NRIAG Journal of Astronomy and Geophysics (2016) 5, 16–22

National Research Institute of Astronomy and Geophysics

NRIAG Journal of Astronomy and Geophysics

www.elsevier.com/locate/nrjag

A comprehensive study of the young open star cluster NGC 6611 based on deep VRI CCD images and 2MASS data

I.M. Selim [a,b,*], **A. Essam** [a], **Y.H.M. Hendy** [a], **R. Bendary** [a]

[a] *National Research Institute of Astronomy and Geophysics, Astronomy Dept., Cairo, Egypt*
[b] *Computer Science Higher Technological Institute (HTI), Egypt*

Received 15 January 2016; revised 9 February 2016; accepted 21 February 2016
Available online 29 March 2016

KEYWORDS

Galaxy;
Open clusters and associations;
Individual;
NGC 6611

Abstract In the present study, we have used Deep CCD images of the extremely young open star cluster NGC 6611, up to a limiting magnitude of $V \sim 22.86$ mag in V, R and I passbands. The resulting color-magnitude V; $(V\text{–}I)$ diagram as well as their radial density profiles has been determined. Using 2MASS data, we confirmed the consistency between the 2MASS photometry, by fitting isochrones, the extinction $E_{(V-I)} = 0.530 \pm 0.04$ mag, $E_{(J-H)} = 0.31 \pm 0.02$, from the color magnitude diagram the cluster distance $= 2.2 \pm 0.21$ kpc and age $= 3.6$ Myr, based on the fitting of theoretical stellar isochrones of solar metallicity $Z = 0.019$. The distance modulus of the cluster is estimated at 12.3. The radial stellar density profiles and the cluster center have been determined by two methods. The core and cluster radii are determined from the radial stellar density profiles. Only about 40% of the cluster members are present in the core region. The cluster luminosity function has been calculated. The mass function slope of the entire cluster is $\sim -0.67 \pm 0.12$. The effects of mass segregation, most probably due to dynamical evolution, have been observed in the cluster.

1. Introduction

Studying massive young open star clusters is not only very important investigations for understanding star formation and chemical evolutionary processes in the galaxy, but also a good tool for the basic information to estimate parameters such as age, distance, metallicity and age-metallicity relationship. Open star cluster NGC 6611 is a very young and it is embedded in a star formation region. NGC 6611 is located near the external border of the Sagittarius Carina spiral arm $l = 170°$ and b $+0.8°$. Walker (1961), Sagar and Joshi

* Corresponding author at: National Research Institute of Astronomy and Geophysics, Astronomy Dept., Cairo, Egypt.
E-mail address: i_selim@yahoo.com (I.M. Selim).
Peer review under responsibility of National Research Institute of Astronomy and Geophysics.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.nrjag.2016.02.006
2090-9977

(1979) and The et al. (1985) found that the stars of the open star cluster NGC 6611 are still in the stage of evolution toward their hydrodynamically stable state of the main sequence. NGC 6611 is the massive young cluster with 2–3 Myr that ionizes the Eagle Nebula (Oliveira, 2008).

The first photometric study of NGC 6611 was carried out by Walker (1961) from photoelectric and photographic UBV observations, and he used color excesses of stars as a criterion to pick out cluster members. Sagar and Joshi (1979), The et al. (1990) and Hillenbrand et al. (1993) studied this cluster by combining CCD observations in the UBV system and infrared (JHK) photometric data. Oliveira (2008) found that the IMF of NGC 6611 is well described by a lognormal distribution. However, a lognormal distribution, the IMF of NGC 6611 seems to peak at higher masses than the Galactic field and the solar neighborhoods IMF.

Belikov et al. (1999) summarize that the NGC 6611 is known as part of a star-forming region at a distance of 2100 pc and an age of about 3 Myr. Hillenbrand et al. (1993) and Belikov et al. (2000) found that this cluster is very young, with an age of (2–3 Myr), While (Hillenbrand et al., 1993; Belikov et al., 2000; Dufton et al., 2006) considerable age for sources in the Eagle Nebula about (<1–6 Myr). Martayan et al. (2008) redetermined the age of NGC 6611 and found it is about 1.2–1.8 Myr. Hillenbrand et al. (1993) combined CCD UBV observations with near-infrared JHK ones to establish a theoretical HR diagram for the cluster, from which they conclude that NGC 6611 is actively forming 3–8$M_{\odot}$ stars. Recent distance determinations and values around 1.8 kpc are derived using spectroscopic parallaxes Dufton et al. (2006). The cluster is probably associated with the extensive bright emission nebula M 16 (The Eagle Nebula) and suffers from strong differential reddening. The massive stars in NGC 6611 are responsible for the ionization of the HII region M16, the Eagle Nebula, the higher concentration of within 4 arcmin radius central area, while the cluster members are distributed over a region of $\sim$14 arcmin radius, Belikov et al. (2000). Hillenbrand et al. (1993) and Oliveira, 2008 have found a large number of massive stars as well as a large population of pre-main-sequence stars in NGC 6611.

In this paper, we discuss new observations of NGC 6611 at optical wavelengths and we used near-IR wavelength (2MASS) data to study the cluster. This paper is organized as follows. First, we describe the observation and its reduction process by IRAF and the photometry and its calibration. This is followed by the Color Magnitude Diagram (CMD) identification, the spatial structure of the cluster and selection of candidate cluster members have been done. After that we discuss the luminosity, mass function and dynamical state of the cluster. Finally, we concluded and compare its main features to other clusters.

2. Observations and data reduction

CCD VRI images were carried out at the night of 06 June, 2013 using the EEV 42-40 CCD camera mounted at the Newtonian focus of the 188 cm telescope, located at the Kottamia astronomical observatory of NRIAG in Egypt, with pixel size of 13.5 μm × 13.5 μm and a CCD size of 2048 * 2048 pixels^2 cooled by liquid nitrogen each pointing a 10 × 10 arcmin field of view on the sky. More details about the instrument and telescope can be found in Azzam et al. (2009). A number of bias and flat frames were also taken by the target of cluster field. At least 20 flat field exposures were available in filters V, R and I, from the dome and sky illumination. To calibrate the observations, standard field SA 107 (Landolt, 1992) were observed in the same period of observation. In order to provide accurate photometric measurements for faint stars, several deep exposure frames in each filter have been taken. The journal of 78 exposure observations of the cluster is given in Table 1 and the image in filter V shown in Fig. 1.

Images were processed with the help of IRAF software package using standard procedures. Preliminary reductions of all CCD Images for the cluster and stander stars, to apply bias subtraction, flat field corrections and removal of cosmic rays, have been done with standard package in the IRAF software of CCDRED and FORTRAN program. Observations of standard field SA 107 (Landolt, 1992) in the same period of observation have been used for the corrected atmospheric extinction. Instrumental magnitudes for all measured stars were transformed into a standard system using fitting coefficients derived from observations of standard stars whose magnitudes have been well established in Landolt (1992).

The usual reduction procedure has been done with the IRAF packages of CCDRED, DAOPHOT, ALLSTAR and PHOTOCALL to get the magnitudes of the stars using the point spread function (PSF) method. The estimated magnitude has been carried out using DAOPHOT profile fitting software, as described by Stetson (1987, 1992), so that it can be determined reliably to faint levels. The stellar PSF used by DAOPHOT is evaluated from the sum of several uncontaminated stars present in each image to obtain the instrumental magnitudes; the instrumental corrections were then applied for obtaining the standard magnitudes and colors of the stars in each frame. Further processing and conversion of these raw instrumental magnitudes into the standard photometric system have been done using the procedure outlined by Stetson (1992). The adopted photometric calibration equations using the transformation coefficients between instrumental and standard magnitude are the following equations:

$$v = V + Z_v + k_v * X + a_v * (V - R)$$
$$r = R + Z_r + k_r * X + a_r * (V - R)$$
$$i = I + Z_i + k_i * X + a_i * (I - R)$$

where V, R and I are standard magnitudes and v, r and i are the instrumental magnitudes respectively, Z_v, Z_r and Z_i are the zero points in v, r and i respectively, X is the airmass for each filter and k_v, k_r and k_i are the extinction coefficients in V, R and I filters respectively. The magnitudes errors of the cluster NGC 6611 are shown in Fig. 2. The values of the zero point, the color coefficients and the extinction coefficients for each filter are listed in Table 2.

Table 1 Journal of observations.

Date	Filter	No. of exp.	Air mass range	Exp. time (s)
2013 June, 06	V	21	1.347	150
2013 June, 06	R	27	1.421	60
2013 June, 06	I	30	1.419	25

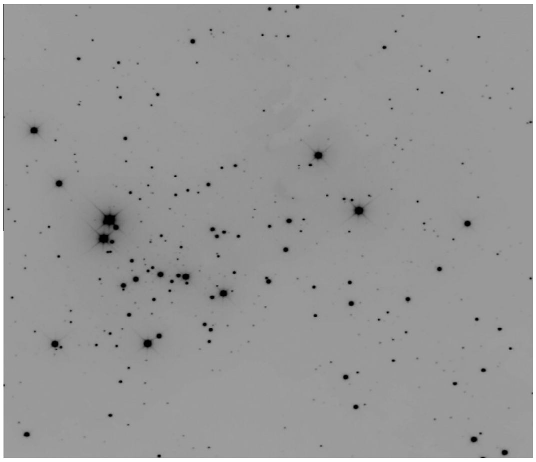

Figure 1 The V image for NGC 6611 cluster regions.

Table 2 The zero point, color coefficients and extinction coefficients for each filter.

Filter vs. parameter	K	a	z
V	0.173	0.0030	2.812
R	0.084	0.002	3.001
I	0.038	−0.001	3.202

3. The Color Magnitude Diagram (CMD)

The deep CMDs extend down to $V = 22.86$ mag in the cluster regions have been done. We use the Color Magnitude Diagrams (CMDs), to determine the age, reddening, distance and other parameters. So, the optical (V, $V–I$), and infrared (J, $J–H$), CMDs for the total number of the observed stars in the decontaminated cluster region ($r < rlim$) are constructed for the cluster NGC 6611 and presented in Figs. 3 and 4 respectively. A well defined cluster main sequence (MS) clearly separated from the bulk of field stars is visible in both CMDs of the cluster region. Evolutionary effects such as the presence of a pre-main sequence branch are clearly visible in the cluster main sequence. The cluster sequences fainter than $V = 20$ mag have a large scatter and perhaps are not clearly defined. The number of main sequence star present in the V, ($V–I$) diagram is therefore fewer in comparison with the J, ($J–H$) diagram. However, these stars provide valuable information to understand the advanced stages of stellar evolution in cluster. The field population dominates the fainter as well as the bluer part of the CMDs and as expected, cluster sequences are better defined in comparison with the previous work. For determining the fundamental cluster parameters, the theoretical Padova isochrones, Bonatto et al. (2004) in different metallicities and ages, in steps of 0.05, and in the logarithm of age have been used. This step was adopted as a typical uncertainty of the log age. We obtain an age estimate is about 3.6 Myr, with the isochrones of the solar metallicity $Z = 0.019$ and the age of cluster has not an exact range may due to the most star in the cluster is the pre-main sequence star. We have determined the optical and infrared color excesses. $E_{(V-I)} = 0.430 \pm 0.04$ mag, $E_{(J-H)} = 0.31 \pm 0.02$ and estimate of the absolute distance modulus $(m–M)o = 12.3 \pm 0.01$ mag, which imply that the distance of the cluster is 2.2 ± 0.21 kpc. The given distance for the cluster by other authors ranges from 1.6 kpc to 3.4 kpc see Sagar and Joshi (1979).

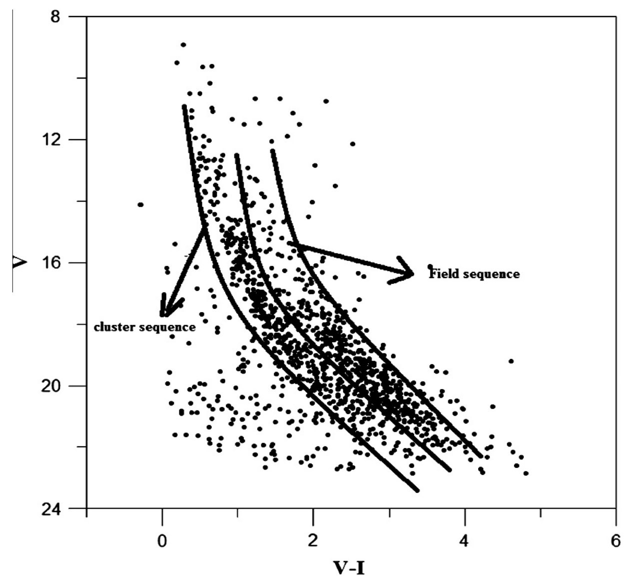

Figure 3 The V; ($V–I$) diagrams for all stars observed in cluster and field regions. The regions delimiting the MS stars of the cluster and field populations are marked, the middle soled line separate between filed star and cluster star.

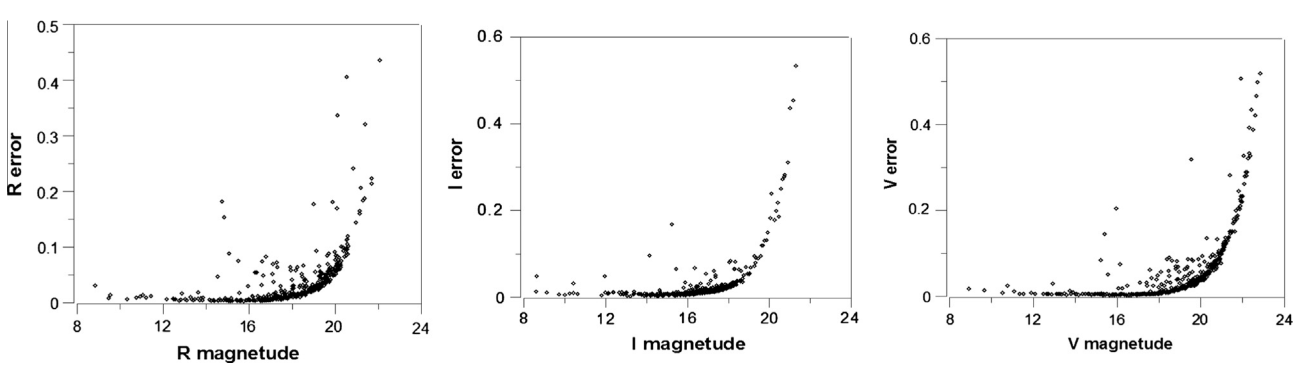

Figure 2 The magnitude errors of the cluster NGC 6611.

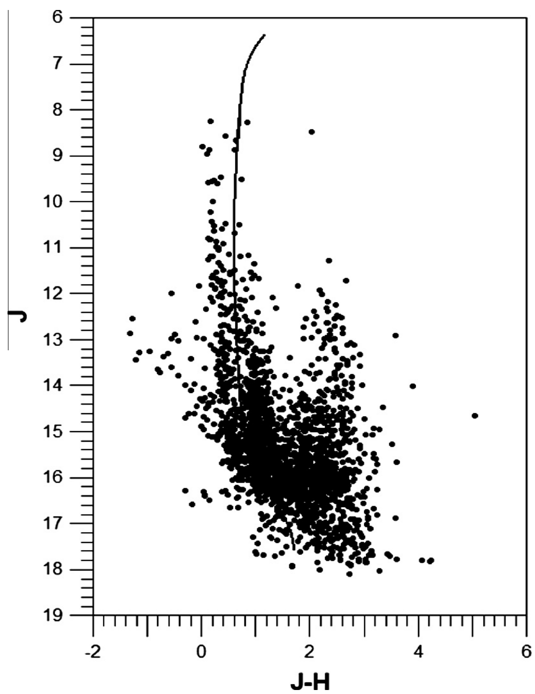

Figure 4 The J; (J–H) diagrams for all stars in the cluster and field regions. The regions delimiting the MS stars of the cluster and field populations are very clear.

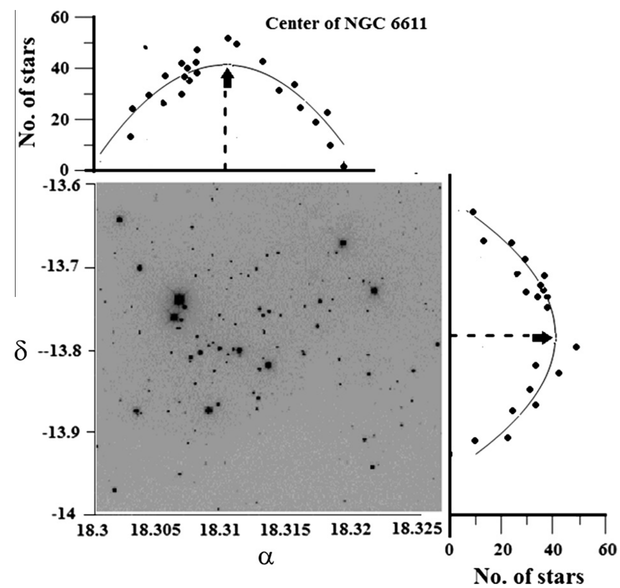

Figure 5 The radial density profile of the cluster. Clusters' limiting radius, core radius, and the background field density are shown in the figure.

4. Radius and spatial structure of the cluster

To investigate the cluster structure and the spatial structure and determine the cluster radius and cluster center we use the radial stellar surface density distribution (ρ). The first step is determining the cluster center by constructing a rectangular strip around the cluster center (visually determined) in α and δ direction, Selim et al. (2014). The number density of stars is the number of stars per unit area in the cluster regions. The cluster region is divided into a number of concentric circles with respect to the cluster center. Then, we count the stars in each strip to build the frequency distribution. These histograms were fitted by a Gaussian function, whereas the location of a maximum number of stars (peak) indicates the new cluster center, as illustrated in Fig. 5. Cluster center corresponds to (α = 18 h 18 m 48 s, and δ = −13 d 47 m 11 s). On the other hand the radial density profiles thus obtained for cluster members and different magnitude intervals of MS and all star members are shown in Fig. 6a, with the core radius = 2.6 arcmin and cluster radius = 9.3 arcmin for NGC 6611. However, the value of 14 arcmin determined by Belikov et al. (2000) as a cluster radius is larger than the present cluster radius. The other method for determining the cluster center based on K-means algorithm (geometry), by El Aziz et al. (2015), has been used, and the maximum spatial density value and the center of the open star cluster are usually at the maximum value of the radial density profile. Also determining the cluster center (c_x, c_y) with largest number of elements (high density) maximum density of stars located within the center in the value of (x, y) using K-means algorithm we found that the new cluster center corresponds to (α = 18 h 18 m 46 s, and δ = −13 d 47 m 13 s) as shown in Fig. 6b. The cluster radius by maximum spatial density of the open star cluster is usually at the minimum value of the radial density profile.

5. Photometric selection of candidate cluster members

In this section we determine the open cluster membership based on geometry and photometric properties through two stages: the first one is to clustering stars based on K-means algorithm (geometry). Determining the cluster center by maximum spatial density value and the center of the open star cluster is usually at the maximum value of the radial density profile as show on above in Fig. 6b. The cluster radius by maximum spatial density of the open star cluster is usually at the minimum value of the radial density profile as show in Fig. 6a. The second stage is clustering the results from first stage based on physical properties (photometric) and then we compute the difference in magnitude of color index

$$VI = V_{\mathrm{mag}} – I_{\mathrm{mag}}\ (\text{color index}),\ \text{such that}\quad -0.2 \leqslant \text{color index} \leqslant 0.2.$$

Then, superimpose the CMDs and adopt the above (V–I) value. In Fig. 7, we only show the CMDs of the NGC 6611 stars member located within its radius, as well as the probable cluster members according to the photometric criteria.

6. The luminosity and mass function

As we know that one of the fundamental and most important properties in a stellar system is the luminous and the fainter stars, but dynamically more important low mass stars is the Mass Function (MF). For NGC 6611, the MF can be obtained reliably because our deep observations cover regions of the cluster also where the presence of low mass stars is expected. The first step in MF determination is finding the Luminosity Function (LF) from the observed CMD using

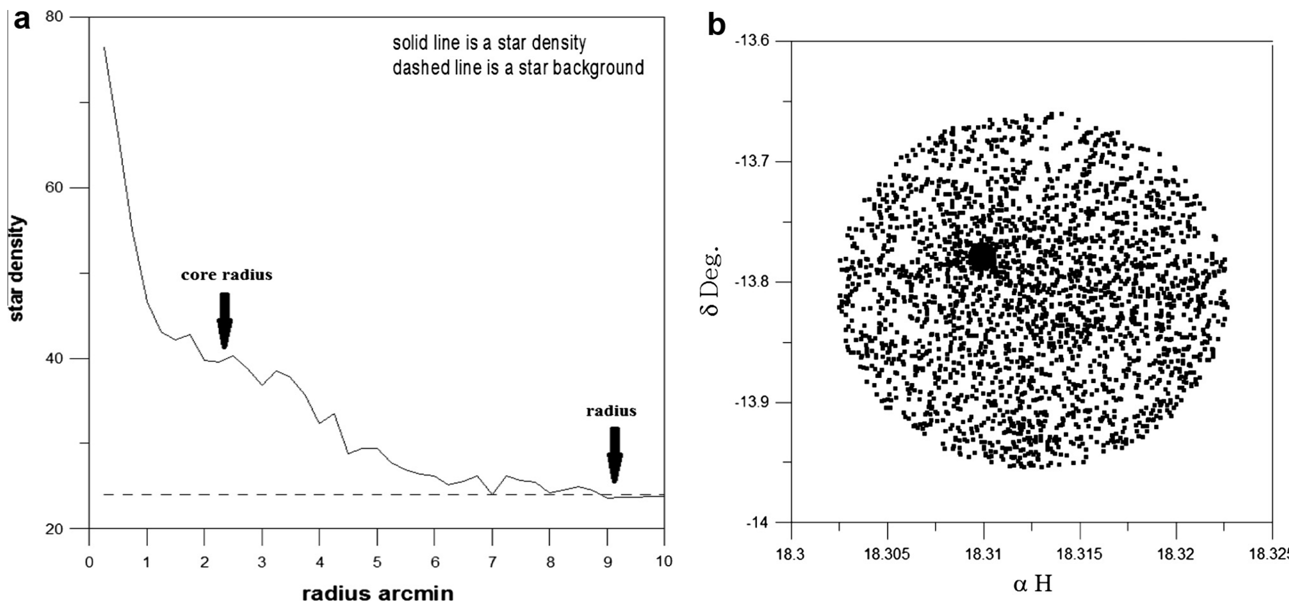

Figure 6 The cluster center and the star radius of the star density.

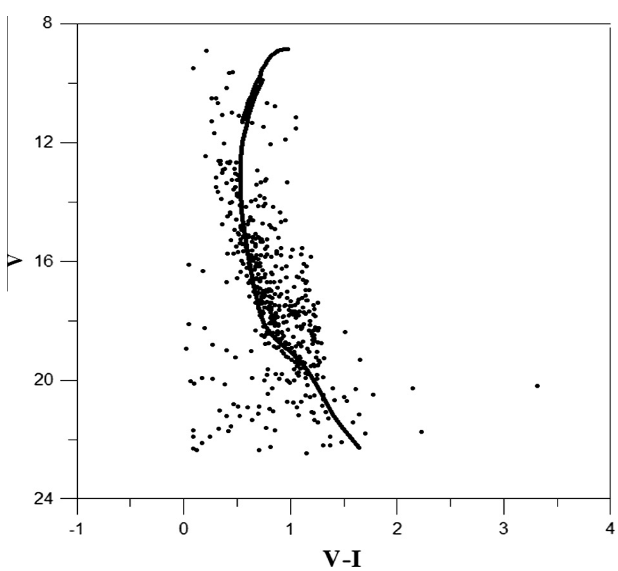

Figure 7 The V; (V–I) diagrams for all probable star members in cluster NGC 6611.

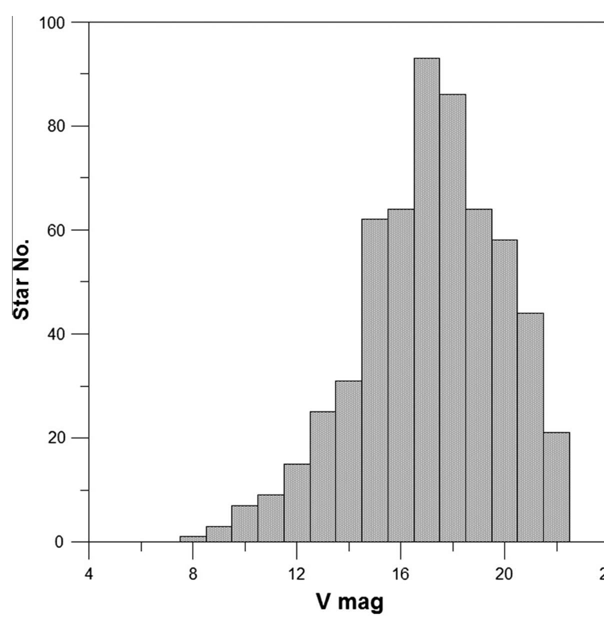

Figure 8 The LF for cluster regions.

the number of star members in the cluster after selecting the stellar membership of the clusters. It is very important in determining the luminosity, mass functions and the total mass of the investigated cluster. Apparent Luminosity Function (LF) for stars member is derived by directly counting them in luminosity bins of 1 mag each. The resulting apparent LFs for the cluster NGC 6611 are shown in Fig. 8. The MF which is the number of stars formed over the masses interval at the same time of the star member, has been studied. The considered MS brightness is in the V; (V–I) diagram. The MF of the cluster is built using the theoretical evolutionary tracks and their isochrones at the specific age of the cluster. For this purpose, the following procedure is considered. The masses of the stars have been estimated from the isochrones of metallicity $Z = 0.019$. Then the liner equations of second degree have been used plot and the MF is shown in Fig. 9. In the present work, for the computation of MF, the masses have been estimated for the cluster members by using the stellar mass–luminosity relation. The slopes of the MF are found to be $\sim -0.67 \pm 0.12$. The resulting shows the number of stars in the range from 0.9 to $35 M_{\odot}$.

Our values, in agreement with Bonatto and Bica (2005) as it is an young age (3.6 Myr) cluster, and the flatness of the MF's slope is not a surprise and it may be due to dynamical evolution rather than the intrinsic difference in the initial MF.

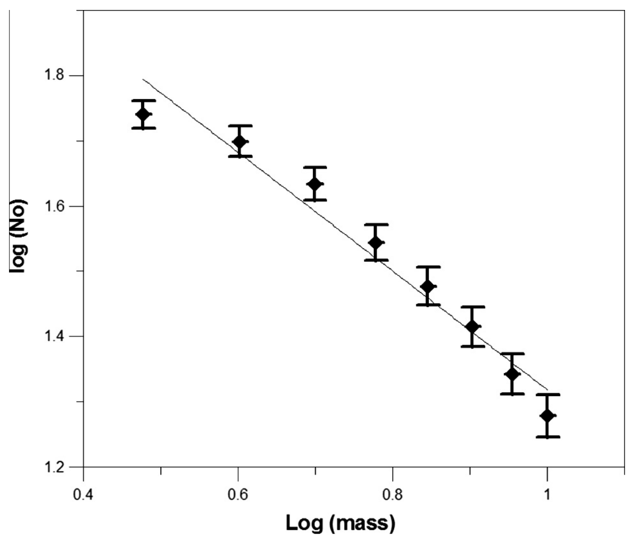

Figure 9 The MF for cluster regions with the error bar.

7. Dynamical state of the cluster

If the cluster has a uniform spatial stellar mass distribution at the time of formation then the spatial stellar mass distribution changes as a cluster evolves dynamically. As a consequence, massive stars concentrated toward the cluster center and low mass stars reach to a high random velocity and move away toward the outer region of the cluster. Meylan and Heggie (1997) conclude that the theory and simulations show that, not only significant mass segregation among heaviest stars in the cluster core occurs in the local relaxation time, but also affecting a large fraction of the mass of the cluster requires a time comparable to the average relaxation time, averaged over the inner half of the mass.

The dynamical relaxation time, Te, is the time in which the individual stars exchange energies and their velocity distribution approaches a Maxwellian equilibrium. It is given by Spitzer and Hart (1971) as follows:

$$Te = \frac{8.9 \times N^{1/2} R_h^2}{\langle m \rangle^2 \log(0.4N)}$$

where N is the number of cluster members, R_h is the radius containing half of the cluster mass and $\langle m \rangle$ is the average mass of the cluster stars. For the halfmass radius, we used half of the cluster extent i.e., $R_h = 4.1$ pc due to inability to estimate R_h from our data. To determine Te, we estimate the total number of cluster stars in the mass range from 0.9 to $35 M_\odot$ as 576 members which yields a total cluster mass of $2260 M_\odot$. It should be noted the above value of star member more than the mass estimated by the Tadross et al. (2002). The mass stars cluster is resulting $2260 M_\odot$. This value is $\sim$1.5 times larger than the estimate by Bonatto and Bica (2005). Belikov et al. (2000) found that NGC 6611 cluster members are distributed over a region of 14 arcmin radius, with a higher concentration in the largely unobscured 4 arcmin radius central area. The value of Te is about 0.027 Myr. However, we conclude that the data considered here up to a certain brightness of cluster members inclusion with the limiting V magnitude will decrease the value of N and increase the value of $\langle m \rangle$. This will result in lowest values of Te. As Te is significantly less than the age of cluster, we conclude that the cluster is dynamically evolved and consequently, we expect concentration of higher mass stars toward the cluster center.

8. Conclusions

The VRI CCD photometric observations are presented for a sample of 1222 stars in the region of open star cluster NGC 6611 up to a limiting magnitude of V about 22.86 mag and the data form 2MASS for a study of photometry, spatial structure and radial variation in the cluster region. The analysis was based mostly on optical V, R, I, and 2MASS J, H and Ks across the region, from which we built radial density profiles and mass functions. The cluster parameters are determined by fitting the theoretical isochrones given by Bonatto et al. (2004) in the V, $(V–I)$ diagrams of the cluster. The main conclusions of the present work are as follows:

1. The value of the core radius is about 2.6 while the extent of the cluster is about 4 times larger with a value of 9.3 arcmin.
2. The MF of the entire cluster appears to be one of the flattest with a value of 1.6 in the mass range $0.9 < M_\odot < 25$.
3. The cluster distance estimated is 2.2 ± 0.21 kpc. It agrees well with earlier determinations. Fitting of the theoretical padvia isochrones given by Bonatto et al. (2004) for $Z = 0.019$ to the CMDs yields an age of 3.6 Myr for the cluster and a value of $E_{(V-I)} = 0.530 \pm 0.04$ mag corresponding to $E_{(J-H)} = 0.31 \pm 0.02$ mag. The present photometry is compared with available previous photometry works. The age of the cluster has been determined by Sagar and Joshi (1979) is 5.5 Myr.
4. The field-star decontamination resulting CMDs present a MS restricted to stars more massive than $\approx 5 M_\odot$ and a collection of PMS stars.
5. Compared to older open clusters in terms of structural and dynamical-evolution-related parameters, the overall cluster behaves as a massive open cluster at young ages.
6. The slope of cluster indicates that the mass segregation has already affected the mass distribution and seems to be related to more massive prototype stars.
7. The cluster relaxation time means that mass segregation did not have time to redistribute stars in large scale throughout the body of cluster.

Acknowledgments

This paper is a part of the project no. STDF-1335; funded by Science & Technology Development Fund (STDF) under the Egyptian Ministry for Scientific Research. The project team expresses their deep appreciation to the administrators of STDF and its organization. This publication also makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

References

Azzam, Y.A., Ali, G.B., Ismail, H.A., Haroon, A., Selim, I., 2009. Current and future capabilities of the 74-inch telescope of Kottamia astronomical observatory in Egypt. Third UN/ESA/NASA Workshop on the International Heliophysical Year 2007 and Basic Space Science. ISBN 978-3-642-03323-0. LCCN 2009933994, pp. 175–187.

Belikov, A., Kharchenko, N., Piskunov, A., Schilbach, E., 1999. The extremely young open cluster NGC 6611: compiled catalogue, absorption map and the HR diagram. A&AS 134, 525B.

Belikov, A., Kharchenko, N., Piskunov, A., Schilbach, E., 2000. The extremely young open cluster NGC 6611 luminosity function and star formation history. A&A 358, 886B.

Bonatto, C., Bica, E., 2005. Detailed analysis of open clusters: A mass function break and evidence of a fundamental plane. A&A 358, 886B.

Bonatto, C., Bica, E., Girardi, L., 2004. Theoretical isochrones compared to 2MASS observations: open clusters at nearly solar metallicity. A&A 415, 571B.

Dufton, P.L., Smartt, S.J., Lee, J.K., Ryans, R.S.I., Hunter, I., Evans, C.J., Herrero, A., Trundle, C., Lennon, D.J., Irwin, M.J., Kaufer, A., 2006. The VLT-FLAMES survey of massive stars: stellar parameters and rotational velocities in NGC 3293, NGC 4755 and NGC 6611. A&A 457, 265D.

El Aziz, Mohamed Abd, Selim, I., Essam, A., 2015. Open cluster membership probability based on *K*-means clustering algorithm (summited for publication).

Hillenbrand, Lynne A., Massey, Philip, Strom, Stephen E., Merrill, K. Michael, 1993. NGC 6611: a cluster caught in the act. AJ 106, 1906H.

Landolt, Arlo U., 1992. UBVRI photometric standard stars in the magnitude range 11.5–16.0 around the celestial equator. AJ 104, 340.

Meylan, G., Heggie, D.C., 1997. Internal dynamics of globular clusters. A&ARv 8, 1M.

Martayan, C., Floquet, M., Hubert, A.M., Neiner, C., Frémat, Y., Baade, D., Fabregat, J., 2008. Early-type objects in NGC 6611 and the Eagle Nebula. A&A 489, 459M.

Oliveira, J.M., 2008. Star formation in the Eagle Nebula. hsf2.book, p. 599O.

Sagar, R., Joshi, U.C., 1979. A study of the young open cluster NGC 6611. Ap&SS 66, 3S.

Stetson, Peter B., 1987. DAOPHOT – a computer program for crowded-field stellar photometry. PASP 99, 191S.

Stetson, Peter B., 1992. More experiments with DAOPHOT II and WF/PC images. ASPC 25, 297S.

Selim, I., Haroon, A., Ismail, H., Ahmed, N., Essam, A., Ali, G.B., 2014. Optical and infrared photometric study of open star cluster NGC2266. RAJ 24, 159.

Spitzer Jr., Lyman, Hart, Michael H., 1971. Random gravitational encounters and the evolution of spherical systems. I. Method. ApJ 164, 399S.

The, P.S., Cuypers, H., Djie, Tjin A., Feinstein, A., Westerlund, B.E., 1985. NGC6611 – W409 – a remarkable Be star with a strong variable near-infrared excess. A&A 150, 345T.

The, P.S., de Winter, D., Feinstein, A., Westerlund, B.E., 1990. The extinction law, the distance and the HR diagram of the extremely young open cluster NGC 6611. A&AS 82, 319T.

Tadross, A.L., Marie, M.A., Osman, A.I., Hassan, S.M., 2002. Astrometry of the open cluster M25. Ap&SS 282, 607T.

Walker, Merle F., 1961. Studies of extremely young clusters. IV. NGC 6611. ApJ 133, 438W.