

NEAR-INFRARED PHOTOMETRIC STUDY OF THE GALACTIC OPEN CLUSTERS NGC 1641 AND NGC 2394 BASED ON 2MASS DATA

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ABSTRACT

We present JHK_S near-infrared CCD photometric study for the Galactic open clusters NGC 1641 and NGC 2394. These clusters have never been studied before, and we provide, for the first time, the cluster parameters; reddening, distance, metallicity and age. NGC 1641 is an old open cluster with age 1.6 ± 0.2 Gyr, metallicity $[\text{Fe}/\text{H}] = 0.0 \pm 0.2$ dex, distance modulus $(m - M)_0 = 10.4 \pm 0.3$ mag ($d = 1.2 \pm 0.2$ kpc), and reddening $E(B - V) = 0.10 \pm 0.05$ mag. The parameters for the other old open cluster NGC 2394 are estimated to be age $= 1.1 \pm 0.2$ Gyr, $[\text{Fe}/\text{H}] = 0.0 \pm 0.2$ dex, $(m - M)_0 = 9.1 \pm 0.4$ mag ($d = 660 \pm 120$ pc), and $E(B - V) = 0.05 \pm 0.10$ mag. The metallicities and distance values for these two old open clusters are consistent with the relation between the metallicities and the Galactocentric distances of other old open clusters. We find the metallicity gradient of 53 old open clusters including NGC 1641 and NGC 2394 to be $\Delta[\text{Fe}/\text{H}]/\Delta R_{gc} = -0.067 \pm 0.009$ dex kpc^{-1} .

Key words : open clusters and associations: individual (NGC 1641 and NGC 2394) – Galaxy: disk – Galaxy: stellar content – Galaxy: structure – Hertzsprung-Russell diagram

I. INTRODUCTION

The Milky Way Galaxy has more than 1800 known open star clusters and most of these clusters reside in the Galactic disk, while Piskunov et al. (2006) estimate that the total number of open clusters (OCs) in the Galactic disk to be of order of 10^5 at present. OCs, therefore, are very important tools to study the formation and evolution of the Galactic disk and the star clusters themselves, and the stellar evolution. The fundamental physical parameters of open clusters, such as distance, interstellar reddening, chemical composition, age and metallicity, are necessary for the study of the clusters and the Galactic disk. The Galactic (radial and vertical) abundance gradient also can be studied by open clusters (Hou, Prantzos, & Boissier 2000; Chen, Hou, & Wang 2003; Kim & Sung 2003; Kim et al. 2005).

Despite the large number of open clusters in the Galaxy, much of them were discovered quite recently. While the Lyngå (1987) "Catalog of Open Cluster Data" (COCD) lists about 1200 clusters, recent discoveries of new open clusters including Dias et al. (2002, <http://www.astro.iag.usp.br/~wilton/>, version 2.7, 2006 October 27, 1759 clusters), Bica, Dutra, & Barbuy (2003a), Dutra et al. (2003), Bica et al. (2003b), Alessi, Moitinho, & Dias (2003), Borissova et al. (2003), Bica, Bonatto, & Dutra (2004), Kharchenko et al. (2005b), Mercer et al. (2005) and Kronberger et al. (2006) make the number of Galactic open clusters well over 1800. Very recently, Froebrich, Scholz, & Raftery (2006) have identified 1021 new (out of 1788 total) star cluster candidates only at $|b| < 20^\circ$.

Most of the above OCs and OC candidates were discovered very recently and lack detailed photometric studies. This situation is almost the same even for the clusters that have been known to human for decades. Only for about 400 out of ~ 1200 COCD clusters (Lyngå 1987) we have accurate, but heterogeneous UBV photometry, and photometric distances, reddening and age values (Piskunov et al. 2006). Dias et al. (2002)'s version 2.7 catalog gives the following statistics: out of 1759 OCs, only for 148 (8.41%) clusters we have abundance values, for 316 (17.96%) clusters we have distance, age, proper motion and radial velocity values, and for 862 (49.00%) clusters we have distance, reddening and age values. The fact that there are more clusters to be studied than the clusters with studies already performed might be due to the higher speed of discovery of new clusters than that of study of each known cluster. Some overall properties of the Galactic OCs have been recently discussed by Piskunov et al. (2006), Kharchenko et al. (2005a), and von Hippel (2005).

Recently the Two Micron All Sky Survey (Skrutskie et al. 1997, Skrutskie et al. 2006, 2MASS, available at <http://www.ipac.caltech.edu/2mass/releases/allsky/>) including the Point-Source Catalogue and Atlas, has produced huge amounts of near-infrared data (25.4 Tbytes of raw imaging data) covering 99.998% of the celestial sphere from the observations between 1997 June and 2001 February. In this paper, we have used the 2MASS photometry data to study the previously unstudied open clusters NGC 1641 and NGC 2394. The preliminary results on NGC 1641 presented in a conference proceedings (Kim 2006) are superseded by this

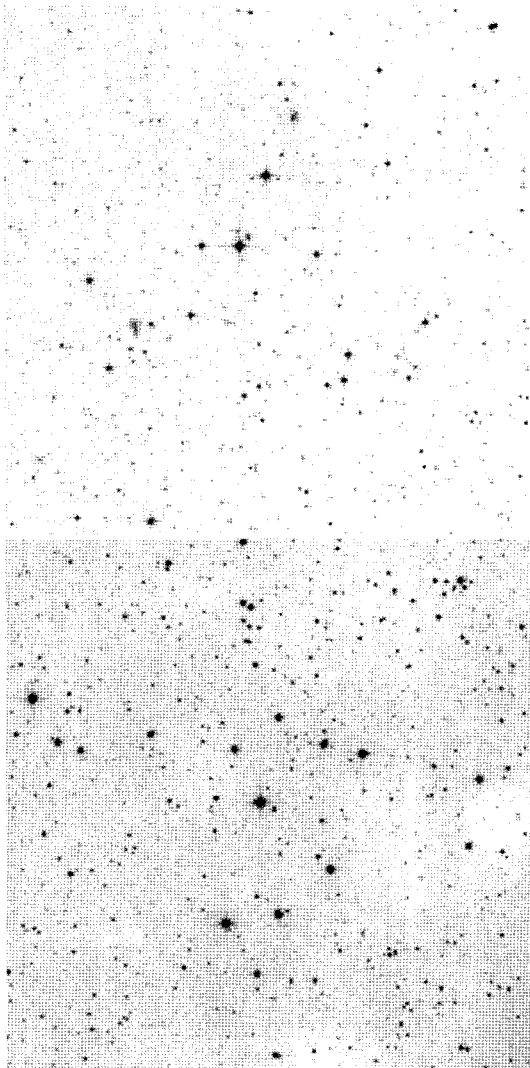


Fig. 1.— Grey-scale images of NGC 1641 (upper panel) and NGC 2394 (lower panel) as taken from the Digitized Sky Surveys (DSS). North is at the top and east is to the left. The size of each field is $15' \times 15'$.

paper.

Section II describes the near-infrared data. Section III and IV present the analyses for NGC 1641 and NGC 2394, respectively. Section V discusses the results and a summary and conclusions are given in Section VI.

II. THE 2MASS DATA

The 2MASS project (Skrutskie et al. 2006) have used two dedicated 1.3 m diameter telescopes located at Mount Hopkins, Arizona, and Cerro Tololo, Chile and 256×256 NICMOS3 (HgCdTe) arrays manufactured by Rockwell International Science Center (now Rockwell Scientific), which give field-of-view of 8.5×8.5 and pixel scale of $2'' \text{ pixel}^{-1}$. The photometric system comprise J ($1.25 \mu\text{m}$), H ($1.65 \mu\text{m}$) and K_S ($2.16 \mu\text{m}$)

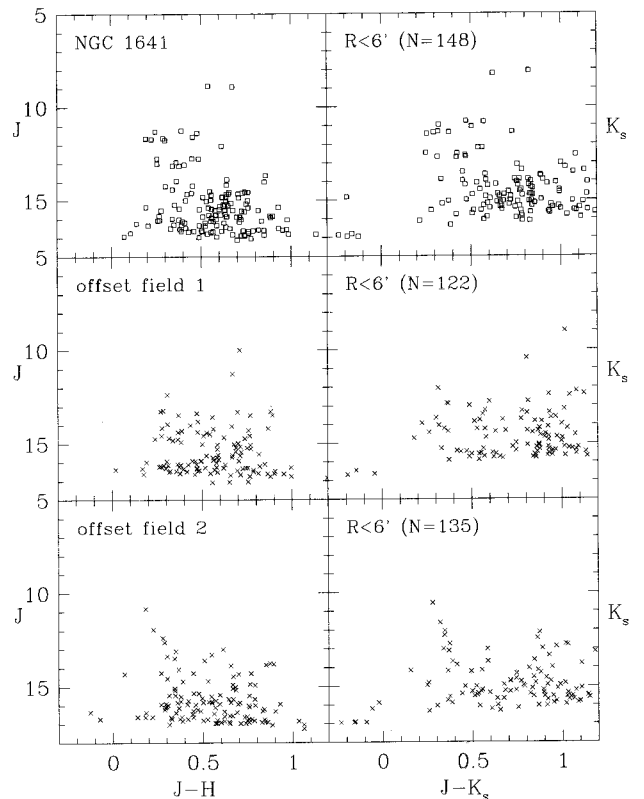


Fig. 2.— J vs. $(J - H)$ (left panels) and K_S vs. $(J - K_S)$ (right panels) color-magnitude diagrams of the stars in NGC 1641 (upper panels), offset field 1 (middle panels) and offset field 2 (lower panels). Extraction radius is $6'$ for each field. Offset field 1 is the region with the same Galactic latitude and one degree larger Galactic longitude than that of NGC 1641, while offset field 2 is the region with the same Galactic latitude and one degree smaller Galactic longitude than that of NGC 1641.

bands, where the “ K -short” (K_S) filter excludes wavelengths longward of $2.31 \mu\text{m}$ to reduce thermal background and airglow and includes wavelengths as short as $2.00 \mu\text{m}$ to maximize bandwidth (see Figure 2 of Skrutskie et al. 2006 or Figure 7 of Bonatto, Bica, & Girardi 2004 for the transmission curves of the 2MASS filters; Carpenter 2001).

VizieR¹ was used to extract J , H , and K_S 2MASS photometry data in circular areas centered on the two clusters. The photometry data are extracted for $R \leq 6'$ for NGC 1641 and for $R \leq 4'$ for NGC 2394, where R means radius. Figure 1 displays the grey-scale images of NGC 1641 (upper panel) and NGC 2394 (lower panel) as taken from the Digitized Sky Surveys (DSS), which shows that both objects are loose clusters. The centers of NGC 1641 and NGC 2394 are estimated

¹<http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=2MASS>

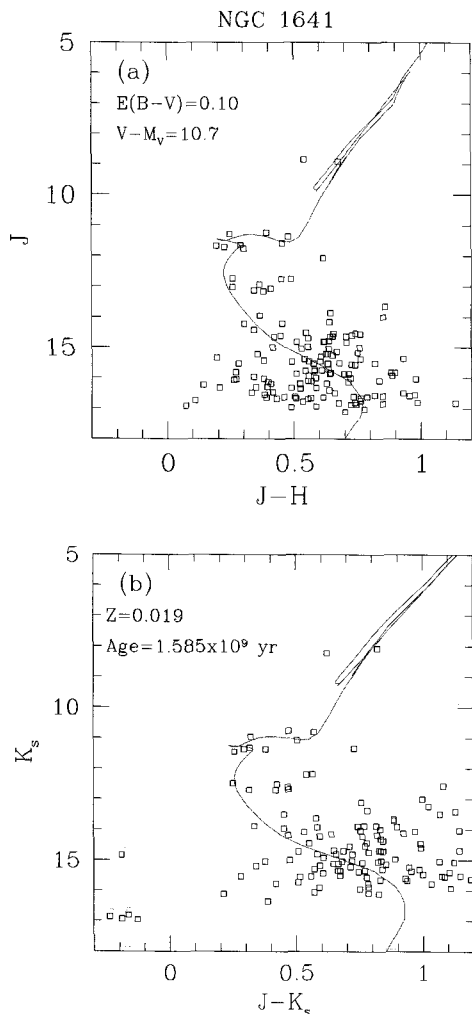


Fig. 3.— Padova isochrone fittings for NGC 1641 in (a) the J vs. $(J-H)$ and (b) K_S vs. $(J-K_S)$ color-magnitude diagrams. The solid lines represent the Padova isochrones for $E(B-V) = 0.10$, $V - M_V = 10.7$, $Z = 0.019$, and age = 1.6 Gyr.

approximately to be at R.A.(2000) = $04^h 35^m 32^s$, Decl.(2000) = $-65^\circ 45' 00''$ and R.A.(2000) = $07^h 28^m 36^s$, Decl.(2000) = $+07^\circ 05' 12''$, respectively. The Galactic coordinates of NGC 1641 and NGC 2394 are $l = 277.^\circ 20$, $b = -38.^\circ 32$ and $l = 210.^\circ 78$, $b = +11.^\circ 47$, respectively. The approximate radii of NGC 1641 and NGC 2394 are estimated to be $6'$ and $4'$, respectively.

III. ANALYSIS FOR NGC 1641

(a) The Color-Magnitude Diagrams

Figure 2 shows the J vs. $(J-H)$ (left panels) and K_S vs. $(J-K_S)$ (right panels) color-magnitude diagrams (CMDs) of stars in the region of NGC 1641 (upper panels), offset field 1 (middle panels) and offset field 2 (lower panels). For each field, objects in the radius

of $6'$ are used to draw the CMDs. Two offset fields are chosen at the same Galactic latitude, but with one degree larger and one degree smaller Galactic longitude for offset field 1 and offset field 2, respectively, than that of NGC 1641.

Although there are some possible field star contaminations at $J > 13$ mag or $K_S > 12.5$ mag, it is clear that the region of NGC 1641 contains much larger number of stars at the brighter magnitude range, where the main sequence and possible red giant branch or red giant clump (RGC) star(s) can be seen.

(b) Padova Isochrone Fitting

The near-infrared Padova isochrones of Girardi et al. (2000) have used the Johnson's K band (Bessell & Brett 1988, Cohen et al. 1992), while NGC 1641 and NGC 2394 have been observed and calibrated with the 2MASS K_S filter. Therefore, we have fitted the new theoretical Padova isochrones computed with the 2MASS J, H and K_S filters (Bonatto et al. 2004; Bica, Bonatto, & Blumberg 2006) to derive the cluster parameters. Figure 3 shows the best matched isochrones, which give the interstellar reddening of $E(B-V) = 0.10 \pm 0.05$ ($E(J-H) = 0.309E(B-V)$, $E(J-K_S) = 0.488E(B-V)$), the true distance modulus $(m-M)_0 = (V - M_V) - 3.1 \times E(B-V) = 10.4 \pm 0.3$ ($d = 1.2 \pm 0.2$ kpc), metallicity $[\text{Fe}/\text{H}] = 0.0 \pm 0.2$ dex, and age = 1.6 ± 0.2 Gyr. The color excess ratios we adopted (Bonatto et al. 2004) were derived from absorption ratios in Schlegel, Finkbeiner, & Davis (1998) and the ratio $A_{K_S}/A_V = 0.118$ from Dutra, Santiago, & Bica (2002).

In Figure 4 we plotted a few more isochrones with different ages (panels (a) and (b)) and metallicities (panels (c) and (d)) for comparison. Isochrones of twice the uncertainty smaller and larger age values are plotted as blue and green dotted lines, respectively, in panels (a) and (b), and isochrones of one grid smaller and larger metallicity values are plotted as blue and green dotted lines, respectively, in panels (c) and (d). The uncertainties for the ages and metallicities of NGC 1641 are estimated from this comparison.

IV. ANALYSIS FOR NGC 2394

(a) The Color-Magnitude Diagrams

Figure 5 shows the J vs. $(J-H)$ (left panels) and K_S vs. $(J-K_S)$ (right panels) CMDs of stars in the region of NGC 2394 (upper panels), offset field 1 (middle panels) and offset field 2 (lower panels). For each field, objects in the radius of $4'$ are used to draw the CMDs. As in the case of NGC 1641, two offset fields are chosen at the same Galactic latitude with NGC 2394, but with one degree larger and one degree smaller Galactic longitude for offset field 1 and offset field 2, respectively, than that of NGC 2394.

Although there are some possible field star contaminations at J or K_S magnitudes fainter than 13 mag and offset field 2 has some more brighter stars than offset

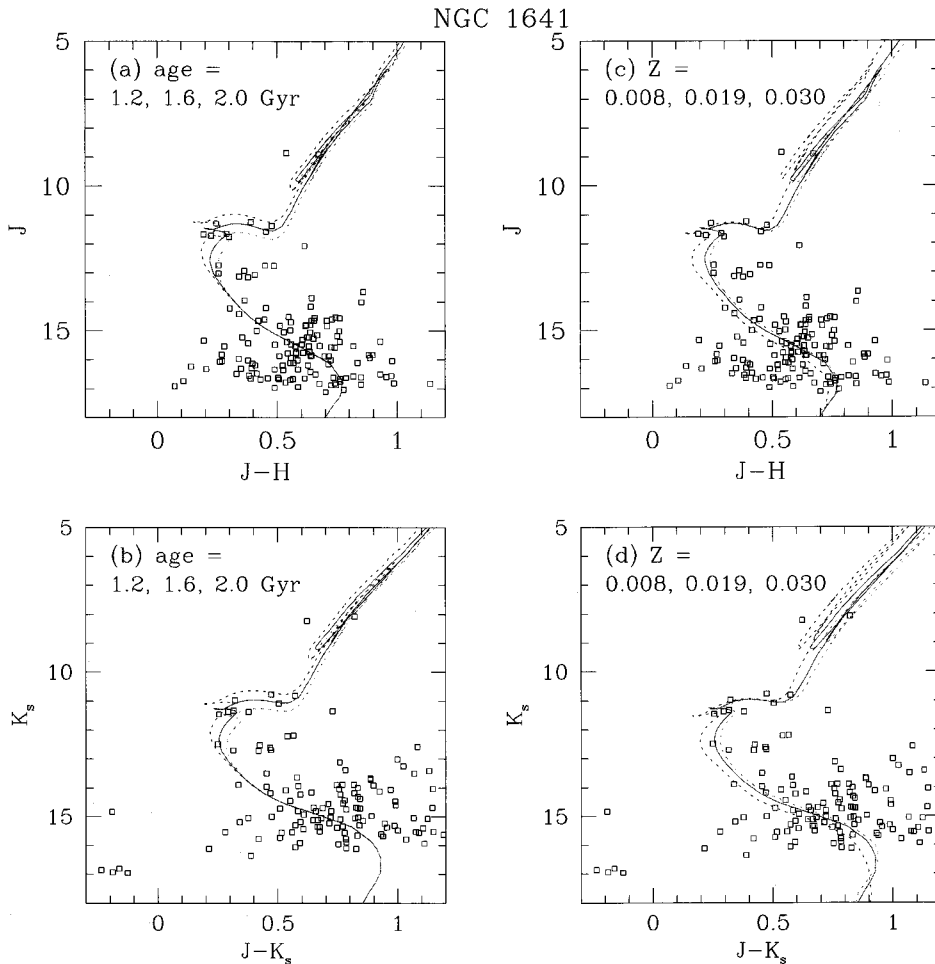


Fig. 4.— Padova isochrone fittings for NGC 1641 with different ages (panels (a) and (b)) and different metallicities (panels (c) and (d)) which are shown for comparison. In the panels (a) and (b), isochrones of twice the uncertainty smaller and larger age values are plotted as blue and green dotted lines (left and right of the central red solid line), respectively. In the panels (c) and (d), isochrones of one grid smaller and larger metallicity values are plotted as blue and green dotted lines (left and right of the central red solid line), respectively.

field 1, it is clear that the region of NGC 2394 contains larger number of stars at the brighter magnitude range. The CMDs of the region of NGC 2394 show the main sequence and possible red giant branch or RGC stars.

(b) Padova Isochrone Fitting

We have fitted the new theoretical Padova isochrones computed with the 2MASS J , H and K_S filters to derive the parameters of NGC 2394 as in the case of NGC 1641. Figure 6 shows the best matched isochrones, which give the interstellar reddening of $E(B - V) = 0.05 \pm 0.10$, the true distance modulus $(m - M)_0 = (V - M_V) - 3.1 \times E(B - V) = 9.1 \pm 0.4$ ($d = 660 \pm 120$ pc), metallicity $[\text{Fe}/\text{H}] = 0.0 \pm 0.2$ dex, and age = 1.1 ± 0.2 Gyr.

The derived rather large age for an OC, and the existence of the red giant branch and sub giant branch stars imply that the star at $J = 9.119$, $J - H = 0.533$, $K_S = 8.496$, and $J - K_S = 0.623$ could be one of the RGC stars of NGC 2394. Since the RGC, which are the stars of helium-burning stage, is a typical feature of intermediate-aged and old OCs (Kronberger et al. 2006), a future deeper photometry of the cluster will be helpful for the confirmation of this. Furthermore, RGC stars can be used as a standard candle for the determination of a cluster's distance and reddening (Janes & Phelps 1994; Phelps, Janes, & Montgomery 1994).

In Figure 7 we plotted a few more isochrones with different ages (panels (a) and (b)) and metallicities (panels (c) and (d)) for comparison. Isochrones of twice the uncertainty smaller and larger age values are plot-

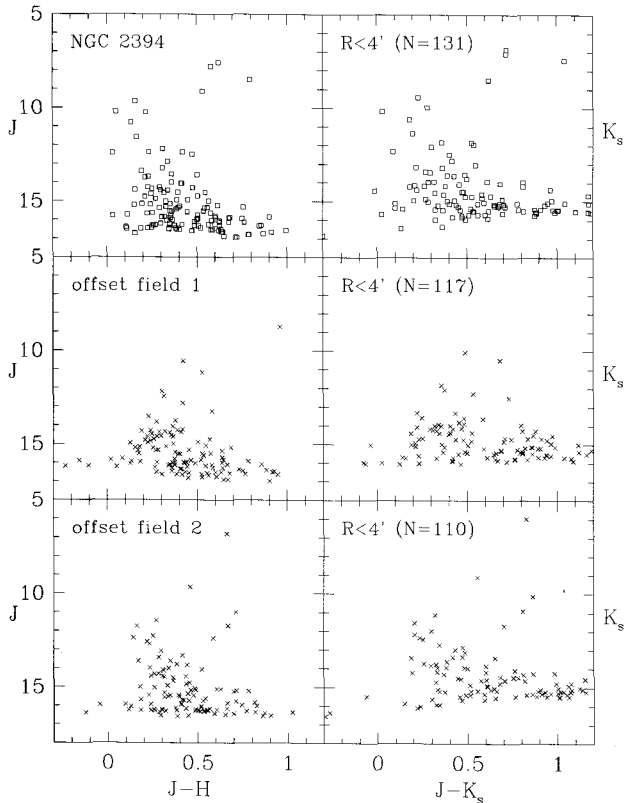


Fig. 5.— J vs. $(J - H)$ (left panels) and K_S vs. $(J - K_S)$ (right panels) color-magnitude diagrams of the stars in NGC 2394 (upper panels), offset field 1 (middle panels) and offset field 2 (lower panels). Extraction radius is $4'$ for each field. Offset field 1 is the region with the same Galactic latitude and one degree larger Galactic longitude than that of NGC 2394, while offset field 2 is the region with the same Galactic latitude and one degree smaller Galactic longitude than that of NGC 2394.

ted as blue and green dotted lines, respectively, in panels (a) and (b), and isochrones of one grid smaller and larger metallicity values are plotted as blue and green dotted lines, respectively, in panels (c) and (d). The uncertainties for the ages and metallicities of NGC 2394 are estimated from this comparison.

V. DISCUSSION

(a) Color-Color Diagrams

Figure 8 shows the $(J - H) \times (H - K_S)$ color-color diagrams of the stars with K_S magnitude errors less than 0.1 in (a) NGC 1641 and (b) NGC 2394. The main sequence ranges of the Padova isochrones are overplotted as solid lines ($0.15 - 1.75M_\odot$ for NGC 1641 and $0.15 - 1.55M_\odot$ for NGC 2394) and the reddening vector $E(J - H) = 1.72 \times E(H - K_S)$ for $A_V = 1$ are denoted as arrows.

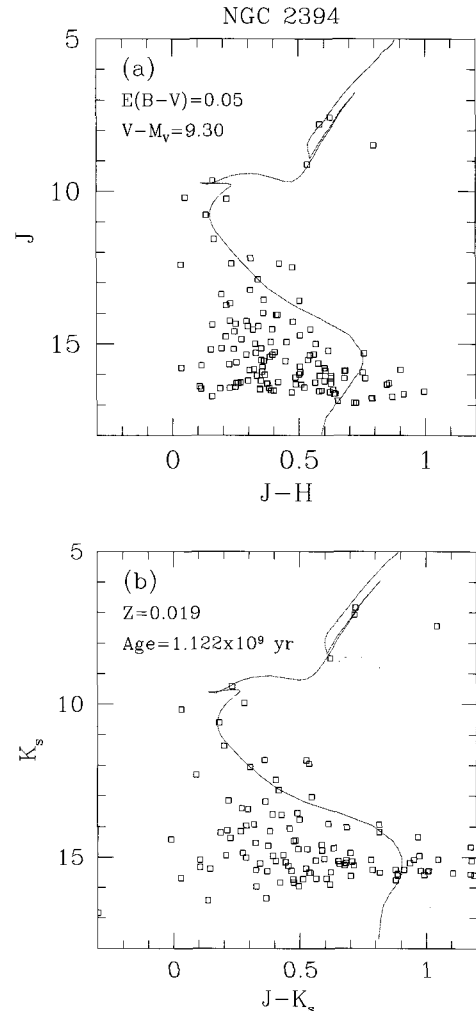


Fig. 6.— Padova isochrone fittings for NGC 2394 in (a) the J vs. $(J - H)$ and (b) K_S vs. $(J - K_S)$ color-magnitude diagrams. The solid lines represent the Padova isochrones for $E(B - V) = 0.05$, $V - M_V = 9.30$, $Z = 0.019$, and age = 1.1 Gyr.

Most of the stars in NGC 1641 and NGC 2394 are distributed along the main sequences of the Padova isochrones and this suggests that the reddening values in the fields of these clusters are not so high. The fact that stars in NGC 2394 are more tightly gathered around the Padova isochrones than those in NGC 1641 is consistent with the somewhat lower reddening value for NGC 2394 derived in Section IV than that for NGC 1641.

(b) $[\text{Fe}/\text{H}]$ –Galactocentric Radius Relation

Using the Galactic coordinates and distances of NGC 1641 and NGC 2394 from the Sun derived above, we have calculated the Galactocentric distances of these clusters to be 8.4 ± 0.01 kpc and 9.1 ± 0.1 kpc, respec-

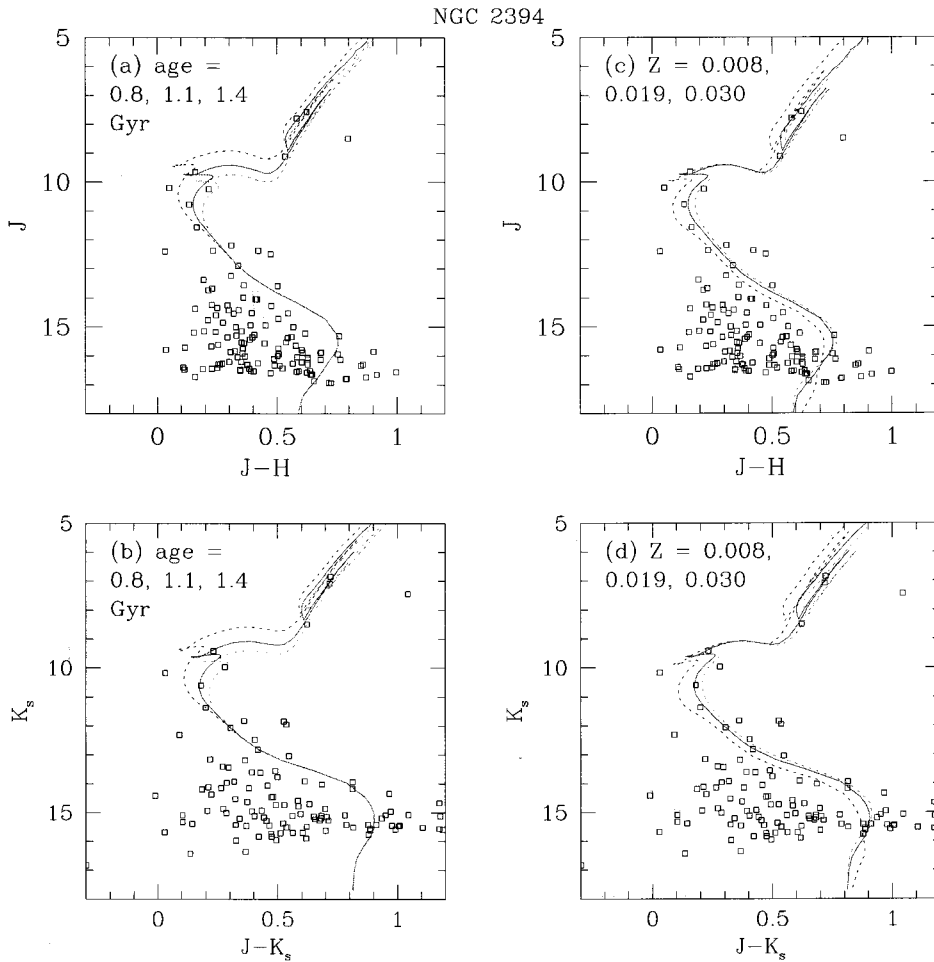


Fig. 7.— Padova isochrone fittings for NGC 2394 with different ages (panels (a) and (b)) and different metallicities (panels (c) and (d)) which are shown for comparison. In the panels (a) and (b), isochrones of twice the uncertainty smaller and larger age values are plotted as blue and green dotted lines (left and right of the central red solid line), respectively. In the panels (c) and (d), isochrones of one grid smaller and larger metallicity values are plotted as blue and green dotted lines (left and right of the central red solid line), respectively.

tively (adopting the Galactocentric distance of the Sun as 8.5 kpc). If we adopt the Galactocentric distance of the Sun of 8.0 kpc, these distances become 7.9 ± 0.01 kpc and 8.6 ± 0.1 kpc for NGC 1641 and NGC 2394, respectively.

Kim et al. (2005) have compiled the recent results of the various estimates of the slopes of the Galactocentric radial $[\text{Fe}/\text{H}]$ gradient of old open clusters in their Table 2, whose mean value is $\Delta[\text{Fe}/\text{H}]/\Delta R_{gc} = -0.066 \pm 0.019$ dex kpc^{-1} . They obtained a new value of the gradient -0.064 ± 0.009 dex kpc^{-1} for 51 OCs including the cluster Czernik 24.

From including the current two old open clusters NGC 1641 and NGC 2394 and using the parameters obtained in this study in the plot of Figure 9, we re-determined the gradient value to be -0.067 ± 0.009 dex

kpc^{-1} denoted as the solid line. Again this value is in very good agreement with the mean values obtained in Kim et al. (2005), and it can be said that the metallicities and the Galactocentric distances of NGC 1641 and NGC 2394 obtained in this study are consistent with the general trend of old open clusters.

VI. SUMMARY AND CONCLUSIONS

We have used the JHK_S 2MASS near-infrared photometric data of the old open clusters NGC 1641 and NGC 2394 to study these clusters photometrically and determined the fundamental parameters of ages, metallicities, distances, and interstellar reddening values. This is the first photometric study for these two clusters. The resulting fundamental parameters for the two

TABLE 1.
BASIC INFORMATION OF NGC 1641 AND NGC 2394

Parameter	NGC 1641	NGC 2394	Reference
α_{2000}	04 ^h 35 ^m 32 ^s	07 ^h 28 ^m 36 ^s	This study
δ_{2000}	-65° 45' 00"	+07° 05' 12"	This study
l	277.°20	210.°78	This study
b	-38.°32	+11.°47	This study
Reddening, $E(B - V)$	0.10 ± 0.05 mag	0.05 ± 0.10 mag	This study
Distance modulus, $V_0 - M_V$	10.4 ± 0.3 mag	9.1 ± 0.4 mag	This study
Distance, d	1.2 ± 0.2 kpc	660 ± 120 pc	This study
Galactocentric distance, R_{gc}	8.4 ± 0.01 kpc	9.1 ± 0.1 kpc	This study
Metallicity, Z	0.019	0.019	This study
Age, t	1.6 ± 0.2 Gyr ($\log t = 9.20$)	1.1 ± 0.2 Gyr ($\log t = 9.05$)	This study

clusters are summarized in Table 1. It is very anticipated to perform further optical photometric and/or deeper near-infrared photometric study for these clusters in the future.

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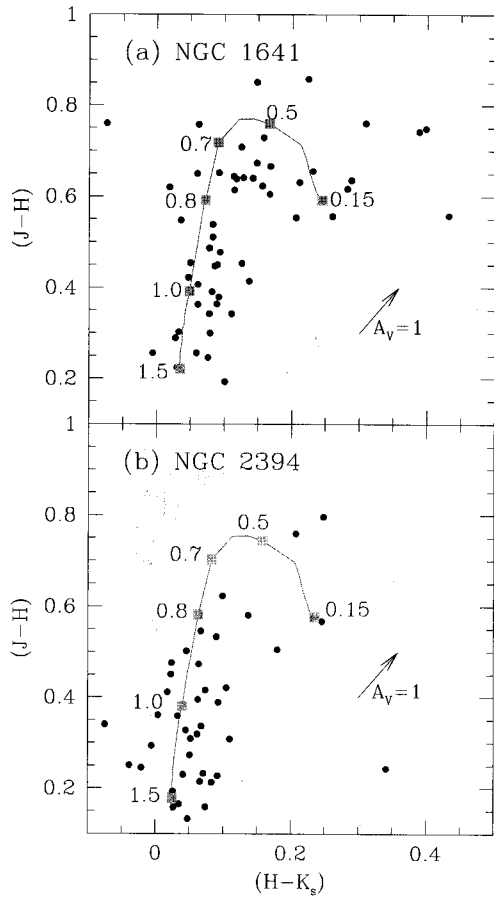


Fig. 8.— Color-color diagrams of the stars in (a) NGC 1641 and (b) NGC 2394 for K_S magnitude errors less than 0.1. Solid lines are main-sequence ranges of the Padova isochrones of ages 1.6 Gyr for NGC 1641 and 1.1 Gyr for NGC 2394. Arrows are reddening vectors $E(J-H) = 1.72 \times E(H-K_S)$ for $A_V = 1$. Representative masses in M_\odot are indicated along the isochrones.

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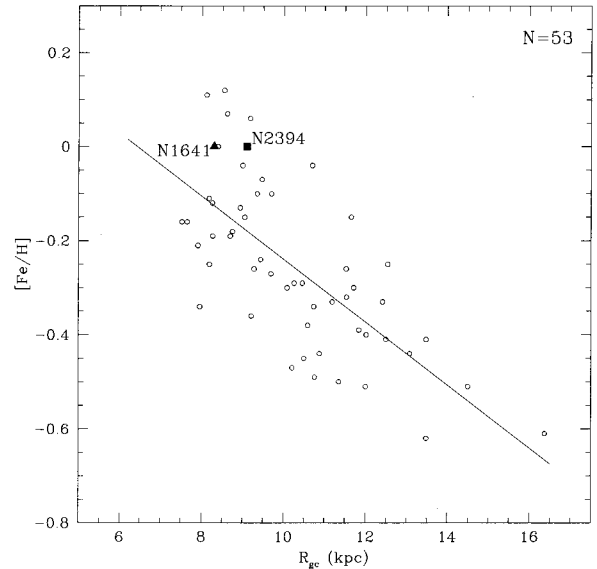


Fig. 9.— Radial abundance gradient for 53 old open clusters including NGC 1641 (filled triangle) and NGC 2394 (filled square). The solid line is a least-squares fit to the data that yields an abundance gradient of $\Delta[\text{Fe}/\text{H}]/\Delta R_{gc} = -0.067 \pm 0.009 \text{ dex kpc}^{-1}$.

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