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Candidate Runaway Stars in the Cluster NGC 2180

Efrem Ambaye Kahsay[1] and Yikdem Mengesha Gebrehiwot[2*]
[1]Department of Physics, College of Natural and Computational Sciences, Mekelle University, Mekelle, Tigray, Ethiopia (ambayeafrem1219@gmail.com, ORCID: https://orcid.org/0009-0007-0596-7842).
[2]Department of Physics, College of Natural and Computational Sciences, Mekelle University, Mekelle, Tigray, Ethiopia (*yikdem.mengesha@mu.edu.et, ORCID: https://orcid.org/0000-0003-4907-1726).

ABSTRACT

The relative proper motions and tangential velocities of four stars from the cluster NGC 2180 are investigated using Gaia DR3 data. Our approach is to subtract the mean proper motion of the fields (the stars within a 1” radius around each target star) and the cluster from the motion of the target stars to calculate the relative proper motions with respect to their field and the cluster, respectively. From the relative proper motions of the target stars with respect to the field stars and the distance to the center of the cluster, we estimated the relative tangential velocities of our target stars. We use the astrometric excess noise information to filter the field stars from star-like objects, such as unresolved binaries. To eliminate foreground contaminations of the field stars used to figure out the relative proper motions of the target stars, we made a parallax cut, Color Magnitude Diagram (CMD) cut, and proper motion (PM) selection. The flight times of the target stars to the cluster NGC 2180 (kinematic ages) are calculated using angular separations from the cluster and their relative proper motions with respect to the cluster. All of the target stars have kinematic ages less than the age of the cluster. The stars, ID1 and ID3 have and with respect to their fields, which corresponds to the relative velocities respectively. These two stars could be runaways from the cluster because they have flight times from the cluster agreed with late ejection from the cluster and have larger proper. The remaining two stars, ID 2 and ID 4 have and with respect to the fields, which corresponds to the relative velocities and respectively, and could not be runaways as they have smaller proper motions, although their flight times to the cluster agreed with late ejection from the cluster.

Keywords: Stars, Runaway stars, Proper motion, NGC 2180.

1. INTRODUCTION

A star cluster is described as gravitationaly bounded group of stars for some period of time and share a common origin. Galactic Plane star clusters were well-known to classical astronomers such as Claudius Ptolemy of the 2nd century and Abd al-Rahman al-Sufi of the 10th century (Collinder, 1931; Mark Allison, 2006). Star clusters are of great astrophysical significance for evaluating stellar evolution and dynamic models, investigating the mechanism of star formation, calibrating the extragalactic distance scale and, most significantly, calculating the age and evolution of the Galaxy (El-Depsey et al., 2023; Noormohammadi et al., 2023). While only a

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small portion of stars are contained in stellar clusters in our galaxy, they are important astronomical objects that can be very useful to obtain a better understanding of stars (Burningham et al., 2003; Hartmann et al., 2011).

There are two different types of stellar clusters: open (sometimes also called galactic clusters) and globular clusters. Globular and open clusters are very distinct from one another in almost every respect. Open clusters are relatively young, while globular clusters are older stars (Catharine Garmany, 1994; Yadav, 2023). Open clusters are composed of 100 - 1000 loosely bounded stars. The loose state makes them star structures which are potentially short-lived. They have an estimated dimension of 10pc. Open clusters are formed along the gaseous and dust-rich Galactic plane and the stars distributed in an approximately spherical structure of up to a few parsecs in radius (Bica et al., 2004; Richard Larson and Beatrice TiNSLEY, 1978).

Open clusters often have no determinable shape or structure, and are usually irregular and loosely shaped, as opposed to globular clusters that are spherical in nature and densely packed with stars. These clusters are relatively young objects made up of population-I stars and are stars of the early type . They are found in our galaxy mostly in the spiral arms of the galactic disk (Aidelman et al., 2018; Mark Allison, 2006; Ahumada and Lapasset, 1995).

Globular clusters are much more closely bound than open clusters that lead to their spherical form with far greater star concentration in their central region. Globular clusters are usually made up of very old stars of Population II just a few hundred million years younger than the universe which are mostly yellow and red, with masses below two solar masses, but few rare blue stars exist in globular, thought to be formed by stellar mergers in their dense inner regions; these stars are known as blue stragglers (Guzik Joyce et al., 2023; Balona et al., 2013). In our Galaxy, globular clusters are distributed roughly spherically in the galactic halo, around the Galactic Center, orbiting the center in highly elliptical orbits. GC are of great interest as nearby representatives of simple stellar systems whose stars share the same age and initial chemical composition and they are also close enough to identify the cluster. (Michael Kuhn et al., 2017; Banerjee Sambaran and Kroupa Pavel, 2017).

The disrupting open cluster NGC 2180 has been first observed and described as a cluster by W. Herschell (Dreyer, 1888). In order to maximize the cluster/background contrast, the CMDs have been built with stars extracted within 10 degree for NGC 2180. This cluster can be recognized as a cluster by the presence of the main sequence and a group of bright giants. The recent study open clusters NGC 2180 highlighted as a possible cluster remnant candidate because the age of the cluster is above 600 million years and its over all distance from the galaxy. The NGC catalogue classified this object as an open cluster, in Orion, and the cluster demonstrates signs of star erosion and mass segregation (redistributing stars of different masses and distances) from tidal forces tugging at the cluster. This cluster lies at a distance approximately 0.1 kpc, with an estimated age of 710 million years (Myr), observed stellar mass of $m_{obs} \sim 47M_{\odot}$, core radius of 0.7pc and a diameter of 9.5 pc it is relatively young for a remnant, it is still relatively large. So it is actually closer to the galactic plane than many normal open clusters. NGC 2180 is believed to be a halfway-house object, an old evolved cluster, but not yet a fully blown remnant (Jeffrey Silverman et al., 2013; Bonatto et al., 2004; Anthony-Twarog et al., 1991).

Our motivation to work with Gaia DR3 is that Gaia provides the proper motion of the target stars along with proper motions across the full field of the NGC 2180 to a new combination of precision and density (Gaia Collaboration, 2022). This allowed us to work differently, by obtaining proper motion differences with respect to the local NGC 2180 motion within each subfield (by imposing a 10 arc sec radius area around each of the target stars) and with respect to the cluster NGC 2180.

In this study, we crossmutchdasd the coordinates of the high In This study, we cross matched the coordinates of the star members of the cluster NGC 2180 with higher proper motions with Gaia coordinates and only four of these stars match within a 0.01'' radius. We calculated the relative proper motions of these four stars (our target stars) of NGC 2180 cluster with respect to their fields stars and with respect to the cluster using Gaia DR3 (Gaia Collaboration, 2022). Field stars are stars within 10″ (10 arc minute) radius from each target stars. We made a photometric selection to isolate stars within the NGC 2180 cluster region.

To exclude foreground contamination of the member stars of each subfield, we used techniques like parallax cut, CMD cut and proper motion cut (PM) cut, for details refer (Teklehaimanot and Gebrehiwot, 2023). Together with the relative proper motions and tangential velocities, the flight times of the target stars to the NGC 2180 cluster were calculated and used to identify runaways from this cluster.

The origin of the data we used and the Gaia DR3 data analysis process including the selections that we performed to obtain the final samples of field stars are described under methodology and the main results of this work are analyzed and discussed in the later sections.

2. METHODOLOGY

2.1 Gaia DR3 data selection

In this work, we used the Gaia DR3 data from Gaia archive available in the home page (*https://gea.esac.esa. int/archive/*) to identify the field stars around each target stars by imposing 10′′ (10 arc minute) radius. We select four stars, that have coordinates cross matched with Gaia coordinates, from the local NGC 2180 cluster to study their relative proper motions with respect to the fields and the cluster itself. The mean proper motion of the corresponding field stars and the cluster are subtracted from the proper motion of the target star to obtain the star's motion with respect to its field stars and the cluster. To use the Gaia DR3 data, we cross-match the coordinates of the target stars with Gaia DR3 data and extract their proper motions and their Gaia DR3 ID as presented in table 1.

Table 1. The Gaia DR3 coordinates and proper motions of the target stars. The first and second columns of this table are the ID we give and Gaia DR3 ID respectively. The parallax π in mas and uncertainties (values in brackets), coordinates in α and δ for target stars are presented in columns 3 - 5 respectively; and the proper motions and uncertainties in α and δ for target stars are presented in columns 6 and 7 respectively.

ID	DR3 ID	π	α	δ	μ_α	μ_δ
1	3318219787895607168	0.96(0.03)	92.56815	4.85719	2.46(0.03)	-3.52(0.03)
2	3318235524655811968	1.03(0.04)	92.39738	4.95767	1.11(0.05)	-2.12(0.04)
3	3318217172257699200	1.07(0.07)	92.58337	4.80296	2.31(0.07)	-4.79(0.06)
4	3318222193077506816	1.06(0.03)	92.29356	4.71367	2.56(0.03)	-3.50(0.03)

2.2 Gaia DR3 Data Analysis

The proper motions of the field stars within 10 arc minutes radius area around each of our target stars are extracted from Gaia DR2 data . We used the astrometric excess noise (exclude stars with non-zero astrometric excess noise value) to select stars which are consistent with the star models and exclude contamination like unresolved binaries. We incorporate only stars with parallax and proper motion information consistent with the cluster NGC 2180 in each sub-fields using different data cutting methods adopted from (Gebrehiwot and Teklehaimanot, 2022). We made a parallax cut to the field stars to identify the cluster NGC 2180 members of the field stars and eliminate the foreground contamination using parallax information.

We plotted a color magnitude diagram(CMD), Bp vs Bp - Rp, of the new sample to enable us to visually inspect the field star members of the cluster NGC 2180 by choosing young and massive main sequence stars restricted with equation 1. The CMD of field stars of the four target stars are presented in figure 1 (the upper panel, from left to right, is for star1 and star 2 and the lower panel is for star 3 and star 4 respectively). The red squares in figure 1 represent the field stars with astrometric excess noise value of 0, the blue circles represent the field stars filtered by parallax selection, and the green dots represent the field stars filtered by CMD selection using equation 1 to choose the young and massive main sequence star members of the cluster NGC 2180 and to minimize the back ground contaminations.

$$12 < \mathrm{Bp_{mag}} < 19$$
$$0.7 < \mathrm{Bp_{mag}} - \mathrm{Rp_{mag}} < 1.3 \qquad \text{-----------------(1)}$$

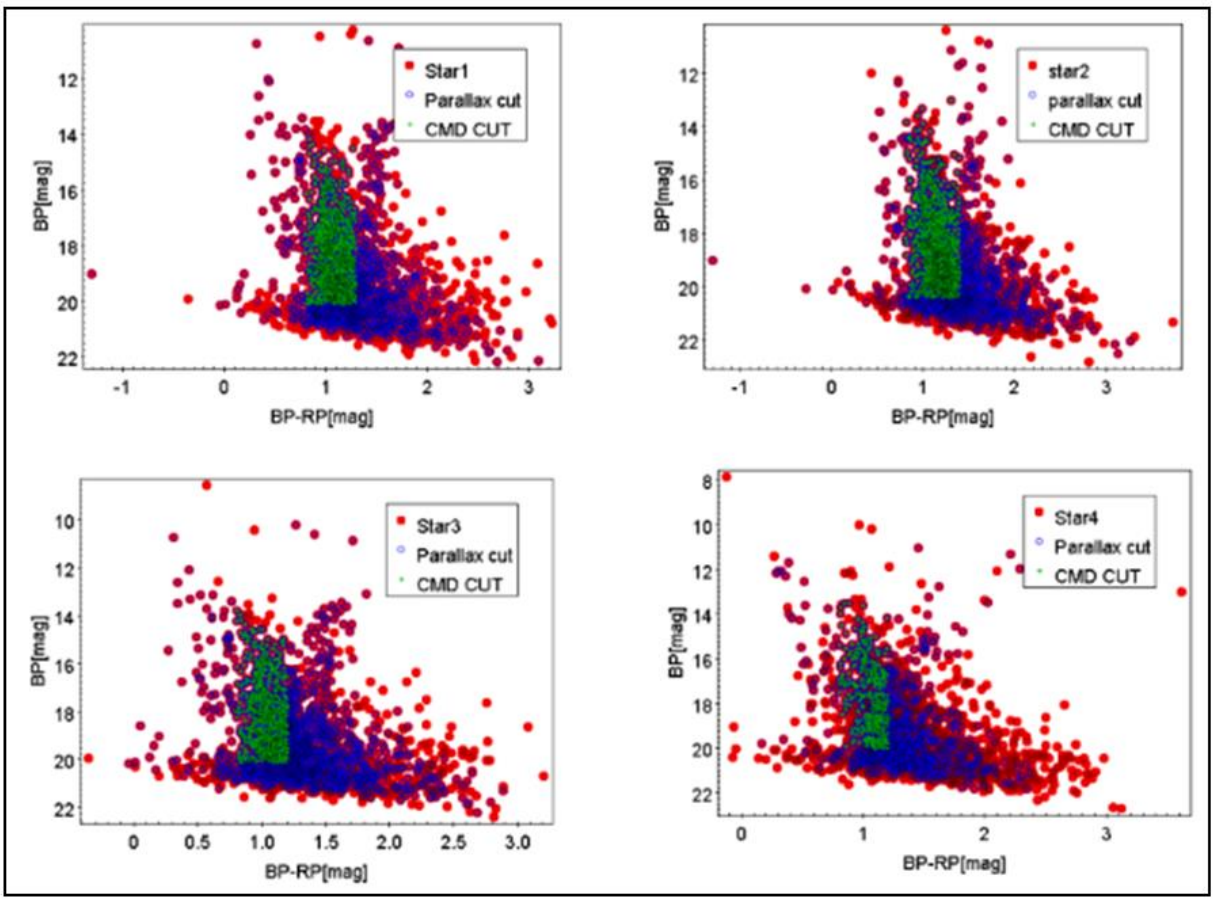

Figure 1. The color magnitude diagram for the 10 arcminute radius field stars centered around the target star with the Gia DR3 data. The complete sample of the field stars with astrometric excess noise value of 0 are shown in red solid square, the field stars filtered by parallax cut are shown in blue circle, and the field stars with CMD cut using Equation 1 corresponds to the green dotes.

Finally, we used the proper motion information to further clean the foreground contamination of the parallax cut and Color Magnitude Diagram (CMD) cut sample. We plotted a Point-Vector Diagram and eye selected the densest clump of stars as shown in figure 2, removing any outliers and these are the final samples of each fields.

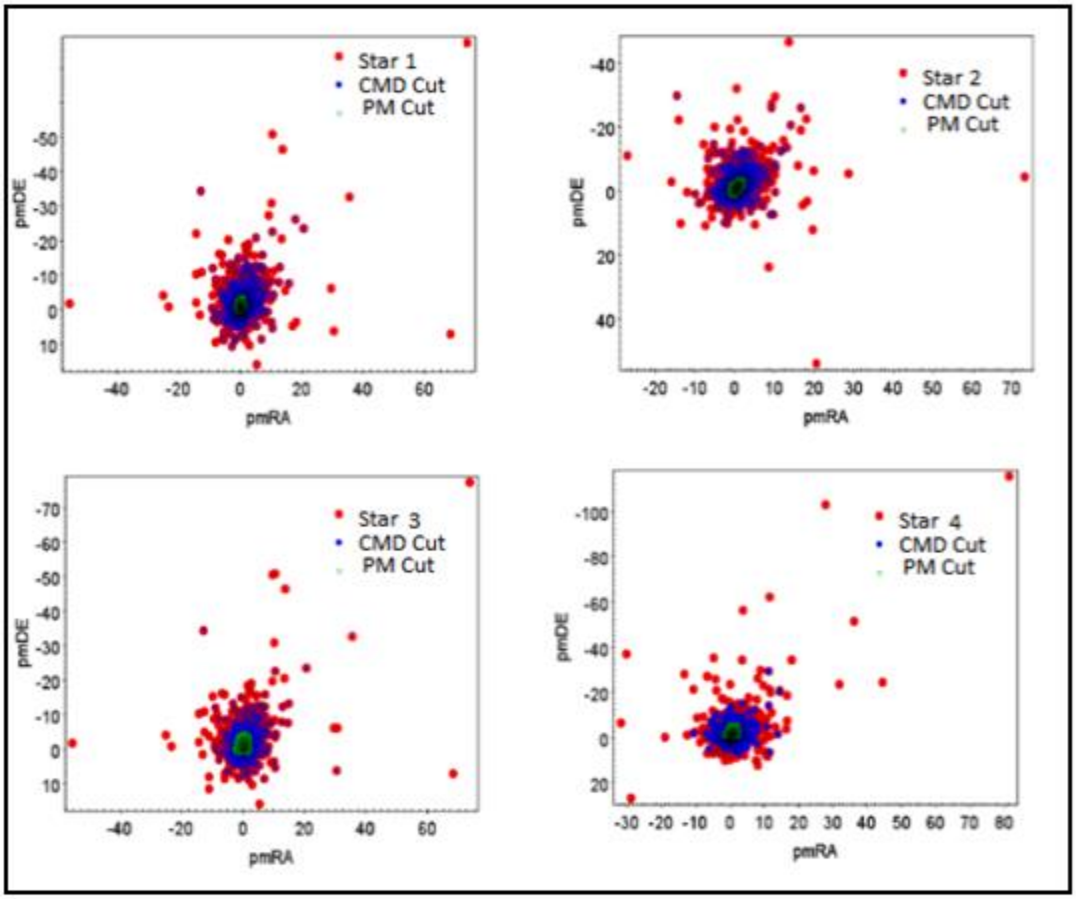

Figure 2. Proper-motion diagram of the field star. The densest clump with green dotes at the center are stars remaining after applying the parallax cut and are selected field stars to determine the mean proper motion of each fields.

After the above selection processes, we identified the cluster NGC 2180 members of each sub-fields that move together in the sky. Then, we generated the average (mean) of the proper motions of each field stars and this local field motion is then subtracted from the proper motion of the target star to obtain the star's motion with respect to its neighbors.

3. RESULT AND DISCUSSION

The relative proper motions of each target stars are estimated by taking the differences between the proper motion of the target stars and the mean of each field stars as shown in table 2.

Table 2. The calculated mean proper motions field stars and proper-motion differences between the target and field stars.The first columns of this table is the given ID. The proper motions and uncertainties (values in brackets) in α and δ for target stars are presented in columns 2 and 3 respectively; The number of field stars in each sub-field,the calculated mean proper motions and uncertainties (values in brackets) in α and δ for field stars are presented in columns 4, 5 and 6 respectively; the values of the proper motion differences between the target star and the mean of the field in α and δ are presented in column 7 and 8 respectively.

ID	μ_α	μ_δ	N^f_{stars}	μ^f_α	μ^f_δ	$\Delta\mu_\alpha$	$\Delta\mu_\delta$
1	2.46(0.03)	-3.52(0.03)	1123	0.35684(0.127)	-1.06808(0.172)	2.5472(0.041)	-2.6859(0.099)
2	1.11(0.05)	-2.12(0.04)	1038	0.43052(0.139)	-0.51861(0.289)	2.47345(0.048)	-1.7194(0.204)
3	2.31(0.07)	-4.79(0.06)	1048	-0.20397(0.157)	-0.91800(0.288)	2.3560(0.003)	-4.0190(0.105)
4	2.56(0.03)	-3.50(0.03)	1012	0.52753(0.484)	-0.82523 (0.768)	0.4924(0.4506)	-2.6708(0.712)

The standard errors of the proper motion in right as ascension and declination for the target stars (the values in brackets in table 2 columns 2 and 3 respectively) are taken from Gaia DR3, whereas the standard errors of proper motion in right ascension and declination (the values in brackets in table 2 columns 5 and 6 respectively) for each sub-fields are determined from the standard deviation of sub-field star by using uncertainty equation $\frac{\epsilon}{\sqrt{N^f_{stars}}}$, where, ϵ and N^f_{stars} are the standard errors of proper motion in right ascension and declination deviation, and the number of selected stars in each sub-field stars respectively. As N^f_{stars} of stars increases, the uncertainty in mean proper motion of the sub-field stars decreases, which is strongly agreed with statistical assumptions.

The standard errors of the relative proper motions in right ascension and declination (the values in brackets in table 2 columns 7 and 8 respectively) are calculated using the quadratic sum of the errors of the target stars and the mean of the sub-fields using equation 2.

$$\epsilon_{\Delta\mu} = \sqrt{\left(\frac{2\Delta\mu_\alpha}{\sqrt{\Delta\mu_\alpha^2+\Delta\mu_\delta^2}}\right)^2 \epsilon^2_{\Delta\mu\alpha} + \left(\frac{2\Delta\mu_\delta}{\sqrt{\Delta\mu_\alpha^2+\Delta\mu_\delta^2}}\right)^2 \epsilon^2_{\Delta\mu\delta}} \quad \text{---------------(2)}$$

In similar manner, we also calculated the relative proper motions of our target stars with respect to cluster NGC 2180 mean proper motion, which is $\mu_{\alpha clus} = (1.43 \pm 0.47) mas/yr$ and $\mu_{\delta clus} = (-0.56 \pm 0.39) mas/yr$ (Gaia Collaboration 2022). Subtracting the mean proper motion of NGC 2180 from the proper motion of each target stars we calculated the relative proper motion with respect to the cluster and we used these relative proper motions to estimate the kinematic age of our target stars.

Table 3. The calculated relative proper motions, tangential velocities and kinematic age of the target stars.

ID	$\Delta\mu_f$ *[mas/yr]*	$\Delta\mu_{cl}$*[mas/yr]*	ΔTV_f*[km/s]*	ΔTV_{cl}*[km/s]*	R_{clu}*[KPc]*	τ_{Kin}*[Myr]*
1	3.702(0.154)	2.479(0.849)	17.018 (3.284)	11.399(2.907)	0.1281	0.1123
2	3.012(0.246)	0.408(0.770)	13.689(2.853)	1.854(3.499)	0.4805	0.2591
3	4.659(0.181)	3.211(0.589)	21.656(3.423)	14.928(2.741)	0.4805	0.0089
4	2.716(1.409)	1.696(0.836)	13.129(2.833)	8.201(4.042)	0.1815	0.2213

Table 3 presents the given ID, the relative proper motions and uncertainties (values in brackets) relative to the field stars ($\Delta\mu_f$) and the mean proper motion of the cluster ($\Delta\mu_{cl}$) of the target stars, the relative tangential velocities with respect to the mean motion of the cluster (ΔTV_{cl}), the calculated angular distance from NGC 2180 (R_{clu}) in KPc using equation 3, and the flight time to the cluster NGC 2180 (τ_{Kin}) using Equation 4 from column1 - 6 respectively.

We calculated the angular distance of each target stars from NGC 2180, using the distance between two points with celestial coordinates (α_x, δ_x) and (α_y, δ_y), according to equation 3.

$$R = \sqrt{(\alpha_y - \alpha_x)^2(\cos\delta_x)^2 + (\delta_y - \delta_x)^2}. \qquad \text{------------------(3)}$$

Taking the assumption that all the target stars are escaping from the cluster NGC 2180 and the proper motions align along the position angle to the cluster, the flight times or kinematic ages of each target stars, presented in the last column of table 3 were calculated using equation 4.

$$\tau_{Kin} = \frac{R_{cl}}{\Delta\mu_{cl}}, \qquad \text{-------------------(4)}$$

Where, R_{cl} is the angular distance to the cluster in KPc, $\Delta\mu_{cl}$ is the relative proper motions of the target star in mas/yr, and τ_{Kin} the kinematic age in years.

The calculated flight time to the cluster (τ_{Kin} in Table 3) of the target stars are much smaller than the age of NGC 2180 (~710 Myr), which is estimated by (C. Bonatto et al., 2004). Accordingly, all the target stars have ejection scenario consistent with recent ejection from the cluster NGC 2180. The relative proper motion of the stars with ID 1 and ID 3 are larger than that of the remaining two stars, as presented on figure 3.

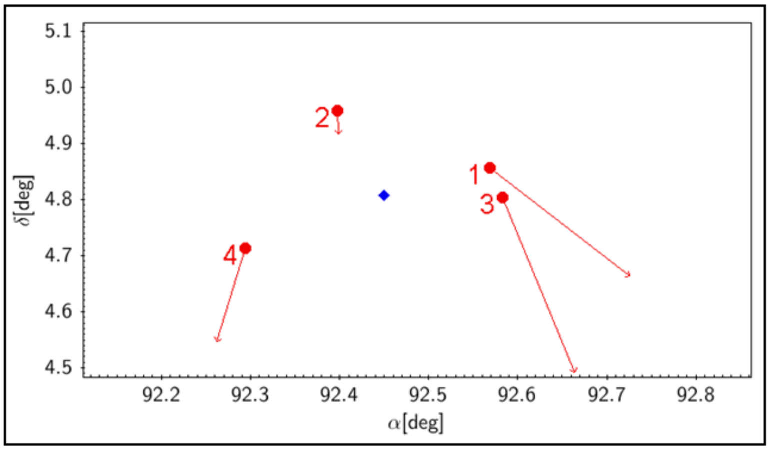

Figure 3. Right ascension vs declination of the target stars and the cluster at the center (the blue) diamond. The length of the arrows from the target stars are scaled by the relative proper motion of the target stars with respect to the filed stares.

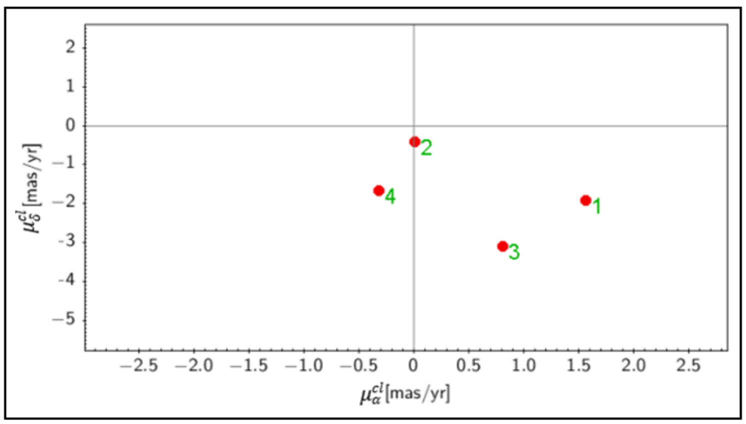

Figure 4. The relative proper motion in right ascension vs relative proper motion in declination of the target stars with respect to the cluster.

The relative proper motions of our target stars with respect to cluster NGC 2180, with objects that deviate from the origin (0,0) indicate larger differences in proper motion from the mean motion of the cluster are shown in figure 4. The stars ID 1 and ID 3 deviates significantly larger from the origin (0,0) than the other two stars, confirmed that stars ID1 and ID 3 could be runaway stars in the tangential plane of the cluster NGC 2180 with relative proper motions $\Delta\mu_f \leq 4.659$ mas/yr which corresponds to a tangential velocity of < 22 km/s.

4. CONCLUSION

The relative proper motions and tangential velocities of four stars, from the NGC 2180 cluster, are calculated to verify if the stars are runaways and ejected from the tangential plane of the cluster. The target stars have relative proper motions $\Delta\mu_f \leq 4.659$ mas/yr and $\Delta\mu_{cl} \leq 3.211$ mas/yr with respect to the field stars and the cluster respectively, that corresponds to tangential velocities ≤ 22km/s and ≤15km/s with respect to the field stars and the cluster respectively. Two of the stars, ID 1 and ID 3 are runaways as these stars have $\mu_f = (3.702 \pm 0.154)\text{mas/yr}$ and $\mu_f = (4.659 \pm 0.181)\text{mas/yr}$ with respect to their fields, which corresponds to the relative velocities $V_f = 17.018\, km/s$ and $V_f = 21.656\, km/s$ respectively and the estimated traveled distance of the stars in their life span consistent with late ejection scenario from the tangential plane of the cluster NGC 2180. This result is consistent with the criteria proposed for minimum runway velocity in the galactic plane (Carretero-Castrillo et al., 2023).

The other two Stars, ID 2 and ID 4 have $\mu_f = (3.012 \pm 0.246)\text{mas/yr}$ and $\mu_f = (2.716 \pm 1.409)\text{mas/yr}$ with respect to the fields, which corresponds to the relative velocities $V_f = 13.689\ \text{km/s}$ and $V_f = 13.129\ \text{km/s}$ respectively, could not be runaways from the cluster NGC 2180 as they have relatively smaller relative proper motions and tangential velocities with respect to the field stars and the cluster NGC 2180, although the estimated flight times to the cluster or the kinematic age agreed with late ejection from the cluster.

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6. CONFLICT OF INTERESTS

No conflict of interests.

7. REFERENCE

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