ISSN 1990-3413, Astrophysical Bulletin, 2022, Vol. 77, No. 1, pp. 78–83. © Pleiades Publishing, Ltd., 2022.

Photometric Study of the Open Cluster NGC 225

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Received November 7, 2021; revised December 14, 2021; accepted December 14, 2021

Abstract—NGC 225 is a young moderately populated cluster with discrepant age, distance, and color excess estimates reported by different authors. We combine our photometry with the data from large surveys (2MASS, WISE, Pan-STARRS) to derive the parameters of NGC 225 and study the extinction law in the near infrared in the direction of the cluster. We use theoretical isochrones to infer the color excess $E(B-V) = 0.29 \pm 0.01$, distance $D = 667 \pm 18$ pc, and Age = 100–160 Myr. We fit extinction in the infrared by a power-law relation, $\lambda^{-\alpha}$, and find $\alpha = 2.16 \pm 0.34$.

Keywords: (Galaxy): open clusters and associations: general—(Galaxy): open clusters and associations: individual: NGC225—techniques: photometric

DOI: 10.1134/S1990341322010126

1. INTRODUCTION

The study of the Galaxy, its structure and evolution has always been one of the main and most important branches of the astronomy. As a stage in the hierarchy of star formation, open star clusters (OC) may serve as a key to a deeper understanding of the processes occurring in the Milky Way. Members of an OC share some of the physical properties, offering an opportunity to investigate them with special methods, yielding more accurate results.

NGC 225 is a moderately populated open star cluster, for which, however, quite discrepant parameter estimates have been published. The cluster age estimates reported by different authors range from less than 10 Myr (Subramaniam et al., 2006) to 900 ± 100 Myr (Bilir et al., 2016). According to Lattanzi et al. (1991), the distance to the cluster is $d = 525 \pm 73$ pc, whereas a recent analysis based on Gaia DR2 (Brown et al., 2018) yields $d = 684.3$ pc (Cantat-Gaudin et al., 2018). Svolopoulos (1962), Subramaniam et al. (2006) reported color excess $E(B-V) = 029$, whereas Bilir et al. (2016) found $E(B-V) = 0151 \pm 0047$. We aim to resolve the above discrepancies and investigate the extinction law toward NGC 225 using both our own U, B, V, R_c, I_c-band photometric observations and the data from large photometric surveys.

2. CLUSTERING ALGORITHM

To assign membership probabilities we performed cluster analysis in 3-dimensional space. We analyzed proper motions and parallaxes from Gaia DR2 (Brown et al., 2018) for stars within the 25′ radius field centered on $\alpha = 00^h43^m31^s$, $\delta = 61°47'43''$. We used only the data for stars with fractional parallax errors less than 20%. Applying clustering algorithms with no prior knowledge about the properties of the groups studied is usually quite a complicated and even challenging task. Fortunately, in the case of NGC 225 cluster stars form a prominent clump in vector-point diagram around $\mu_\alpha^* \approx -5.3$ mas yr^{-1}, $\mu_\delta \approx -0.15$ mas yr^{-1}, where $\mu_\alpha^* = \mu_\alpha \cos\delta$ and μ_δ are the proper-motion components in right ascension and declination, respectively. The mean parallax of stars with such proper motions is $plx \approx 1.4$ mas. We used these proper-motion values as a first approximation for the cluster center in our clustering procedure.

We adopted the Python implementation of the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm provided by the SCIKIT-LEARN library (Pedregosa et al., 2011). DBSCAN partitions the input data into groups and noise points, where the latter are unassociated with any groups. Inside a particular group the algorithm treats all points either as core points or as neighbors of core points. DBSCAN requires two main parameters—*eps*, the maximum distance between two points

Table 1. Photometric observations of NGC 225

Date	Filter	Exposures, s	Airmass
Aug. 17, 2020	U	3×100	1.05
		3×150	1.05
	B	3×10	1.05
		3×30	1.05
	V	3×3	1.05
		3×5	1.05
	R_c	3×1	1.05
		3×2	1.05
	I_c	3×2	1.05
		3×3	1.05
Sep. 15, 2020	U	5×50	1.10
		3×150	1.09–1.10
	B	5×10	1.10
		3×50	1.09
	V	5×1	1.10
		3×10	1.09
	R_c	5×1	1.10
		3×5	1.09
	I_c	5×1	1.10
		3×5	1.09

for one of them to be considered a neighbor of the other, and N, the minimum number of points in a neighborhood for a particular point to be considered a core point. We performed clustering with the parameters spanning the intervals $eps = 0.01$–0.99, $N = 1$–150, and fitted the result of cauterization to the model consisting of two groups—one with the mean parameters as found above for NGC 225 and the second group consisting of foreground stars plus noise. We then counted the number of times each star belonged to the first group and considered this number to be proportional to the membership probability. We found 128 stars with membership probability greater than 50%.

3. OBSERVATIONS AND DATA REDUCTION

We performed two runs of photometric observations on the nights of August 17/18 and September 15/16, 2020, using 60-cm Sternberg Astronomical Institute Moscow State University Telescope at Caucasian Mountain Observatory equipped with an Andor iKon-L CCD camera (2048×2048 pixels, a pixel size of 13.5 μm, a scale of $0\farcs67$/pixel) and a set of photometric filters (for more details, see Berdnikov et al. (2020)). We acquired photometry for the central

Table 2. Photometric observations of NGC 7790

Date	Filter	Exposures, s	Airmass
Aug. 17, 2020	U	3×100	1.05
	B	3×60	1.05
	V	3×10	1.05
	R_c	3×5	1.05
	I_c	3×5	1.05
Sep. 15, 2020	U	3×150	1.08–1.09
	B	3×60	1.09
	V	3×10	1.08
	R_c	3×5	1.08
	I_c	3×10	1.08

part of the cluster within a field of about $22'\times22'$. We performed observations in the U, B, V, R_c, I_c filters in two modes with short and long exposers for the brightest and fainter stars, respectively (Table 1). All frames were bias and flat-field corrected, using zero exposure frames and flats that were taken every night. We performed PSF photometry (Stetson, 1987) using IRAF DAOPHOT/ALLSTAR PSF fitting software. The PSF was calculated for each frame separately using 10–20 isolated bright stars all over the frame and all stars were then aperture corrected. The correction was determined from aperture photometry obtained for the same stars that were used in PSF modelling. 0mm normal.

We transformed instrumental magnitudes into the standard Johnson–Kron–Cousins system using the data from Stetson's database[1] for stars of the open cluster NGC 7790, which we observed on the same nights (Table 2). We used the following equations for transformation:

$$\begin{aligned} u &= U + u_1 + u_2(U - B), \\ b &= B + b_1 + b_2(B - V), \\ v &= V + v_1 + v_2(B - V), \\ r &= R_c + r_1 + r_2(R_c - I_c), \\ i &= I_c + i_1 + i_2(V - I_c), \end{aligned} \qquad (1)$$

where u, b, v, r, i are instrumental magnitudes, U, B, V, R_c, I_c are standard magnitudes, and u_1, u_2, b_1, b_2, v_1, v_2, r_1, r_2, i_1 and i_2 are the fitted parameters. As is evident from Table 1 and Table 2, both clusters were observed at the same air mass, so we exclude the dependence on airmass from equations. We used Astrometry.net tool (Lang et al., 2010) to transform pixel coordinates to equatorial right ascension and declination for the equinox J 2000.0.

[1] https://www.canfar.net/storage/list/STETSON/Standards.

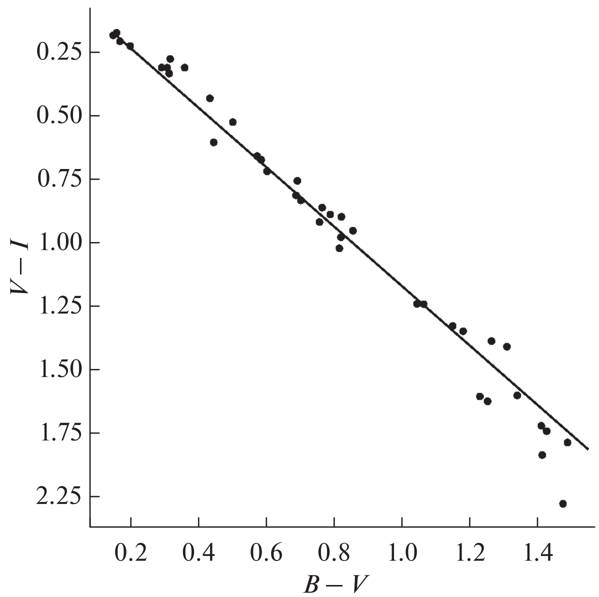

Fig. 1. $V - I$ vs. $B - V$ "color–magnitude" diagram.

As a result, we obtained U, B, V, I_c, and R_c-band photometry for 29, 36, 40, 39, and 54 stars, respectively. The four brightest stars in the B-band filter turned out to be saturated, and we computed their V-band magnitudes via the $(V - I_c)$ color index. The obtained photometric data for the cluster members are available at the following link: http://www.sai.msu.ru/groups/cluster/cl/Ngc225_photometry/.

We compared our photometric results with UBV photoelectric photometry from Hoag et al. (1961) and found 11 stars in common with magnitudes in V filter and 7 stars in common with $B - V$ and $U - B$ color indices. The comparison yields the following differences (hereafter in the sense our data minus published data):

$$\begin{aligned} \Delta V &= -0.060 \pm 0.013, \\ \Delta(B - V) &= -0.056 \pm 0.011, \\ \Delta(U - B) &= 0.294 \pm 0.012. \end{aligned} \tag{2}$$

As we mentioned above, stars s1, s2, s3 and s4 were saturated in the B-band filter and we therefore adopted their $U - B$ and $B - V$ color indices from Hoag et al. (1961). Note that $\Delta(U - B)$ is much greater than the corresponding differences in V and $B - V$, and for this reason we shifted our color indices accordingly to eliminate this difference between our data and $U - B$ from Hoag et al. (1961).

We compared our data with The AAVSO Photometric All Sky Survey (APASS) (Henden et al., 2015) and found 25 stars in common with V-band magnitudes and 21 stars in common with $B - V$ color indices. The comparison yielded the following results:

$$\begin{aligned} \Delta V &= -0.050 \pm 0.006, \\ \Delta(B - V) &= -0.014 \pm 0.015. \end{aligned} \tag{3}$$

We also used equations for transforming Gaia G, B_P, and R_P-band magnitudes into Johnson–Cousins photometric system[2] to obtain:

$$\begin{aligned} \Delta V &= 0.030 \pm 0.008, \\ \Delta I &= 0.030 \pm 0.009, \\ \Delta R &= -0.019 \pm 0.009. \end{aligned} \tag{4}$$

4. PHOTOMETRIC DISTANCE AND AGE

To find photometric distances and investigate conditions in the nearest vicinity of the cluster, we followed steps, described in Yalyalieva et al. (2020). First, we calculated the total-to-selective extinction ratio, $R_V = A_V / E(B - V)$, toward the cluster and the slopes of the reddening vector $(U - B)/(B - V)$ using Cardelli et al. (1989) equations for the optical and NIR bands. For this purpose we found the slope of the reddening vector $(V - I)/(B - V)$ via weighted least squares fit for the $(V - I)$ vs. $(B - V)$ "color–color" diagram, where stars are distributed along parallel line (Fig. 1). We found $R_V = 3.03 \pm 0.02$ and $(U - B)/(B - V) = 0.767 \pm 0.001$. A very close value $R_V = 3.04$ for this cluster was earlier obtained by Turner (1976).

We fitted the theoretical zero-age main sequence (ZAMS) from Turner (1996) to the $(U - B)$ vs. $(B - V)$ "color–color" diagram to estimate the color excess $E(B - V) = 0.29 \pm 0.01$ (Fig. 2). We then adopted this color excess to determine the apparent distance modulus by fitting ZAMS to the V vs. $(B - V)$ color–magnitude diagram and found $(m - M)_V = 10^{\mathrm{m}} \pm 0\overset{\mathrm{m}}{.}05$ (Fig. 3). We used these results to infer the cluster distance modulus $(m - M)_0 = 9\overset{\mathrm{m}}{.}12 \pm 0\overset{\mathrm{m}}{.}06$ and distance $D = 667 \pm 18$ pc and fitted theoretical PARSEC + COLIBRI isochrones (Bressan et al., 2012) to infer an age estimate of $\log \mathrm{Age} = 8.0$–8.2.

We compared our photometric distance with the data from Bailer-Jones et al. (2021). The median (*rgeo*), 16th percentile (*b_rgeo*), and 84th percentile (*B_rgeo*) geometric distances are equal to 682, 664, 707 pc, respectively, and agree well with our estimate. The inferred distance also agrees well with the estimate obtained by Cantat-Gaudin et al., $d = 684.3$ pc.

It is curious to note, that in the color range $0.3 < (B - V) < 0.8$ the sequence of probable double

[2] https://gea.esac.esa.int/archive/documentation/GDR2/.

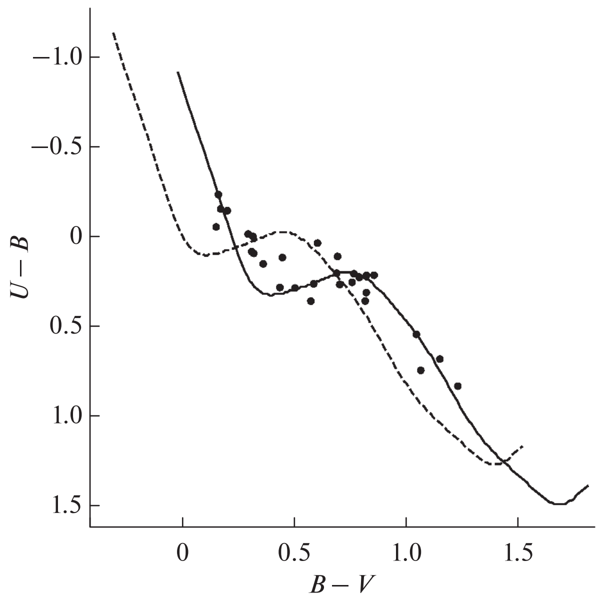

Fig. 2. $U-B$ vs. $B-V$ "color–color" diagram. The dashed and solid lines show the intrinsic and reddening-shifted ZAMS, respectively.

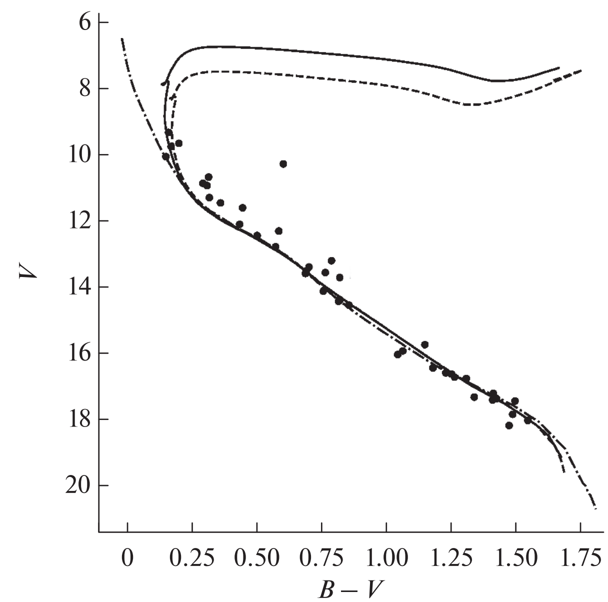

Fig. 3. V vs. $B-V$ "color–magnitude" diagram. The solid and dashed lines show the shifted isochrones with $\log \mathrm{Age} = 8.0$ and $\log \mathrm{Age} = 8.2$. The dash-and-dotted line shows the shifted ZAMS.

stars is well recognisable (Fig. 3). The binary fraction in open clusters differs from one cluster to another and may be as high as 70% (Sollima et al., 2010). To reveal the binary fraction of NGC 225 the further investigation is needed, which is beyond the scope of this study.

5. EXTINCTION IN NEAR INFRARED

Extinction in near infrared is supposed to be described quite well by a power-law function $A_\lambda \propto \lambda^{-\alpha}$. In their classic work Cardelli et al. (1989) find $\alpha = 1.61$ for the wavelength range $0.9\ \mu\mathrm{m} < \lambda < 3.3\ \mu\mathrm{m}$, however, over the years different authors have reported values spanning the $1.5 \lesssim \alpha \lesssim 2.3$ interval and even estimates as large as $\alpha \approx 2.6$ (Matsunaga et al., 2018). In order to calculate α in case of NGC 225 field direction, we used the photometry in the following near-infrared filters: J, H, K_s from 2MASS Cutri et al. (2003), y, z, i from Pan-STARRS (Chambers et al., 2016) and W1-band filter from WISE (Cutri and et al., 2012). The mean wavelengths λ of these filters are listed in Table 3. We avoided using W2-band filter (mean wavelength $\lambda = 4.6\,\mu\mathrm{m}$) from WISE due to the possible peak of absoption that is supposed to be near 4.5 μm (Gontcharov, 2016).

We performed photometric observations in filter U, B, V only for an area about $22' \times 22'$, whereas the cluster radius is believed to be of about 25. For these reason, we prefer to base calculations on G_{Gaia} magnitude, given that Gaia was our main catalogue for identification of cluster members. We followed the procedure described by Yalyalieva et al. (2018). We used the distance modulus estimate $(m-M)_0$ to compute the apparent distance modulus in Gaia G-band filter, and found it to be $(m-M)_G = 9\overset{\mathrm{m}}{.}86$. We then adopted the data from Bressan et al. (2012) isochrones to assign to each star the temperature estimate T according to the absolute magnitude in the G-band filter. Given the temperature, we can compute the absolute magnitudes M_λ in the filters listed in Table 3. To obtain the apparent magnitudes m_λ we cross-matched our list of probable members with catalogues with a matching radius of $r = 1\overset{''}{.}5$. We found 125 stars in common with 2MASS and Pan-STARRS and 110 stars in common with WISE. We then use the known distance modulus $(m-M)_0$ to compute extinction in each filter for each

Table 3. Mean wavelengths λ of the filters

Survey	Filter	λ, μm
*Pan-STARRS	i	0.75
	z	0.87
	y	0.96
*2MASS	J	1.24
	H	1.65
	K_s	2.16
WISE	$W1$	3.38

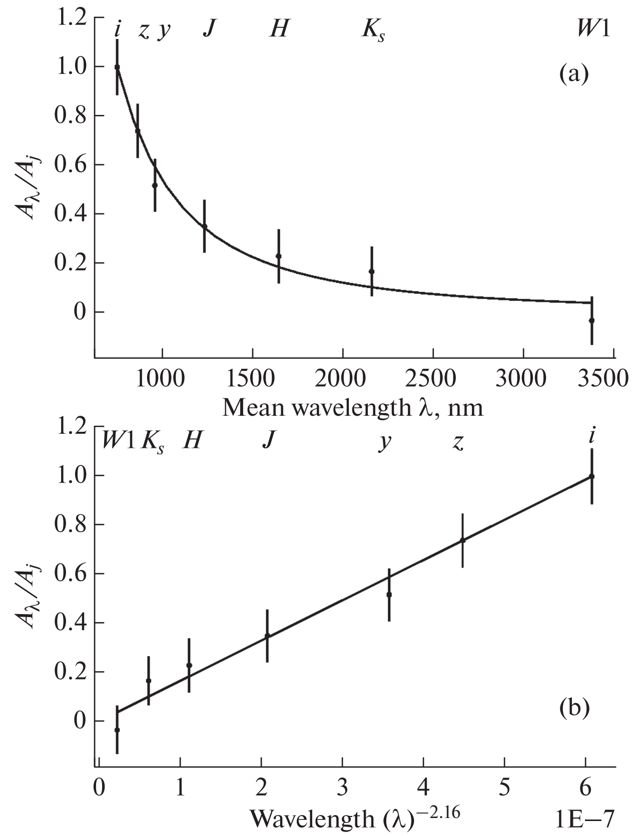

Fig. 4. Panel (a) shows extinction A_λ/A_i vs. λ. The solid line shows the power-law fit $A_\lambda \propto \lambda^{-2.16}$. Panel (b) shows extinction A_λ/A_i vs. $\lambda^{-2.16}$.

star as $A_\lambda = (m-M)_\lambda - (m-M)_0$. We then compute the mean cluster extinction. To this end, we applied kernel density estimator to A_λ distributions with optimal bandwidth calculated by cross-validation method. We used a minimization procedure to find the value of A_λ corresponding to the maximum of the distribution. To take into account uncertainties in magnitudes, we added them to magnitudes and repeated the calculations. We treated the resulting differences between extinction uncertaineties σλ and fitted the mean A_λ values to the power-law function $A_\lambda \propto \lambda^{-\alpha}$ using weights $1/\sigma_\lambda^2$. As a result, we found $\alpha = 2.16 \pm 0.34$ (Fig. 4).

6. CONCLUSIONS

In this work we performed photometric study of open star cluster NGC 225. We used both our own U, B, V, R_c, I_c-band photometry and infrared data from 2MASS, WISE, Pan-Starrs. We obtained a list of probable cluster members by applying DBSCAN clustering algorithm in 3-dimensional space of proper motion and parallaxes. We used the $(U-B)$ vs. $(B-V)$ "color–color" diagram and the V vs. $(B-V)$ "color-magnitude" diagram to infer a color excess $E(B-V) = 0.29 \pm 0.01$, distance $D = 667 \pm 18$ pc, and $\log \mathrm{Age} = 8.0$–8.2 or 100–160 Myr. We used 2MASS, Pan-STARRS, and WISE data to study extinction law in the near infrared. We assumed that it can be approximated by a power-law function $A_\lambda \propto \lambda^{-\alpha}$ and found $\alpha = 2.16 \pm 0.34$.

ACKNOWLEDGMENTS

The authors thank Andrey Dambis for the help with the preparation of the article for publication.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

This publication 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.

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under Grant no. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation Grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), the Los Alamos National Laboratory, and the Gordon and Betty Moore Foundation.

FUNDING

The reported study was funded by the Russian Foundation for Basic Research, project no. 20-32-90124.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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