OPTICAL AND INFRARED PHOTOMETRIC STUDY OF OPEN STAR CLUSTER NGC2266

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Abstract. We present deep CCD photometry ($V \sim 21$ mag) in BVRI Johnson-Cousin filters supported with 2MASS JHK data set for the old open star cluster NGC 2266. The cluster's parameters such as reddening, distance, metallicity and age, etc ..., are derived using two color diagrams in optical and near-infrared bands. These parameters are $E_{B-V} = 0.196 \pm 0.02$, $E_{J-H} = 0.068 \pm 0.001$ and $E_{J-Ks} = 0.163 \pm 0.01$ mag, the distance modulus of $(m-M)_0 = 12.08 \pm 0.11$ mag, which gives a distance of 2.6 ± 0.15 kpc, the metallicity, $Z = 0.004$, and age of 1 Gyr (obtained by fitting the observed CMDs with Padova isochrones). The limiting radius of the cluster is obtained of 7.03 ± 0.27 arc minutes from the analysis of 2MASS data; it reflects that the cluster is a compact cluster. Luminosity and mass functions are investigated as well as the dynamical relaxation time of NGC 2266 is determined of about 0.02 of its age, which means that the cluster is dynamically relaxed.

Key words: Galaxy, open clusters and associations, individual, NGC 2266 .

1. INTRODUCTION

The open star cluster NGC 2266 (Melotte 50) is located in Gemini at $\alpha_{2000.0} = 06h43m19s$, $\delta_{2000.0} = 26^o58'$, and $l = 187.8^o$, $b = 10.3^o$. It was discovered by Cuffey (1938), who determined the cluster's distance of 3.1 kpc. Kaluzny & Mazure (1991) obtained its distance of 3.4 kpc, E_{B-V} = 0.1 and age of 0.8 Gyr based on CCD observation in UBV and Washington color systems. While, the basic dataset for NGC 2266 published in the WEBDA database (Mermilliod, 1995) are $E_{B-V} = 0.15 \pm 0.01$, $(m-M)_o = 12.6 \pm 0.2$ mag, $Age = 0.7 \pm 0.1$ Gyr, $Rgc = 11.8$ Kpc and $z = 0.59$ Kpc. Phelps *et al.*(1994) defined NGC 2266 belongs to the old cluster populations, and Salaris *et al.*(2004) determined the cluster's age of 870 Myr. Paunzen & Netopil (2006) included NGC 2266 in a set of 72 standard open clusters, while Ahumada & Lapasset (1995) discovered two candidates of the blue stragglers in the cluster.

In 2007, Maciejewski & Niedzielski determined the following cluster parameters: age of 1 Gyr, $E_{B-V} = 0.00$, and the distance of 2.8 Kpc. Maciejewski *et al.*(2008) studied the cluster in UBV and 2MASS JH photometric system, and they found out the limiting radius is 6.2 arcmin, age of 1.2 Gyr, metallicity is lower than solar one with $Z = 0.004$ ([Fe/H]= -0.68), interstellar reddening $E_{B-V} = 0.17$ and its distance of 2.8 ± 0.15 Kpc. They also found 12 variable stars in the cluster through inspection the magnitudes of 7200 stars, these variable stars are distributed outside the cluster radius. Carrera (2012) determined the mean radial velocity (-16 ± 15 km s^{-1}) and metallicity ([Fe/H] = -0.38 ± 0.07 dex) for NGC 2266 based on infrared Ca II triplet spectroscopy.

Deep CCD photometry ($V \sim 21$ mag) in BVRI Johnson-Cousin filters beside 2MASS JHK bands enables us to investigate the photometric and structure parameters of the old open star cluster NGC 2266.

The paper is organized as follows: the observations and data reduction was described in the Section 2. In Section 3, the radial density profile is presented. The field star decontamination algorithm is given in section 4. The analysis of the color-magnitude diagrams and the derived photometric parameters are given in Section 5. The luminosity function and mass function are described in Section 6, while the mass segregation and dynamical relaxation state of the cluster are described in Section 7. The last section presents summary of our result and conclusion.

2. OBSERVATIONS AND DATA REDUCTION

2.1. OPTICAL DATA

CCD BVRI Observations for the open star cluster NGC 2266 were carried out with the 188 cm reflector telescope at Newtonian focus (f/4.9) during one night on February 15, 2013. The telescope is operating by Kottamia Observatory, Astronomy Department of NRIAG, Egypt. The telescope was equipped with a 2kx2k EEV 42-40 CCD camera, with a pixel size of 13.5 µm. The telescope and this CCD camera gave us a square field of view of about 10×10 arcmin^2 on the sky with a scale of 0.30 arc sec per pixel. More information about the capabilities of Kottamia telescope are presented in Azzam *et al.*(2010). Table 1 lists the observations log of 48 science exposures. Bias and twilight flat field frames were taken in the four filters. The observations of the standard stars in the selected area SA 107 (Landolt, 1992) have been performed to calibrate the target observations.

The standard CCD reduction processing was done under IRAF software for the cluster and standard stars CCD frames. These processes included bias subtraction, flat field corrections, removal of cosmic rays, aperture and point spread function photometry and magnitude transformation to the standard system.

We determined the calibration coefficients that transform the instrumental magnitudes to the standard ones using the observation of the standard stars. The transfor-

Table 1

Log of observations

Date	Filter	No. of exp.	Air mass range	Exp.Time (sec)
Feb. 15, 2013	B	12	1.002 - 1.098	120
Feb. 15, 2013	V	12	1.009 - 1.094	80
Feb. 15, 2013	R	12	1.010 - 1.091	60
Feb. 15, 2013	I	12	1.001 - 1.089	40

Table 2

The zero point, color and extinction coefficients for each filter

Filter vs. Parameter	k	a	z
b	0.35	0.004	3.02
v	0.17	0.002	2.80
r	0.08	0.001	2.71
i	0.03	-0.003	3.19

mation equations are in the following form:

$$b = B + z_b + k_b \cdot X + a_b \cdot (B - V) \quad (1)$$

$$v = V + z_v + k_v \cdot X + a_v \cdot (B - V) \quad (2)$$

$$r = R + z_r + k_r \cdot X + a_r \cdot (V - R) \quad (3)$$

$$i = I + z_i + k_i \cdot X + a_i \cdot (V - I), \quad (4)$$

where B, V, R, i and b, v, r, I are the standard and the instrumental magnitudes respectively. X is the air mass, while z_b, z_v, z_r, z_i and k_b, k_e, k_r, r_i are the photometric zero points and the extinction coefficients in B, V, R, I filters respectively. The a_b, a_v, a_r, a_i are the color coefficients. The values of extinction coefficients, the color coefficients and the photometric zero points in their corresponding filters are given in Table 2.

2.2. NEAR-INFRARED DATA

The 2MASS photometric data on near-infrared JHKs filters were extracted from Vizier web page for the star cluster NGC 2266. Due to the small area of the optical field of view, we investigate the cluster structure based only on the 2MASS data. Starting with determination of the cluster center by constructing a rectangular strip around the cluster center (visually determined) in α and δ direction with a side of one degree wide. Then, we count the stars in each strip to build the frequency distribution in both directions. These histograms were fitted by a Gaussian function, whereas the location of maximum number of stars (peak) indicates the new cluster center, as illustrated in Fig. 1 and listed in Table 3. Later on, the 2MASS data are extracted again; for further investigation, centered on the new coordinates with an

Table 3

The equatorial and galactic coordinates of the cluster using 2MASS data

RA (2000.0)	Dec (2000.0)	l (deg)	b (deg)
06h43m13.01s	26d58m25.1s	187.77	10.27

aperture radius of 30 arc minutes, the large extraction area around the cluster enables us to determine statistically the surface density distribution of the field stars in the cluster outskirts.

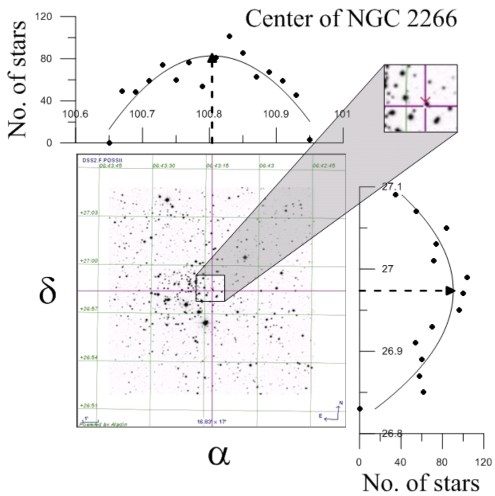

Fig. 1 – The Gaussian fitting Profiles of star counts across Right Ascension (α) and Declination (δ) for the cluster. The peak's position of the profile gives the cluster's center.

3. RADIAL DENSITY PROFILE

The stellar density distribution of a cluster is a result of the internal and external dynamical processes. The Radial Density Profile (RDP), the number of stars per unit area at different radius from cluster's center outward, is an observational tool that reflects the dynamical events acting on the cluster and enables us to determine the angular size of the cluster. The radial density profile is determined through counting the stars in concentric rings around the new cluster's center. We calculated the density of each ring by dividing the number of stars in the ring by its area. The ring radius was chosen to be ranged from 0.25 to 1.5 arc-minutes; to avoid the smallest number of the stars in the ring and then the density profile was chosen by visual inspection of the data for each ring bin size. The density profile must represent the well exponential decreasing of the cluster surface density outward from its center, as well as the constancy of the dense background after the cluster limit. We applied the empirical King model (King, 1966) to fit the observed RDP. The King model of the density function equation is of the following form:

$$\rho(r) = f_{bg} + \frac{f_0}{1+(\frac{r}{r_{core}})^2}, \tag{5}$$

where r_{core}, f_0, and f_{bg} are the core radius, the central surface density and background surface density and their values of $r_{core} = 2.65 \pm 0.43$ arcmin, $f_0 = 6.46 \pm 0.53$ stars/arcmin^2 and $f_{bg} = 2.71 \pm 0.27$ stars/arcmin^2 respectively. The core radius is the cluster radius at which the central surface density drops to its half value. We suppose that the background star density lies within the lines representing the standard deviation of the background density level, therefore we define the cluster limits (cluster limited radius,$r_{lim} = 7.03 \pm 0.27$ arcmin) at the intersection of the King profile with the upper limit of the density standard deviation line (see Figure 2). At this point the background star density $\rho_b = f_{bg} + 3\sigma_{bg}$, where σ_{bg} is uncertainty of f$_{bg}$. Comparing our results from radial density profile analysis; given above with that of both Maciejewski & Niedzielski's (2007) and Maciejewski *et al.*(2008), we found their values of r_{lim} and r_{core} are smaller than ours. This may be due to our investigation based upon 2MASS data results instead of the optical data like them.

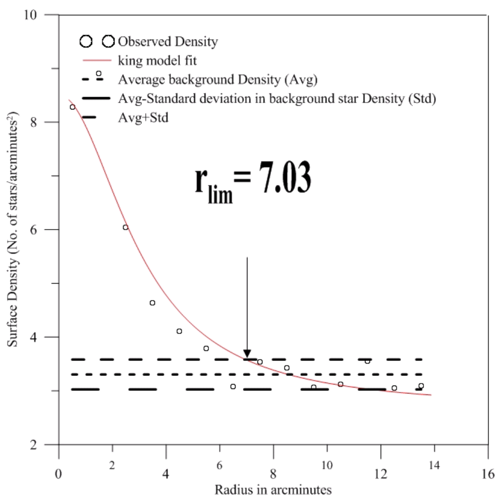

Fig. 2 – The radial density profile for the cluster. The solid curve denotes the fitting with King model, while the dashed lines mark the level of the background density and its standard deviation.

4. MEMBERSHIP OF STAR CLUSTER

The field stars decontamination from a star cluster is an essential task to obtain an accurate photometric study for star clusters. To decontaminate the field stars, we used a star counting technique given by Chen *et al.*(2004) to determine the membership probability of stars in a cluster. In this technique, the number of neighbors around any star in the cluster used to measure the membership probability of this star, π. The cluster parameter pi for each star i is defined as follows:

$$\pi = (Nt - Nf)/Nt = 1 - Nf/Nt, \tag{6}$$

where Nt is the total number of the stars around the star i and Nf is the average number of the field stars, both numbers counted within the same aperture size, but the first in the cluster area and the second in the cluster's outskirts. The clustering parameter, π, ranged from 0 for field stars (*i.e.*$Nt \sim Nf$) to ~ 1 for star members, which means that $Nt \gg Nf$.

Counting the stars within a circle with a specific radius around each star in the cluster field of interest was done using a *Matlab* script written by one of us (Haroon *et al.*, 2014). Different aperture radii were used in this method in order to select the best radius for the further calculation. That is, the aperture gives a constancy of the cluster surface density outside the cluster limit with the smallest dispersion (*i.e.*in the field star region). The stars outside the cluster limit ($r_{lim} + 2$ arc-minutes) are considered as field stars. The stars, whose π values ($\pi > 0.6$) are chosen for further investigation.

5. THE COLOR-MAGNITUDE DIAGRAMS

The Color-Magnitude-Diagram (CMD) for a star cluster enables us to determine its age, reddening and distance. So, three optical $(V, B - V)$, $(V, V - I)$ and $(V, V - R)$, and two infrared $(J, J - H)$ & $(Ks, J - Ks)$, CMDs for the total number of the observed stars in the decontaminated cluster region ($r < r_{lim}$) are constructed for the cluster NGC 2266 and presented in Figures 3 and 4. To derive the fundamental parameters of this cluster, these CMDs were fitted with several theoretical Padova isochrones (Bonatto *et al.*, 2004) in different metallicities and ages, in steps of 0.05, and in the logarithm of age. This step was adopted as a typical uncertainty of the log age. We got a good fit for all CMDs by visual inspection with the isochrone of the metallicity $Z = 0.004$, and the corresponding age of 1.0 ± 0.12 Gyr. The optical and infrared color excesses are determined from CMDs fitting, and using the relations of Fiorucci & Munari (2003). The optical color excess $E_{B-V} = 0.196 \pm 0.02$ and the absolute distance modulus $(m - M)o = 12.08 \pm 0.11$ mag, which gives a distance of 2.6 ± 0.15 kpc. These results agree well with that given by Maciejewski *et al.*(2008): $E_{B-V} = 0.17$ mag and the distance of 2.8 ± 0.15 kpc. Fiorucci & Munari (2003) presented the color excess values for 2MASS photometric system, which enabled us to obtain the following results: $E_{J-H}/E_{B-V} = 0.35 \pm 0.13$, $E_{J-K}/E_{B-V} = 0.82 \pm 0.2$ and $Av = 0.61 \pm 0.08$, where $RV = A_V/E_{B-V} = 3.1$ was adopted.

6. THE LUMINOSITY AND MASS FUNCTION

The number of stars in a cluster with different absolute luminosity describes the stellar luminosity function (LF) of the cluster. So, we transformed the *J* apparent magnitude to absolute magnitude using the cluster's distance modulus, the frequency distribution of the *J* absolute magnitude has been obtained, as shown in Figure 5. This luminosity function is transformed to the mass function based on the dependence of the mass on the luminosity given in the selected theoretical Padova isochrones (Bonatto *et al.*, 2004). The absolute magnitude and the masses for the adopted isochrone with metallicity $Z = 0.004$ are used to construct the relation between $M\odot$ and absolute magnitude M_J. The relation is a polynomial function of the second degree, used to determine masses of the cluster from the observed absolute magnitude M_J, then a histogram for the number of stars as a function of mass interval was preformed and presented in Figure 6. The mass frequency distribution was linearly fitted with the slope value of -2.68 ± 0.51; this value is closer to that of Salpeter (1955) obtained by studied the IMF for massive stars. Note that, the steep slope of the IMF indicates that the number of low-mass stars is greater than the high-mass ones. The masses are integrated to compute the total mass of the cluster $M \approx 287.5 M\odot$.

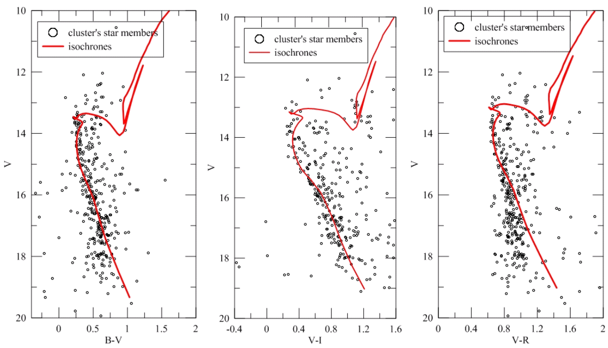

Fig. 3 – Color magnitude diagrams $a-(V, B-V)$, $b-(V, V-I)$ and $c-(V, V-R)$, the solid curve represents the best fitted Padova isochrones with $Z = 0.004$ and age of 1Gyr.

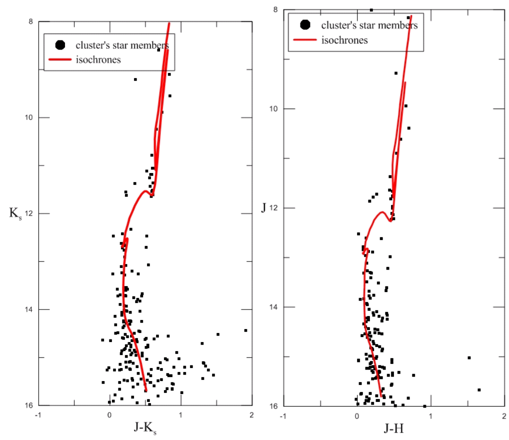

Fig. 4 – 2MASS CMDs: $a-(Ks, J-Ks)$ and $b-(J, J-H)$, the solid curve represents the best fitted Padova isochrone with $Z = 0.004$ and age of 1Gyr.

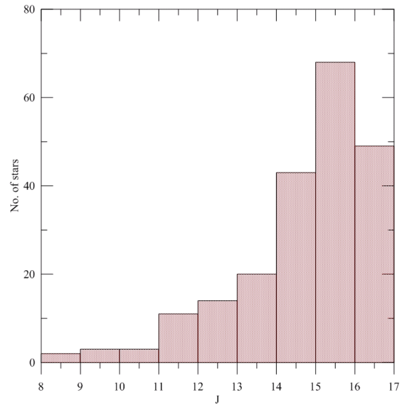

Fig. 5 – The cluster luminosity function.

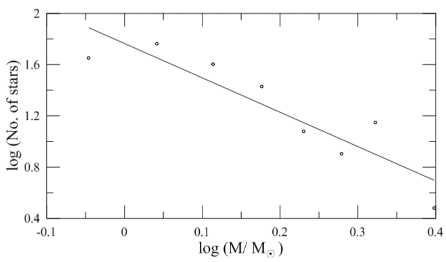

Fig. 6 – The mass frequency distribution is linearly fitted with the slope value of -2.68 ± 0.51.

7. MASS SEGREGATION AND DYNAMICAL RELAXATION TIME

The dynamical relaxation (T_E) is the time in which the individual stars exchange energies and their velocity distribution approach a Maxwellian equilibrium. An examination of the distribution of masses of the stars along the radius of the cluster showed a clear segregation of mass in the cluster, with the massive stars located in the central part of the cluster. To check whether the existing mass segregation is due to dynamical evolution or the imprint of the star formation process, we need to estimate the dynamical relaxation time. Through the dynamical relaxation time, the low mass stars in a cluster may possess the largest random velocities trying to occupy a larger volume than the high mass stars do, Mathieu & Latham, (1986). Here, the relation given by Spitzer and Hart (1971) is used to compute the dynamical relaxation time for the cluster.

$$T_E = \frac{8.9 \times 10^5 N^{1/2} R_h^{3/2}}{< m >^{1/2} \log(0.4N)} \tag{7}$$

where R_h is the radius containing half the cluster mass, N is the number of cluster members and $< m >= 1.35 M\odot$ is the average mass in the cluster. Assuming that the R_h is equal to half of the cluster radius in linear units, we have calculated the dynamical relaxation time ($T_E = 16.46$ Myr). Comparing the values of T_E with the cluster ages, we found $Age/T_E = 60.75$. Since the values of the T_E are smaller than the estimated cluster ages, it may be inferred that the cluster is dynamically relaxed and the mass segregation effect due to dynamical evolution must be important. The cluster relaxation time is very shorter than its age (~ 0.02 of its age), that means the cluster is highly dynamically relaxed.

8. CONCLUSIONS

New CCD BVRI observations and JHKs 2MASS data for the open star cluster NGC 2266 are used to determine the cluster structure and photometric parameters. The infrared dataset reveals NGC 2266 is a compact open cluster, with the limited size of the cluster; its radius is limited to 7.3 arc minute, and its core radius of 2.65 arc minute, these values are larger than the previously determined in literature, while the cluster distance determination 2.6 kpc, age of 1 Gyr and poor metallicity of $z = 0.004$ are very close to that determined earlier. However, the interstellar reddening, $r_{B-V} = 0.196 \pm 0.02$ agrees well with that of Maciejewski *et al.*(2008), but it is larger than the value given by Maciejewski & Niedzielski's (2007). We obtained too the infrared color excess and the visual absorption as follows $E_{J-K} = 0.16 \pm 0.01$, $E_{J-i} = 0.068 \pm 0.004$ and $A_V = 0.61 \pm 0.08$ respectively.

From the investigation of the mass function within the cluster, we found out the stars masses ranged from 0.2 to 2.4 solar mass, with estimated total mass of the cluster members of $\approx 287.5M\odot$ which is smaller than the value $1392M\odot$ of Maciejewski & Niedzielski's (2007). We think this large difference is due to incompleteness in our photometric data. In addition, the cluster dynamical relaxation time ($T_E = 16.46$ Myr) is about 0.02 of its age (1 Gyr), which means that the cluster is dynamically relaxed.

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