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Astrophysical Parameters of the Open Cluster NGC 2509

Talar YONTAN [*1], Seliz Koç[2]

Abstract

This study presents structural and fundamental astrophysical parameters of poorly studied open cluster NGC 2509. We used the third photometric and astrometric data release of the *Gaia* (*Gaia* DR3) to perform analyses. By taking into account the *Gaia* DR3 astrometric data, we calculated the membership probabilities of the stars in the region of NGC 2509. As a result of the membership analysis, 244 stars with membership probabilities $P \geq 50\%$ were determined as the physical members of the cluster. The colour excess, distance and age were obtained simultaneously by fitting solar metallicity PARSEC isochrones to $G \times G_{BP}-G_{RP}$ colour-magnitude diagram. We considered the most likely cluster member stars during the fitting procedure and calculated the colour excess, distance and age of the NGC 2509 as $E(G_{BP}-G_{RP}) = 0.100 \pm 0.184$ mag, $d = 2518 \pm 667$ pc and $t = 1.5 \pm 0.1$ Gyr, respectively.

Keywords: Galaxy: open cluster and associations: individual: NGC 2509, Galaxy: Disc, stars: Hertzsprung Russell (HR) diagram

1. INTRODUCTION

Open star clusters (OCs) are the celestial bodies which consist of tens of to thousands of stars that share similar physical properties under the weak gravitational forces. These objects are located through the Galactic disc within the different distances and have a vast age range from a few million years to a few billion years. Because of the components stars of OCs are formed from collapsing of the same molecular cloud, their age, heliocentric distance, metallicities are similar [1]. These properties make OCs important tools to study star formation process, stellar evolution as well as the formation and chemical evolution of the Galactic disc ([2-4]). Due to their same formation origin, the movement vectors of proper-motion components of cluster stars are similar. This knowledge is useful to define the membership properties of stars in the direction of open cluster ([5]). Moreover, astrometric, photometric and spectroscopic data of *Gaia* observations provided essential results for OCs and Milky Way Galaxy (e.g., [6-10]).

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Table 1 Fundamental parameters for NGC 2509 estimated in this study and compiled from the literature. Columns denote the colour excess ($E(B-V)$), metallicity ([Fe/H]), distance moduli and distance (μ, d), age (t), proper-motion components ($\mu_\alpha\cos\delta$, μ_δ) and trigonometric parallaxes (ϖ). Errors of the parameters are shown in parenthesis

***E*(*B*-*V*)** (mag)	**[Fe/H]** (dex)	**μ** (mag)	***d*** (pc)	***t*** (Gyr)	**$\mu_\alpha\cos\delta$** (mas/yr)	**μ_δ** (mas/yr)	**ϖ** (mas)	**Reference**
0.15	---	---	912 (15)	8	---	---	---	[11]
0.1	---	12.5 (0.10)	2900	1.2	---	---	---	[12]
0.104	---	11.2	1711	1.6	-3.82	4.24	---	[13]
0.104	---	---	1711	1.6	---	---	---	[14]
---	---	---	2549 (695)	---	-2.708 (0.076)	0.764 (0.075)	0.363 (0.039)	[6]
---	---	---	---	2.3 (0.140)	-2.712 (0.160)	0.771 (0.138)	0.369 (0.032)	[15]
0.1	---	11.72	---	1.8	---	---	---	[16]
---	---	---	2549 (695)	---	-2.708 (0.076)	0.764 (0.075)	0.363 (0.039)	[17]
0.074	---	11.99	2495	1.5	-2.708 (0.076)	0.764 (0.075)	0.363 (0.039)	[18]
0.242	---	12.36	---	0.86	---	---	---	[19]
0.105 (0.021)	0.082 (0.137)	---	2411 (118)	1.5	-2.708 (0.098)	0.766 (0.089)	0.364 (0.041)	[20]
0.071 (0.130)	0.00	12.191 (0.509)	2518 (667)	1.5 (0.1)	-2.718 (0.002)	0.803 (0.002)	0.37 (0.03)	This study

NGC 2509 ($\alpha_{2000.0}$ = 08^{h}00^{m}48^s.2, $\delta_{2000.0}$ = -19^{o}03'22"; l = 237^o.8442, b =05^o.8465) [17] is an intermediate age open cluster located in the second Galactic quadrant towards the Galactic anti-centre region. Due to the cluster is situated very close to the Galactic disc, its embedded in field star contamination. [13] found reddening, distance and age of the cluster as $E(B-V)$ =0.104 mag, d = 1711 pc, log t = 9.2 yr, respectively. [18] used *Gaia* DR2 astrometric and photometric data and determined distance and age of NGC 2509 as d = 2495 pc and log t = 9.18 yr, respectively. They obtained extinction in the cluster direction as A_V = 0.23 which corresponds colour excess to be $E(B-V)$ = 0.074 mag. Also, researchers calculated mean proper-motion components of the NGC 2509 as ($\mu_\alpha\cos\delta$, μ_δ) = (-2.708±0.076, 0.764±0.075) mas/yr. [19] found extinction, distance and age of the cluster as A_V =0.75, which corresponds $E(B-V)$ to be 0.242 mag, μ = 12.36 mag and t = 860 Myr, respectively. [20] using *Gaia* DR2 astrometric and photometric data obtained the extinction, metallicity, distance and age of the cluster as A_V = 0.23 mag, which corresponds $E(B-V)$ to be 0.105 mag, [Fe/H] = 0.082±0.137 dex, d = 2411±118 pc and log t = 9.18 yr, respectively. Moreover, in the study researchers determined mean proper-motion components as ($\mu_\alpha\cos\delta$, μ_δ) = (-2.708±0.098, 0.766±0.089) mas/yr. For detailed literature study results see Table 1.

In this study, we used *Gaia*'s the third release (hereafter *Gaia* DR3, [21]) of astrometric and photometric data to analyse NGC 2509 open cluster. To remove field star contamination and perform precise selection of cluster members we used *Gaia* DR3 proper-motion components ($\mu_\alpha\cos\delta$, μ_δ), trigonometric parallaxes (ϖ) and their uncertainties for each star in cluster region and calculated their membership probabilities. We took into account the stars with the membership probabilities $P \geq 50\%$ as the most likely cluster members and used them to determine astrometric ($\mu_\alpha\cos\delta$, μ_δ, ϖ) and astrophysical (reddening, distance modulus and age) parameters of the NGC 2509.

1.1. Astrometric and Photometric Data

We used photometric and astrometric data of *Gaia* DR3 ([21]) to analyse NGC 2509 open cluster. We created the catalogue of NGC 2509 by considering 20 arcmin radius circular field from the cluster centre ($\alpha_{2000.0}$ = $01^h51^m12^s.7$, $\delta_{2000.0}$ = 61°03'40"; [17]). Thus, we found 20,391 stars within the magnitude range $7 < G \leq 22$ mag in cluster region. Generated catalogue contains positions (α, δ), photometric magnitude and colours (G, G_{BP}-G_{RP}), proper-motion components ($\mu_\alpha\cos\delta$, μ_δ) and trigonometric parallaxes (ϖ). Identification map of the open cluster NGC 2509 is shown in Figure 1. *Gaia* DR3 ([21]) provides high quality astrometric and photometric data more than 1.5 billion celestial objects. The uncertainties in *Gaia* DR3 are 0.01-0.02 mas for $G \leq 15$ mag, and reach about 1 mas at $G = 21$ mag. The uncertainties of trigonometric parallax are 0.02-0.07 mas for $G \leq 17$ mag, 0.5 mas for $G = 20$ mag and reach 1.3 mas for at $G = 21$ mag. For sources with $G \leq 17$ mag the proper motion uncertainties are 0.02-0.07 mas/yr reaching 0.5 mas mas/yr at $G = 20$, and 1.4 mas/yr at $G = 21$ mag. For sources within $G \leq 17$ mag the G-band photometric uncertainties are 0.3-1 mmag, increasing to 6 mmag at $G = 20$ mag, allowing such separations to be made more accurately ([7, 22]).

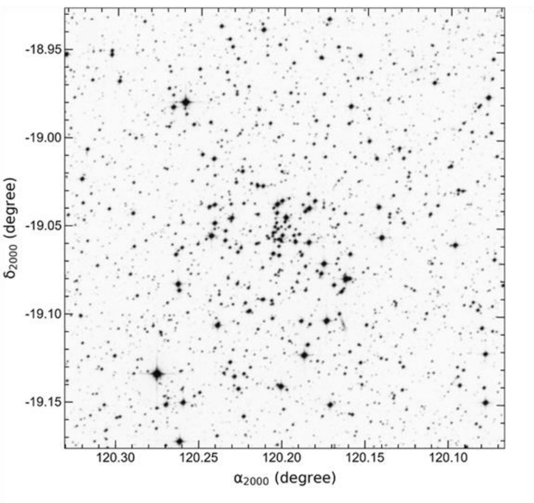

Figure 1 Identification chart of stars located through the area of NGC 2509. Field of view of the optical chart is 20' × 20'. North and East correspond to the up and left directions, respectively

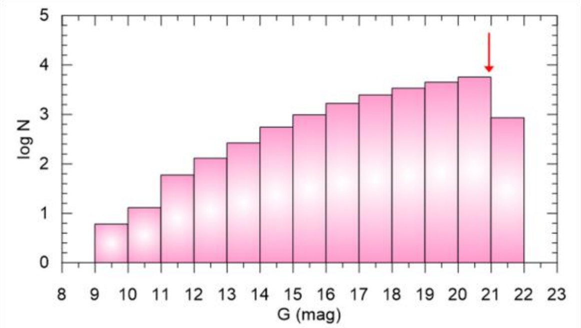

Figure 2 Number of stars versus interval G magnitudes. The red arrow represents the faint limit magnitude of the NGC 2509

Table 2 Mean photometric errors for G magnitude and G_{BP}-G_{RP} colour index as G mag function. N indicates the number of stars within the selected G magnitude intervals

G (mag)	N	σ_G (mag)	$\sigma_{GBP-GRP}$ (mag)
(6, 12]	79	0.003	0.005
(12, 14]	395	0.003	0.005
(14, 15]	552	0.003	0.005
(15, 16]	967	0.003	0.006
(16, 17]	1643	0.003	0.008
(17, 18]	2474	0.003	0.016
(18, 19]	3418	0.003	0.034
(19, 20]	4456	0.004	0.074
(20, 21]	5563	0.009	0.188
(21, 23]	844	0.024	0.383

To perform precise analyses, we investigated photometric completeness limit for the cluster. For this, we determined number of stars in interval G magnitudes. The star count histogram versus interval G magnitude is shown in Figure 2. It can be seen from the figure that number of stars increase up to $G = 21$ mag and start to decrease after this limit where the stellar incompleteness has set in. This value is adopted photometric completeness limit for NGC 2509. We considered the stars fainter than this limit to utilize analyses of the cluster. We also investigated mean photometric errors of G magnitudes and G_{BP}-G_{RP} colour indices as function of G interval magnitudes and listed in

Table 2. It can be seen from Table 2 that the mean errors of G magnitude and G_{BP}-G_{RP} colour indices of the stars reach up to 0.01 and 0.2 mag for completeness limit G = 21 mag, respectively

3 CONCLUSIONS AND DISCUSSION

3.1. Structural Parameters of the NGC 2509

In order to estimate structural parameters of NGC 2509, we visualized the Radial Density Profile (RDP) for NGC 2509 using the centre coordinates given by [17]. The cluster area was divided into concentric circles around the adopted centre. Stellar densities (ρ_i) in each i^{th} ring were calculated by using the expression $\rho_i=N_i/A_i$, where N is the number of stars and A is the area of i^{th} ring. Those calculated stellar densities (ρ) were plotted as a function of radius from the cluster centre (Figure 3). We fitted RDP model of [23] to this distribution considering χ^2 minimization. The RDP model is formulized as $\rho(r) = f_{bg} + (f_0 / (1 + (r/r_c)^2)$, where r represents the radius from the cluster centre, f_{bg}, f_0 and r_c describe the background stellar density, the central density and the core radius, respectively. RDP of the cluster with best fit is shown in Figure 3. As a result of analyses, we estimated the core radius, background stellar density and central density of the NGC 2509 as r_c = 0.578±0.113 arcmin, f_{bg}=15.816±0.511 stars/arcmin^2 and f_0 = 32.334±3.236 stars/arcmin^2, respectively. Also, with visual review of RDP, we obtained limiting radii (r_{lim}) of the cluster. We described the r_{lim} as the radius that cluster density almost meets the background density (Figure 3 grey horizontal line). We considered this limit to be r_{lim} = 7' (5.13±1.35 pc) for the cluster, and we used the stars inside this limiting radius for the determination of fundamental parameters of it.

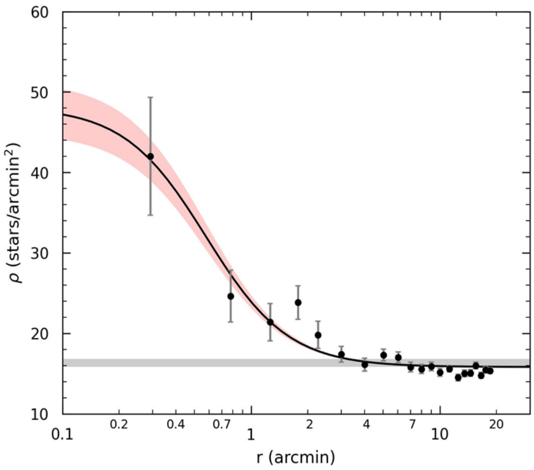

Figure 3 RDP of NGC 2509. Errors were calculated from sampling statistics $1/\sqrt{N}$, where N is the number of stars used in the density estimation. The smooth line shows the best fit profile of [23]. The background density level and its errors are represented with the horizontal grey bands. The King fit uncertainty (1σ) is shown by the red shaded region

3.2. Membership Analyses

OCs are distributed through the densely populated Galactic plane and are mostly affected by foreground/background stars. It is necessary to separate cluster members from field stars to determine more precise fundamental parameters of the OCs. As for the cluster members have same origin, their motion vectors in the sky point in the same direction. Therefore, proper-motion components are useful tools to discriminate cluster members from field stars. The membership analyses carried from astrometric data of *Gaia* catalogue give more reliable results than ground-based data ([24]). We utilized UPMASK (Unsupervised Photometric Membership Assignment in Stellar Clusters; [29]) method by using astrometric data of *Gaia* DR3 for membership analyses. This methodology previously used in many studies ([6, 17, 25-27]). UPMASK is the method of clustering algorithm and detects spatially populated groups and identifies membership probabilities of stars. This clustering method is described as k-means clustering which is the integer number and varies within 5 to 25 and is not set directly by the user ([17, 28]). We used five-dimensional astrometric parameters as inputs which include stars' positions (α, δ), proper-motion components ($\mu_\alpha\cos\delta$, μ_δ), trigonometric parallaxes (ϖ) and their uncertainties. In the method of UPMASK, membership probabilities (*P*) of stars are described as the frequency with which star belongs to a clustered group. Program was run 1000 iterations during the utilization. Best solution was adopted when k-means value was set to 15 for NGC 2509. We considered the stars with membership probability $P \geq 50\%$ as possible cluster members. Moreover, to determine cluster members more precision and get reliable astrometric parameters for NGC 2509, we filtered possible members which brighter than completeness limit $G \leq 21$ mag and within the cluster limiting radius ($r_{\rm lim}$ =7'). Thus, with these criteria we identified a total of 244 stars with probability $P \geq 50\%$. We plotted proper-motion distribution of stars to image the position of the cluster as regards to field stars and shown it in Figure 4.

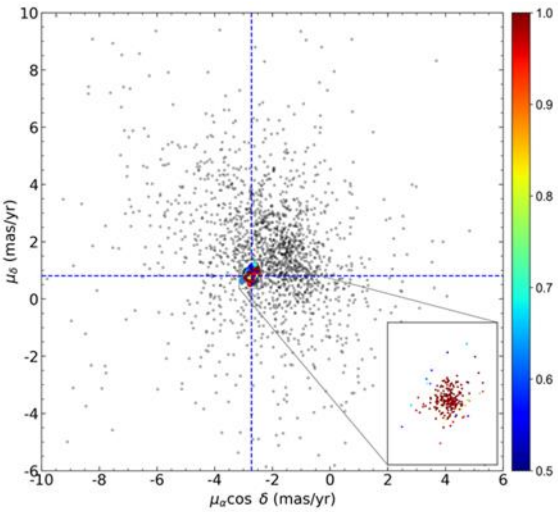

Figure 4 *Gaia* DR3 data based proper-motion distribution of NGC 2509. Colour bar shows the scale of membership probabilities of the stars. Zoomed region shows the location where the cluster is condensed. The intersection of the dashed blue lines is the point of mean proper-motion values

It can be seen in the figure that NGC 2509 is embedded in field stars. In Figure 4, the intersection of blue dashed lines represents the values of mean proper-motion components calculated from the most probable cluster members (244 stars with $P \geq 50\%$). These values were determined as ($\mu_\alpha\cos\delta$, μ_δ) = (-2.718±0.002, 0.803±0.002) mas/yr, which are compatible with the results of all studies performed with *Gaia* observations for the NGC 2509 (see Table 1). To estimate mean trigonometric parallax ⟨ϖ⟩ of NGC 2509, we took into account the most likely member stars with relative parallax error (σ_ϖ/ϖ) less than 0.15 and plotted the histogram for number of stars (*N*) versus trigonometric parallax (ϖ) as shown in Figure 5. We fitted Gaussian function to this distribution and it provided the mean trigonometric parallax ⟨ϖ⟩ to be 0.37±0.03 mas. By using the expression of linear equation *d* (pc) = 1000/ϖ (mas) we calculated trigonometric parallax-based distance of the NGC 2509 as d_ϖ = 2703±190 pc.

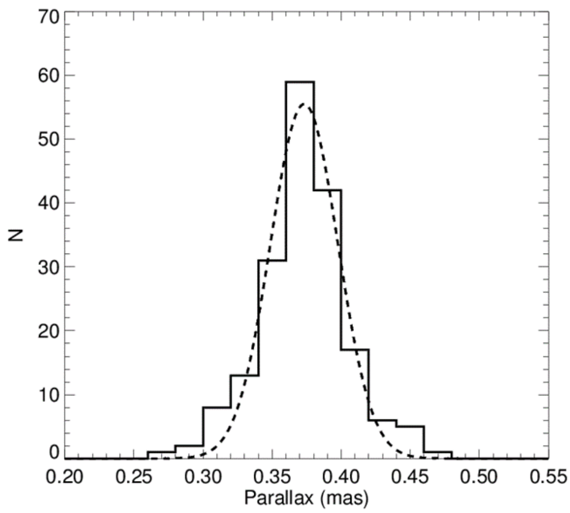

Figure 5 *Gaia* DR3 based trigonometric parallax histogram for NGC 2506. Applied Gaussian fit is shown in black dashed curve

3.3. Fundamental Parameters of NGC 2509

Colour-magnitude diagrams of OCs are important tools to examine morphology of the cluster, as well as to obtain their fundamental parameters such as reddening, metallicity, age and distance.

The reddening, metallicity age and distance of NGC 2509 were derived simultaneously by fitting PARSEC isochrones of [29] to the observed colour-magnitude diagram as shown in Figure 6. During the fitting procedure we concentrated on most likely stars that contain main-sequence, turn-off point and giant region of the cluster. Different age values log t = 8.15, 8.18 and 8.20 yr with metallicity z = 0.0152 of isochrones were superimposed on observable colour-magnitude diagram. Best fit isochrone resulted the reddening, age and isochrone distance of the NGC 2509 to be $E(G_{BP}-G_{RP})$ = 0.100±0.184 mag, d_{iso} = 2518±667 pc and t = 1.5±0.1 Gyr, respectively (see Table 1). To compare with literature, we transformed *Gaia* based reddening to *UBV* based value by using $E(G_{BP}-G_{RP}) = 1.41\times E(B-V)$ equation given by [30]. This equation was used in the studies recently presented [31, 32] and resulted successfully. Thus, we calculated *UBV* based reddening as $E(B-V)$=0.071±0.130 mag. The $E(B-V)$ colour excess and age of the cluster derived in the study are in a good agreement with many values given in the literature (see Table 1). Moreover, the distance value (d_{iso} = 2518±667 pc) found in study is compatible with the values those of represented in *Gaia* era (see Table 1), and with the distance that calculated from trigonometric parallaxes of most likely members in the study. This shows that the cluster's all astrophysical parameters derived in the study are acceptable. Also, results of the study listed in Table 3.

4 CONCLUSION

We performed *Gaia* DR3 astrometric and photometric data-based study of intermediate-age open cluster NGC 2509. We calculated membership probabilities of stars in the region of cluster and classified 244 most likely members with membership probabilities $P \geq 50\%$. We considered these members to estimate astrophysical parameters. The main results of the analyses are as follows:

•Taking into account the RDP results, the limiting radius of the cluster is obtained as r_{lim}=7′ (5.13±1.35 pc)

•Using the distribution of proper-motion components, we determined mean proper-motion of NGC 2509 as $\langle\mu_\alpha\cos\delta, \mu_\delta\rangle$ = (-2.718±0.002, 0.803±0.002) mas/yr.

• On the basis of most likely cluster stars with relative parallax error (σ_ϖ/ϖ) less than 0.15, we calculated trigonometric parallax of the cluster as $\langle\varpi\rangle$ = 0.37±0.03 mas, which corresponds the parallax distance to be d_ϖ = 2703±190 pc.

• PARSEC isochrones of [30] provide an age of t = 1.5±0.1 Gyr and isochrone distance of d_{iso} = 2518±667 pc with the solar metallicity (z = 0.015) for the cluster. Because of astrophysical parameters estimated simultaneously on CMD, the best fit isochrone gives the *Gaia* based reddening as $E(G_{BP}-G_{RP})$ = 0.100±0.184 mag for NGC 2509.

Table 3 Astrophysical parameters of NGC 2509 estimated in the study

Parameter	**Value**
α (hh:mm:ss.s)	08:00:48.2
δ (dd:mm:ss.s)	-19:03:22.0
l (°)	237.8442
b (°)	05.8465
f_0 (star/arcmin^2)	32.334±3.236
r_c (arcmin)	0.578±0.113
f_{bg} (star/arcmin^2)	15.816±0.511
r_{lim} (arcmin)	7
r (pc)	5.13±1.35
$\mu_\alpha\cos\delta$ (mas/yr)	-2.718±0.002
μ_δ (mas/yr)	0.803±0.002
Cluster members ($P \geq 50\%$)	244
ϖ (mas)	0.37±0.03
d_ϖ (pc)	2703±190
$E(G_{BP} - G_{RP})$ (mag)	0.100±0.184
$E(B-V)$ (mag)	0.071±0.130
[Fe/H] (dex)	0.0152
Age (Gyr)	1.5±0.1
Distance module (mag)	12.191±0.509
Isochrone distance (pc)	2518±667
X (pc)	-1333
Y (pc)	-2121
Z (pc)	256
R_{gc} (kpc)	9.57

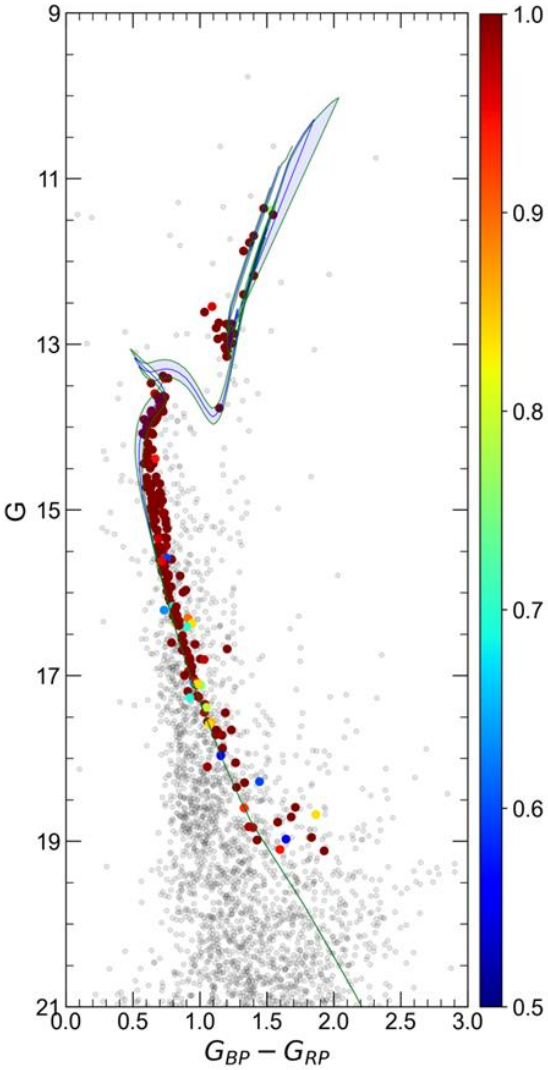

Figure 6 Colour-magnitude diagram with best fit PARSEC isochrones. Colour scaled represent the membership probabilities of stars according to colour bar in right panel. Gray circles show field stars. Blue and green solid lines represent errors in age, with isochrone that best represent cluster parameters, respectively

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Authors' Contribution

Concept: T.Y., S.K., Design: T.Y., S.K., Data Collection or Processing: T.Y., S.K., Analysis or Interpretation T.Y., S.K., Literature Search: T.Y., S.K., Writing: T.Y., S.K.

The Declaration of Conflict of Interest/ Common Interest

The study is complied with research and publication ethics.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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