JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
49: 53∼57, 2016 April

http://dx.doi.org/10.5303/JKAS.2016.49.2.53
pISSN: 1225-4614 · eISSN: 2288-890X
http://jkas.kas.org

PHOTOMETRIC STUDY OF IC 2156

A. L. TADROSS AND Y. H. M. HENDY
National Research Institute of Astronomy and Geophysics, 11421 Helwan, Cairo, Egypt; altadross@yahoo.com

Received November 18, 2015; accepted January 12, 2016

Abstract: We present an optical *UBVRI* photometric analysis of the poorly studied open star cluster IC 2156 using Sloan Digital Sky Survey data in order to estimate its astrophysical properties. We compare these with results from our previous studies that relied on the 2MASS JHK near-infrared photometry. The stellar density distributions and color-magnitude diagrams of the cluster are used to determine its geometrical structure, real radius, core and tidal radii, and its distance from the Sun, the Galactic plane, and the Galactic center. We also estimate, the age, color excesses, reddening-free distance modulus, membership, total mass, luminosity function, mass function, and relaxation time of the cluster.

Key words: galaxy: open clusters and associations — individual: IC 2156 — astrometry — stars: luminosity function — mass function.

1. INTRODUCTION

Open star clusters are important celestial bodies for understanding star formation and stellar evolution. Color-magnitude Diagram (CMD) analysis through isochrones gives us good estimates of the astrophysical parameters of clusters, e.g., age, reddening, and distance. In the last decades, many studies have been performed using different instruments; starting from photographic photometry to the current charge-coupled device (CCD) photometry, and employing many different isochrones models. The large amount of results produced in the literature is gathered in catalogs and databases, e.g., Webda[1] and Dias[2]. We have presented a series of papers that have contributed to these results (Tadross 2011, 2009a, 2009b, 2008a, 2008b).

The present study exploits the last version of the Sloan Digital Sky Survey data release, Alam et al. (2015) - (SDSS DR12)[3], which provides homogeneous *ugriz* photometry for stars in the northern sky. The most important reason for using SDSS lies in the *ugriz* point-spread function (PSF) photometry for setting the zero points of *UBVRI* (Chonis & Gaskell, 2008). Tadross (2009b) previously studied IC 2156 using JHK photometry from the 2MASS survey. Figure 1 shows the composite SDSS image of IC 2156, taken from the survey website[3].

This paper is organized as follows. Data extraction is presented in Section 2, while the data analysis and estimation of the parameters are described in Section 3. Finally, the results and conclusion of our study are summarized in Section 4.

2. DATA EXTRACTION

The open star cluster IC 2156 is located at J2000.0 coordinates $\alpha = 06^h\ 04^m\ 51^s$, $\delta = +24^\circ\ 09'\ 30''$, $\ell = 186.291^\circ$, $b = 1.297^\circ$. We extract PSF magnitudes of stars within a 10 arcmin radius from the cluster center from the SDSS data in ugriz bands. The *ugriz* magnitudes were converted into the *UBVRI* photometric system (Johnson-Cousins) using Chonis & Gaskell (2008). The standard errors of the transformation equations for *U*, *B*, *V*, *R*, and *I* are 0.007, 0.007, 0.005, 0.005 and 0.009, respectively. Figure 2 shows the magnitude of the errors in each filter.

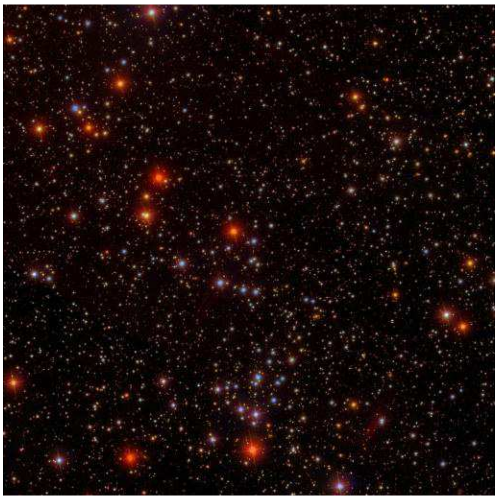

Figure 1. Composite SDSS $10' \times 10'$ colored image of IC 2156.

To get robust data for investigating the cluster, a photometric completeness limit has been applied to the photometric SDSS data to avoid over-sampling of the lower parts of the cluster's CMDs (cf., Bonatto et al. 2004). Stars with observational uncertainties ≥ 0.20 mag have been removed. In addition, we adopt stellar photometric membership criteria which require stars to be within 0.1 mag around the zero age main sequence (ZAMS) curves in the CMDs (Clariá & Lapasset 1986).

CORRESPONDING AUTHOR: A. L. Tadross
[1]http://www.univie.ac.at/webda/navigation.html
[2]http://www.wilton.unifei.edu.br/ocdb/
[3]http://www.sdss.org/dr12/

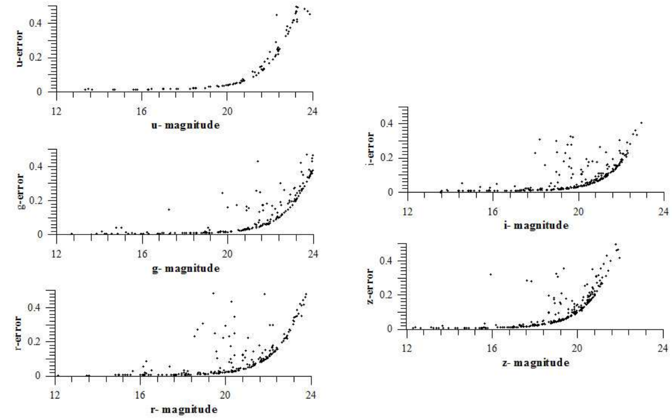

Figure 2. Photometric errors versus magnitude in the ugriz bands for the cluster IC 2156.

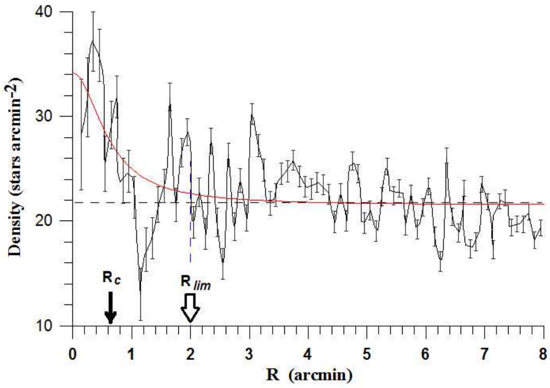

Figure 3. The radial density profile of the cluster IC 2156. The real radius, core radius, and the background field density are shown in the figure. The curved solid line represents the fitting of King model. Error bars are determined from sampling statistics $[1/(N)^{0.5}$ where N is the number of stars used in the density estimation at that point].

3. DATA ANALYSIS

3.1. Cluster's Radial Density Profile

To establish the radial density profile (RDP) of IC 2156, the area is divided into concentric circles $\leq$ 1 arcmin and increasing distance from the cluster center. The number density, R_i, in the ith zone is calculated by using the formula $R_i = N_i/A_i$, where N_i is the number of stars within the ith circle and A_i is the area of that circle. We subtract the number of stars in the (i+1)th circle from the number of stars in the ith circle so as to obtain the number of stars within the relevant shell's area instead of a cumulative count. The density uncertainties in each shell are assumed to follow the Poisson noise. The empirical King model (1966) is applied for parametrizing the density function $\rho(r)$ as:

$$\rho(r) = f_{bg} + \frac{f_0}{1 + (r/r_c)^2}, \tag{1}$$

where f_{bg}, f_0 and r_c are background and central star density and the core radius of the cluster, respectively. The real radius of the cluster can be defined at the radius which covers the entire cluster area and for which the stellar cluster density converges to the background field density. Because of the strong background contamination, it is not possible to completely separate field stars from cluster members. The real radius of the cluster can be described as an observational border that depends on the spatial density distribution of the cluster members and the degree of field-star contamination. Figure 3 shows the RDP of IC 2156. The real radius, core radius and the background field density are shown in the figure. Finally, knowing the total mass of the cluster (Section 3.4), the tidal radius can be calculated by the equation of Jeffries et al. (2001):

$$R_t = 1.46(M_c)^{1/3}, \tag{2}$$

where R_t and M_c are the tidal radius and total mass of the cluster, respectively.

3.2. Photometry

Here, we determine the main astrophysical parameters of IC 2156, i.e., color excesses, age, and distance modulus. First we use stars with high membership probability (i.e., stars with good precision and located very close to the cluster's center) to derive the reddening value from the Color-Color, (U–B)-(B–V), diagram. The color excesses are found to be E(B–V)= 0.55 mag and E(B–U)= 0.39 mag, as shown in the upper panel of Figure 4.

Next, we determine the age and distance modulus of IC 2156 by fitting isochrones to the CMDs of the cluster. Several isochrones have been applied using the stellar evolution models of Girardi et al. (2010), as shown in the lower panels of Figure 4.

It is worth mentioning that the assumption of solar metallicity is quite adequate for young and intermediate age open clusters, which are close to the Galactic disk. However, for a specific age isochrones, the fit is obtained at the same distance modulus (12.30 mag) and the same age (250 Myr) for all the diagrams V-(B–V), V-(V–I), V-(V–R), and V-(R–I). The color excesses follow the Fiorucci & Munari (2003) relations for interstellar medium as shown in Figure 4 (lower panel). These are found to be 0.55, 0.70, 0.32, and 0.44 mag, respectively.

Under the assumption of $R_{gc_\odot}$= 8.34 ± 0.16 kpc (Reid et al. 2014, based on high precision measurements of the Milky Way) the distance of IC 2156 from the Galactic center R_{gc} is estimated to be 11.20 kpc. Also, the projected distances on the Galactic plane from the Sun ($X_\odot$ & $Y_\odot$) and the distance from the Galactic plane ($Z_\odot$), are determined to be 2865, –315, and 65 pc, respectively (Table 1). For more details about the geometry and Galactic distances calculations, see Tadross (2011).

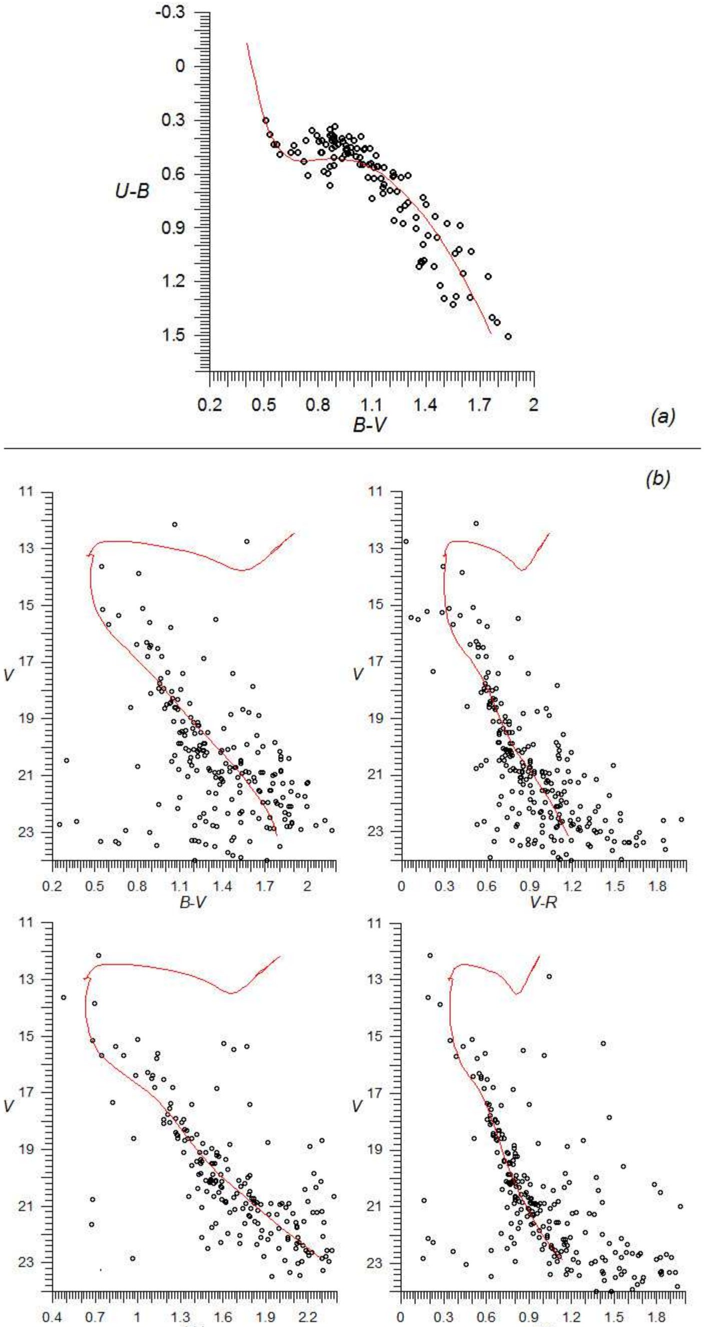

Figure 4. (a) CC-Diagram of the reliable membership probability of IC 2156, where E(B-V)= 0.55 mag and E(U-B)= 0.39 mag. (b) CM-Diagrams of the cluster, where the reddening-free distance modulus is taken at 12.30 mag, and the color excesses, E(B-V), E(V-R), E(V-I) and E(R-I), are taken to be 0.55, 0.32, 0.70 and 0.44 mag, respectively.

3.3. Luminosity Function

It is difficult to determine the membership of a cluster using only the stellar RDP. It might be claimed that most of the stars in the inner concentric rings are quite likely members, whereas the external rings are more contaminated by field stars. Therefore, the stars, which are close to the center of the cluster and near the main-sequence (MS) in CMDs are taken to have a high probability membership. These MS stars are important in determining the luminosity, mass function, and the total mass of the cluster. For this purpose, we obtained the Luminosity Function (LF) of the cluster by summing up the V band luminosities of all stars within the determined real area of the cluster. Before building the LF, the apparent V band magnitudes of the cluster members were converted into absolute magnitude using the distance modulus of the cluster. For the best counting statistics, we constructed a histogram of LF to include a reasonable number of stars in each absolute V magnitude bins (Figure 5).

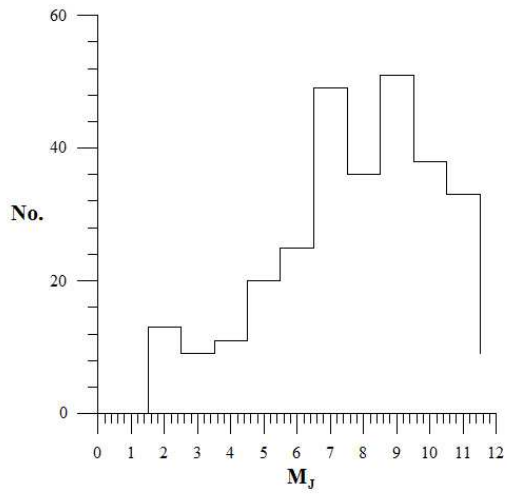

Figure 5. The luminosity function of IC 2156. The histogram represents the number of stars in each magnitude bin width.

3.4. Mass Function and Total Mass

The mass function (MF) of the cluster is built using the theoretical evolutionary tracks and their isochrones at the specific age of the cluster. The masses of the cluster members can be calculated using the polynomial expression developed by Girardi et al. (2010) and assuming solar metallicity.

The LF and MF are correlated with each other according to the known Mass-luminosity relation. The accurate determination of both (LF & MF) suffers from field star contamination, membership uncertainty, and mass segregation, which affects relatively young clusters (Scalo 1998). On the other hand, the properties and evolution of a star are closely related to its mass, so the determination of the initial mass function (IMF) is needed. The IMF is an empirical relation that describes the mass distribution of a population of stars in terms of their theoretical initial mass. It is defined in terms of a power law as

$$\frac{dN}{dM} \propto M^{-\alpha}, \tag{3}$$

where $\frac{dN}{dM}$ is the number of stars within a mass interval (M:M+dM), and α is a dimensionless exponent. The IMF of massive stars ($> 1\ M_\odot$) has been studied and well established by Salpeter (1955), with $\alpha = 2.35$. Thus the number of stars in each mass range decreases rapidly with increasing mass. The investigated MF slope of IC 2156 is found to be –2.7, which is close to Salpeter's value, as shown in Figure 6.

We estimate the total mass of the cluster by deriving the mass of each star based on a polynomial fit to the solar metallicity isochrones (absolute magnitudes versus actual masses) at the age of the cluster. The sum of products of the number of stars in each bin by the mean mass of that bin yields the total mass of the cluster, which is found to be 310 $M_\odot$.

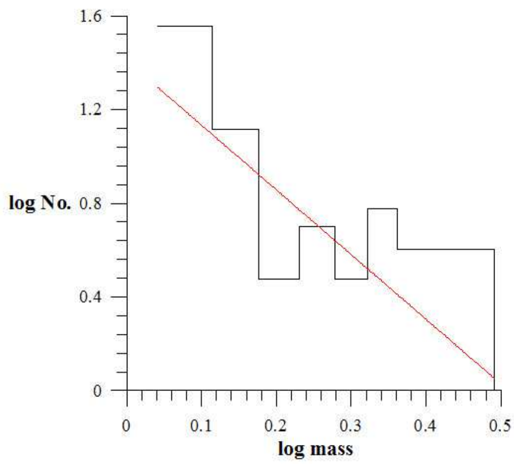

Figure 6. The mass function of IC 2156. The inclined red line represents the slope of the MF, which is 2.7.

3.5. Dynamical State and Relaxation Time

The time that the cluster needs to build itself and reach an equilibrium state against the contraction and destruction forces is known as the relaxation time (T_{relax}). This time depends mainly on the number of members and the cluster diameter. To describe the dynamical state of the cluster, the relaxation time can be calculated as

$$T_{relax} = \frac{N}{8 \ln N}\, T_{cross} \quad , \tag{4}$$

where $T_{cross} = D/\sigma_V$ denotes the crossing time, N is the total number of stars in the investigated region of diameter D, and σ_V is the velocity dispersion (Binney & Tremaine 1998) with a typical value of 3 km s^{-1} (Binney & Merrifield 1987). Using the above formula we estimate the dynamical relaxation time for IC 2156 to be 5.5 Myr. This implies that IC 2156 is indeed dynamically relaxed.

Table 1
Comparison of Tadross (2009b) and this study.

Parameter	Tadross (2009b)	This work
Membership	—	295 stars
Age	250 Myr	250 Myr
E (B–V)	0.67 mag	0.55 mag
Metal abundance (Z)	0.019	0.019
$(V - M_v)_o$	12.20 mag	12.30 mag
Distance	2750±125 pc	2880±133 pc
Radius	2.0′	2.0′ (1.67 pc)
Core radius	—	0.62′
Tidal radius	—	9.9 pc
R_g	10.6 kpc	11.2 kpc
$X_\odot$	2087 pc	2865 pc
$Y_\odot$	–230 pc	–315 pc
$Z_\odot$	47 pc	65 pc
Luminosity function	—	Estimated
IMF slope	—	–2.7± 0.09
Total mass	—	≈ 310 $M_\odot$
Relaxation time	—	5.5 Myr

4. CONCLUSION

Photometry for the open star cluster IC 2156 has been extracted in the *ugriz* filters from the SDSS survey, converted to *UBVRI* using the transformation equations of Chonis & Gaskell (2008). This open cluster has been studied before by Tadross (2009b) using *JHK* photometry from the 2MASS survey. The comparison of our present study of the cluster with the previous one is summarized in Table 1. We find differences in the distances of the cluster from the Sun, the Galactic center R_{gc}, the Sun's projection location on the Galactic plane ($X_\odot$ & $Y_\odot$), and from the Galactic plane ($Z_\odot$) as well.

ACKNOWLEDGMENTS

This paper is part of the project No. STDF-1335; funded by the Science & Technology Development Fund (STDF) under the Egyptian Ministry for Scientific Research. The authors would like to thank the anonymous referee for his/her considerable contributions to improve the paper. This research has made use of the SDSS DR12 (Sloan Digital Sky Survey SDSS DR12) and the Two Micron All Sky Survey (2MASS).

REFERENCES

Alam, S., Albareti, F. D., Allende, P. C., et al. 2015, The Eleventh and Twelfth Data Releases of the Sloan Digital Sky Survey: Final Data from SDSS-III, ApJS, 219, 12

Binney, J., & Tremaine, S. 1987, in Galactic Dynamics, Princeton Series in Astrophysics (Princeton: Princeton University Press)

Bonatto, C., & Bica, E. 2006, Methods for Improving Open Cluster Fundamental Parameters Applied to M 52 and NGC 3960, A&A, 455,

Carpenter, J. M. 2001, Color Transformations for the 2MASS Second Incremental Data Release, AJ, 121, 2851

Chonis, T. S., & Gaskell, C. M. 2008, Setting *UBVRI* Photometric Zero-Points Using Sloan Digital Sky Survey *ugriz* Magnitudes, AJ, 135, 264

Clariá, J. J., & Lapasset, E. 1986, Fundamental Parameters of the Open Cluster NGC 2567, AJ, 91, 326

Fiorucci, M., & Munari, U. 2003, The Asiago Database on Photometric Systems (ADPS). II. Band and reddening parameters, A&A, 401, 781

Girardi, L., Williams, B. F., Gilbert, K. M., Rosenfield, P., Dalcanton, J., Marigo, P., Boyer, M. L., Dolphin, A., Weisz, D. R., Melbourne, J., et al. 2010, The ACS Nearby Galaxy Survey Treasury. IX. Constraining Asymptotic Giant Branch Evolution with Old Metal-Poor Galaxies, ApJ, 724, 1030

Jeffries, R. D., Thurston, M. R., & Hambly, N. C. 2001, Photometry and Membership for Low Mass Stars in the Young Open Cluster NGC 2516, A&A, 375, 863

King, I. R. 1966, The Structure of Star Clusters. III. Some Simple Dynamical Models, AJ, 71, 64

Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2014, Trigonometric Parallaxes of High Mass Star Forming Regions: the Structure and Kinematics of the Milky Way, ApJ, 783, 130

Salpeter, E. E. 1955, The Luminosity Function and Stellar Evolution, ApJ, 121, 161

Scalo, J. 1998, The IMF Revisited: A Case for Variations, ASPC, 142, 201

Tadross, A. L. 2009a, The Fundamental Parameters of 60 Unstudied Open Star Clusters (Czernik, Dol-Dzim, Kronberger, and Turner), Ap&SS, 323, 383

Tadross, A. L. 2009b, An Investigation of 11 Previously Unstudied Open Star Clusters, New Astronomy, 14, 200

Tadross, A. L. 2008a, A Catalogue of previously unstudied Berkeley clusters, MNRAS, 389, 285

Tadross, A. L. 2008b, The Main Parameters of 25 Unstudied Open Star Clusters, New Astronomy, 13, 370

Tadross, A. L. 2011, A Catalog of 120 NGC Open Star Clusters, JKAS, 44, 1

Binney, J., & Merrifield, M. 1998, in Galactic Astronomy, Princeton Series in Astrophysics (Princeton: Princeton University Press)

Bonatto, C., & Bica, E. 2003, Mass Segregation in M 67 with 2MASS, A&A, 405, 525

Bonatto, C., Bica, E., & Girardi, L. 2004, Theoretical Isochrones Compared to 2MASS Observations: Open Clusters at nearly Solar Metallicity, A&A, 415, 571