King 11 using 2MASS photometry. Error bars represent the mean errors of the magnitudes and colors. The reddening vector with $A_V = 2.0$ is also shown.

KPNO 0.9 m telescope. Aparicio et al. (1991) determined the metallicity to be solar from its optical color-magnitude diagram (CMD) morphology but was not able to get consistent values of metallicity from several independent methods. Recently, Tosi et al. (2007) calculated the ranges of physical parameters of this cluster by employing BVI CCD photometry with Telescopio Nazionale Galileo (TNG) and together with the synthetic CMD method: $Z = 0.01$, age = $3.5 - 4.75$ Gyr, $(m - M)_0 = 11.67 - 11.75$, and $E(B - V) = 1.03 - 1.06$. On the other hand, Friel et al. (2002) independently obtained $[\text{Fe}/\text{H}] = -0.27 \pm 0.15$ by analyzing low resolution spectra of 16 bright member stars in King 11.

In the present work, we made use of JHK_s photometry of the 2MASS data in order to derive the physical parameters of this cluster. 2MASS data are obtained for the entire sky in three near-IR bands, J ($1.25 \mu\text{m}$), H ($1.65 \mu\text{m}$) and K_s ² ($2.16 \mu\text{m}$). Two dedicated 1.3 m Cassegrain equatorial telescopes in the northern hemisphere (Mount Hopkins, Arizona) and in the southern hemisphere (Cerro Tololo, Chile) are used; both are equipped with three NICMOS3 arrays capable of simultaneous observations in the three near-IR bands

²The K_s band (“K-short”) is described by, e.g., Persson et al. (1998).

(Nikolaev et al. 2000).

This paper is arranged as follows. Section 2 describes the near-IR CMD of King 11. In Section 3, we derive physical parameters of this old star cluster by analyzing the red giant branch (RGB) and RGC stars. The isochrone fitting method is applied in order to estimate its reddening value and age. Finally, we summarize the results in Section 4.

2. COLOR-MAGNITUDE DIAGRAM

Fig. 1 depicts 2MASS K_s -band CCD image of King 11 with an equatorial coordinate grid. The JHK_s photometric data within the circular regions ($r < 5'$, $r < 10'$) of King 11 are extracted. Fig. 2 demonstrates ($K_s, J - K_s$) and ($J, J - H$) CMDs representing these regions. Each diagram clearly indicates the existence of RGC stars at $K_s \sim 11.0$, $J - K_s \sim 1.0$ along with a well defined red giant branch. In addition, the subgiant branch is clearly seen near $J \sim 14.9$, $J - H \sim 0.7$ in ($J, J - H$) CMD.

Several stars can be seen in the brighter and bluer region than main-sequence turn-off ($K_s=14$, $J - K_s=0.75$). These stars are the blue straggler (BS) candidates. In order to verify the possibility, we have statistically eliminated the field star contamination by using two nearby control fields. Two control fields are chosen in the region of one degree away in the Galactic longitude from the center of King 11. We count the number of stars for a given magnitude and color range in two CMDs, then remove this number of stars in the King 11 CMD randomly. In Fig. 3, we show the results. Several BS candidates remain in the region after the elimination of field star contamination and the detailed membership studies are needed to make a robust BS list.

However, we cannot simply account for the scatters found in RGB and the RGC based only on the magnitude errors ($\Delta K_s=0.03$, $\Delta(J - K_s)=0.02$ at $K=11$). We also note that the clump is distributed along the reddening vector in the CMD. In the optical CMD (Aparicio et al. 1991; Tosi et al. 2007), one can easily recognize that RGC is tilted along the reddening vector; Apraicio et al (1991) found that King 11 has two distinct groups of stars with different reddening values. Hence, we may conclude that the width of the red giant sequence within $r < 10'$ and the tilted placement of RGC in the ($J, J - H$) diagram suggests that there exists differential reddening within the cluster.

In this paper, we converted JHK_s magnitudes of 2MASS photometric system to Bessell & Brett (1988)'s applying the equation provided by Grocholski & Sarajedini (2002) as follows:

$$\begin{aligned} (J - K_{BB}) &= [(J - K_s) - \\ &\quad - (-0.011 \pm 0.005)] / (0.972 \pm 0.006) \\ K_{BB} &= [K_s - (-0.044 \pm 0.003)] \\ &\quad - (0.000 \pm 0.005)(J - K_{BB}). \end{aligned}$$

Fig. 3.— Statistical elimination of field star contamination. (a) Initial CMD for the stars in the $r < 5'$ field of King 11. (b) and (c) are CMDs for the stars in the control fields 1 and 2 ($r < 5'$). (d) and (e) are the cleaned CMDs of King 11 using the control fields 1 and 2, respectively.

3. PHYSICAL PARAMETERS

3.1 Distance

There have been debates on the idea that helium burning RGC stars are standard candles because the magnitude depends on age and metallicity. However, the RGC magnitude has two big advantages: (1) The RGC magnitude can be measured with high accuracy because the RGC stars are bright enough to be visible even with a large distance. (2) K (RGC) magnitude is not sensitive to the age and metallicity of a cluster than I (RGC) magnitude (Sarajedini 1999; Grocholski & Sarajedini 2002). Alves (2000) and Grocholski & Sarajedini (2002) derived the RGC mean magnitude $\langle M_K(\text{RGC}) \rangle = -1.62$ based on solar neighborhood RGC stars with Hipparcos parallaxes and 2MASS open cluster data, respectively.

We determined the RGC mean magnitude of King 11 to be $m_K = 11.20 \pm 0.10$ (dispersion of Gaussian function), as shown in Fig. 4. Then we calculated the distance modulus $(m - M)_0 = 12.50 \pm 0.10$ adopting

Fig. 4.— $(K, J-K)$ CMD and the histogram of the RGC stars with a bin size of 0.1 mag. The solid box in left panel indicate the location of RGC. The fitted Gaussian function in right panel is marked by the solid line.

Fig. 5.— Dereddened CMD of King 11 with the fitted points (solid circles) and the solid line representing the least-square fit to the RGB star of King 11.

the mean magnitude of $\langle M_K \rangle = -1.62$ (Alves 2000; Grocholski & Sarajedini 2002), $E(B-V) = 0.90$ from Section 3.3 and the interstellar reddening law ($R_V = 3.1$, $A_K = 0.11A_V$) of Rieke & Lebofsky (1985).

3.2 Metallicity

In the case of a star cluster having well-defined red giant sequence, the RGB slope is regarded as very useful indicator of metal abundance. More than a decade ago, Kuchinski et al. (1995) characterized the RGB

Fig. 6.— Isochrone fits to $(K, J-K)$ CMD of King 11. The thick line represents the best fitted Bertelli et al. (1994) model isochrone with $\log t = 9.48$, $E(B-V) = 0.9$, $[Fe/H] = -0.17$ and $(m-M)_0 = 12.50$. Two thin isochrone lines with $\log t = 9.43$ and $\log t = 9.48$ are also shown for comparison.

slope- $[Fe/H]$ relation for the Galactic globular clusters — as the metallicity of a cluster increases, the slope becomes shallower. Years later, Tiede et al. (1997) calibrated the same type of relation for open clusters in the Milky Way. Kyeong & Byun (2001) revised the relation for old open cluster with more cluster samples.

In the present analysis, we limited the giant branch stars with absolute magnitudes in $M_K < -1.9$. In consequence, this criteria excludes the RGC stars with magnitude $M_K \approx -1.6$. The RGB slope is defined as $\Delta(J-K)/\Delta K$ in $(K, J-K)$ CMD. We performed least square fits to the selected RGB stars and iterated the process with 2σ rejection. The resulting best fit is shown in Fig. 5. Even if both the reddening and the distance moduli contain significant errors, the derived RGB slope is hardly affected by these errors. It is because such errors will shift the location of a RGB either horizontally and vertically without changing the slope of the sequence.

The derived RGB slope is -0.103 ± 0.004 (fitting error). We calculate the metallicity $[Fe/H] = -0.17 \pm 0.07$ dex for King 11 with this newly obtained RGB slope and the equation of Kyeong & Byun (2001) as following:

$$[Fe/H] = -17.2(\pm 0.23) \text{ RGB slope} - 1.95(\pm 0.02).$$

The metallicity error is calculated from the slope error propagation. Our metallicity of King 11 based on near-IR RGB slope is lower than that of Aparicio et al.

Table 1. Basic Parameters of King 11

Parameter	Value	Reference
$E(B - V)$	1.0 [†]	Aparicio et al. (1991)
	1.03 $\sim$ 1.06	Tosi et al. (2007)
	0.90 $\pm$ 0.03	This study
$(m - M)_0$	15.3(not reddening corrected)	Kaluzny (1988)
	11.9 [†]	Aparicio et al. (1991)
	11.67 $\sim$ 11.75	Tosi et al. (2007)
	12.50 $\pm$ 0.10	This study
$[Fe/H]$	$\sim$ 0.0 [†]	Aparicio et al. (1991)
	-0.27 $\pm$ 0.15	Friel et al. (2002)
	-0.29	Tosi et al. (2007)
	-0.17 $\pm$ 0.07	This study
Age	5 Gyr	Kaluzny (1989)
	5 Gyr	Aparicio et al. (1991)
	6.3 Gyr	Phelps et al. (1994)
	5.46 Gyr	Salaris et al. (2004)
	3.5 $\sim$ 4.75 Gyr	Tosi et al. (2007)
	3.0 Gyr $\pm$ 0.36	This study

[†] : The values of Aparicio et al. (1991) derived from their CMD fiducial sequence matching method using the open clusters of King 2, NGC 188, and M67 are presented.

(1991) ($[Fe/H] \approx 0.0$), however it is consistent with the results of the previous studies within its error.

3.3 Reddening, age and isochrone fitting

We simultaneously determined $E(B - V)$ and age of the cluster by theoretical isochrone fitting; $E(B - V)$ was obtained by fitting RGB sequence, which is less sensitive to age change, while the age, by fitting the section between the main sequence turn-off (MSTO) and the subgiant branch that is strongly dependent on age. At present work, $E(B - V)$ and age of King 11 are estimated as in the following; $\log t = 9.48 \pm 0.05$ ($t = 3.0 \pm 0.36$ Gyr), $E(B - V) = 0.90 \pm 0.03$ as can be seen from Fig. 6. Our age is rather lower than those obtained by the previous studies, i.e. Kaluzny (1989) and Aparicio et al. (1991) (5 Gyr), Salaris et al. (2004) (6.3 Gyr). These parameters confirm that King 11 is an old open cluster with high extinction in the Milky Way.

4. SUMMARY

The aim of the present study is to derive physical parameters of the highly reddened, old Galactic open cluster King 11 based on the new method and the 2MASS $JHKs$ photometry. While the CMDs of the large area ($r < 10'$) exhibit a relatively broad red giant sequence with an inclined red clump in the $(J, J - H)$ CMD, the $(K, J - K)$ CMDs within $r < 5'$ illustrate the well defined RGB- as well as the RGC sequences. With the mean K magnitude of the RGC stars, we calculated the distance modulus of $(m - M)_0 = 12.50 \pm 0.10$. We also derived the metal abundance as $[Fe/H] = -0.17 \pm 0.07$ using the RGB slope - $[Fe/H]$

relation. By applying the Padova isochrone fits to the 2MASS near-IR CMDs, we estimated the age and reddening value of King 11 as $\log t = 9.48 \pm 0.05$ ($t = 3.0 \pm 0.36$ Gyr), $E(B - V) = 0.90 \pm 0.03$, respectively. Our values are arranged in Table 1.

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