The new detection of blue straggler stars in 50 open clusters using Gaia DR3⋆

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1. Introduction

- Blue straggler stars (BSS) were initially identified by *Sandage (1953)* in the color–magnitude diagram (CMD) of the globular cluster M3, appearing as an extension of the cluster main sequence, blueward and above the main sequence turnoff (MSTO).
- BSS are found in globular clusters in the Milky Way *(Piotto et al. 2004; Leigh et al. 2008)* or dwarf spheroidal galaxies *(Salinas et al. 2012),* and also commonly in the intermediate-age to old open clusters *(Rain et al. 2021; Jadhav & Subramaniam 2021, hereafter Rain21, Jadhav21)* of our Galaxy.
- There are multiple formation scenarios for creating BSS in OCs.
  - — Mass transfer from binary companions can lead to a rejuvenation of the acceptors and the formation of BSS *(McCrea 1964).*
  - — Individual stellar mergers resulting from direct stellar collisions are also linked to BSS formation *(Hills & Day 1976; Leonard 1989).*

1. Introduction

- Andronov et al. (2006) quantified the angular momentum loss induced by magnetic stellar winds in main sequence tidally synchronized binaries and suggested that this mechanism is responsible for at least one-third of the BSS in OCs older than 1 Gyr.
- In recent studies: BSS formed from the merger of main sequence stars previously in a hierarchical triple system as a result of the eccentric Kozai–Lidov mechanism (Perets & Fabrycky 2009; Naoz & Fabrycky 2014), which has a significant role in BSS formation in OCs.
- Based on the WEBDA database, Ahumada & Lapasset (2007, hereafter AL07) identified 1887 blue straggler candidates in 199 OCs, of which 200 (10.6%) stars were classified as reliable blue straggler samples.
    - However, lacking high precision astrometric data at the time AL07 was published, the membership estimation of stars in an OC is usually based on photometric data only, and in many cases with lower reliabilities.

1. Introduction

- The higher precision proper motion and parallax from Gaia data provide an important advantage for distinguishing cluster members from field stars.
- Based on Gaia DR2 data, *Cantat-Gaudin et al. (2018)* used the UPMASK algorithm to select cluster members and provided an updated catalog of 1229 OCs, including previously known clusters and 60 newly discovered clusters.
- Later on, *Cantat-Gaudin & Anders (2020, hereafter CG20a)* obtained more cluster samples while eliminating a number of nonphysical groupings that had been incorrectly cataloged, and finally compiled a list of members for 1481 clusters.
    - — Rain21 updated the BSS sample in AL07 by utilizing members in the 1481 cluster listed in CG20a.

1. Introduction

- *Cantat-Gaudin et al. (2020, hereafter CG20b)* updated a comprehensive list of 1867 bona fide OCs confirmed by analysis based on Gaia data, providing a homogeneous catalog of OC properties and a catalog of cluster member stars.
- Jadhav21 produced a catalog of BSS using CG20b data, identified 868 BSS candidates in 228 clusters and 500 probable BSS (pBS) in 208 clusters.
- Gaia EDR3 *(Gaia Collaboration 2021)* provides astrometric and photometric parameters of 1.5 billion sources with higher accuracy than Gaia DR2.
- Compared to Gaia DR2, Gaia DR3 provides precision that is two to three times better for proper motion and over 20% better for parallax parameters.
- In the present work we searched for BSS in OCs based solely on the Gaia DR3.

2. Data and method

- To date, the most extensive surveys of BSS candidates in OCs have been performed by Rain21 and Jadhav21, both on the basis of Gaia DR2.
  — Rain21 identified BSS in 111 OCs based on the cluster members provided by CG20a.
  — At nearly the same time, Jadhav21 picked out BSS candidates in 228 OCs based on a larger cluster catalog from CG20b.
- In order to obtain a more complete sample of BSS in OCs, we hunted for BSS mainly outside the list of open clusters cataloged in Rain21 and Jadhav21.

2.1. Initial cluster sample

- We collected 1001 newly found OCs based on Gaia data.
  - — Among these new OC samples, which are not included in the catalogs of CG20a or CG20b, a total of 92715 member stars are present in 894 OCs.
  - — 71 OCs listed in *Sim et al. (2019)* and 36 more OCs reported by *Hao et al. (2020)* and *Casado (2021)* have no member star information available. These 107 clusters are also included in our initial sample.

2.2. Data preprocessing

- We downloaded the Gaia DR3 data of cluster samples according to their coordinates, proper motion, and parallax parameters listed in the literature.
  - — limited the Gmag to 19 mag. reduce the faint background sources.
  - — To highlight the cluster members in the proper motion distribution diagram, we cut the downloaded data according to their 3D spatial coordinates, and selected different parallax ranges in different cases:
    - ✓ (1) if d < 2 kpc, we downloaded data in the parallax range 0.4 < parallax < 1.5 mas;
    - ✓ (2) if 2 < d < 3 kpc, data in the range 0.2 < parallax < 1 mas were selected;
    - ✓ (3) if 3 < d < 4 kpc, data in the range 0.1 < parallax < 0.7 mas were downloaded;
    - ✓ (4) d > 4 kpc, the download data have 0.1 < parallax < 0.5 mas.
  - — Where d is the adopted cluster distance from the literature.

2.3. Membership estimation

- We used the pyUPMASK *(Pera et al. 2021)* algorithm to perform a membership estimation for each sample star.
- In the process of determining membership probabilities, this algorithm identifies the samples as members or nonmembers via five-dimensional parameters ($\mu\alpha*$, $\mu\delta$, ϖ, RA, and Dec).
  — (Pmemb = n/N, where N is the repeating times, and n is the number of times when a single star is determined as a member).

2.4. Field star contamination

- We wanted to use as many stars as possible; therefore, we selected stars whose membership probabilities are greater than 0.5 as cluster members.
- The criteria probability of 0.5 is also consistent with the criteria of other works *(e.g., Cantat-Gaudin et al. 2019; Yontan et al. 2019; Akbulut et al. 2021).*

2.5. Identification of BSS

- Blue stragglers stand out from other cluster members due to their position in the CMD that is bluer and brighter than the MSTO region *(Sandage 1953)*.
- Following this definition, we searched for blue stragglers in a specific region of the cluster CMD, which was determined by the procedure described below.

— Differential reddening (DR) correction. Considering that the DR introduces some dispersion at the CMD position, which can affect the selection of BSS, we first referred to the method of *Milone et al. (2012)* to correct the DR of the member stars for each open cluster. Then the corrected G vs. (G − GRP) diagram was drawn.

— Isochrone fitting. We then used the theoretical isochrone from PARSEC *(Bressan et al. 2012)* to perform the CMD fitting.

— BSS identification. Referring to Rain21, the genuine or possible blue stragglers can be in the region roughly delimited by the isochrone and zero age main sequence (ZAMS) as red solid and dashed lines in Fig. 1, respectively.

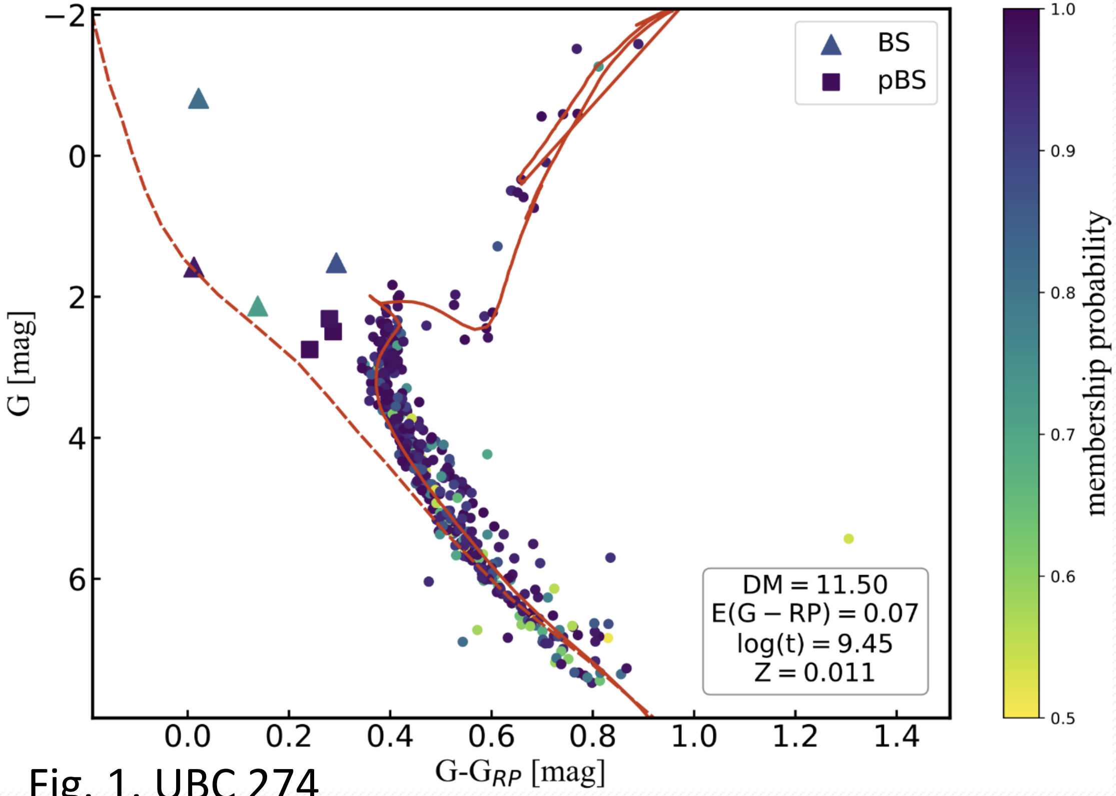


Fig. 1. UBC 274

Differential reddening corrected CMD of UBC 274 with isochrone and ZAMS.
Dots with different colors are cluster members with different membership probabilities, but all have Pmemb ≥ 0.5.
Triangles and squares are respectively the BS and pBS identified in this work.

The derived parameters of UBC 274 from the best fitting isochron are log(t) = 9.45, Z = 0.011, DM = 11.5, E(G − RP) = 0.07.

Isochrone: red solid
zero age main sequence (ZAMS): dashed lines

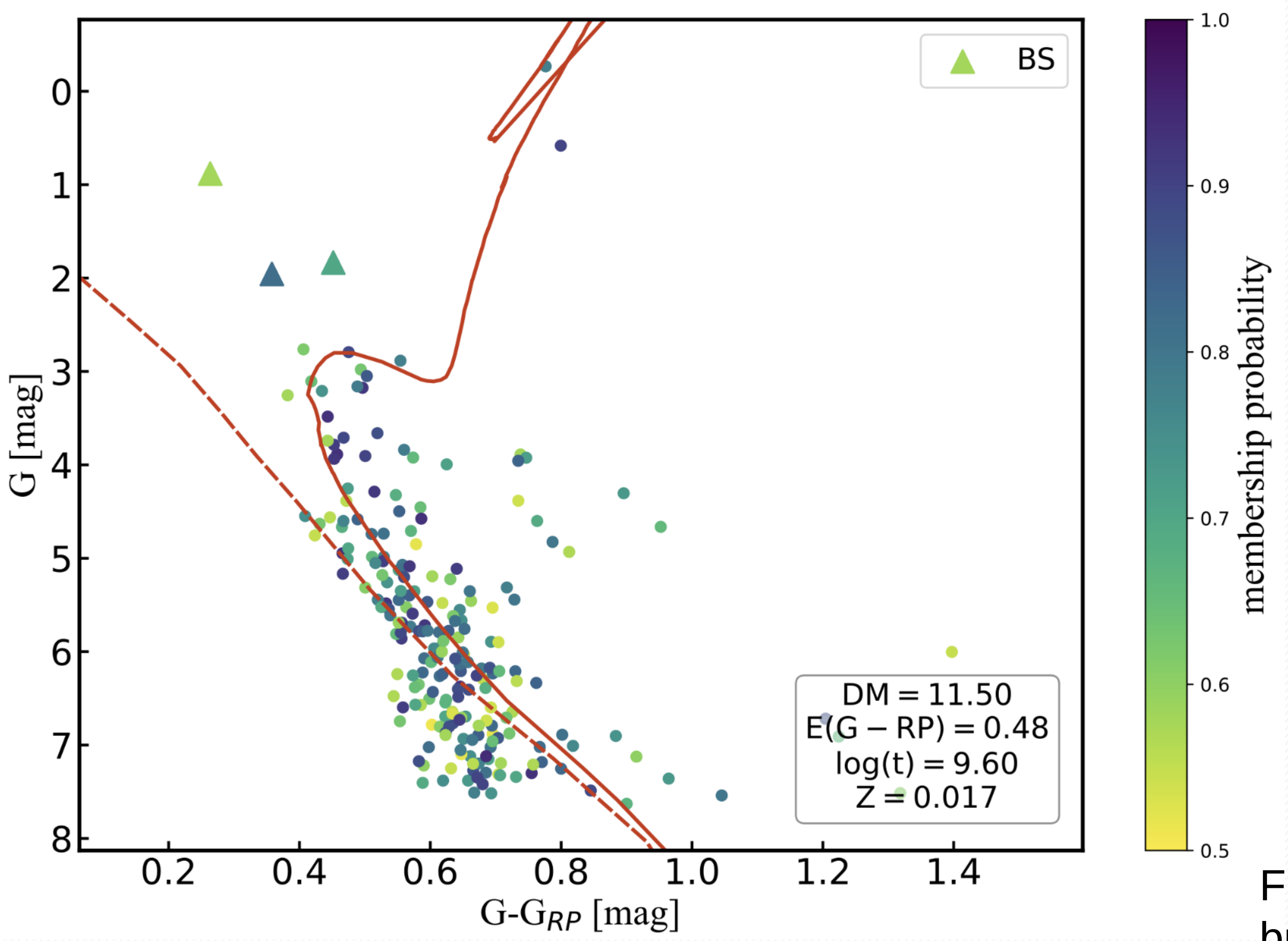


Fig. 2. Same as Fig. 1 but for cluster CWNU 70.

2.6. Yellow stragglers

- Yellow straggler stars (YSS) have colors between those of the TO and the RGB, and brighter than the subgiant branch *(Clark et al. 2004).*
  - — A YSS could be the pairing of a post main sequence star (which is more massive than a TO star and on its way to the RGB) and an evolved BSS *(Mathieu et al. 1990).*
  - — However, the YSS region can also contain the binaries' product of mass transfer or mergers *(Tian et al. 2006; Chen & Han 2008).*
- The methodology followed to find YSS is the same as that in *Rain et al. (2021).*
- A total of 14 YSS candidates were recognized in 7 of our 50 sample clusters.

3. Results

- We compared our results to those of Rain21 and Jadhav21.
- A sample of 138 new BSS within 50 open clusters were categorized; these stars have not been reported in previous works.
- The number of BSS in Galactic open clusters is increased by about 10%, and the number of open clusters hosting BSS is increased by nearly 17%.

3. Results

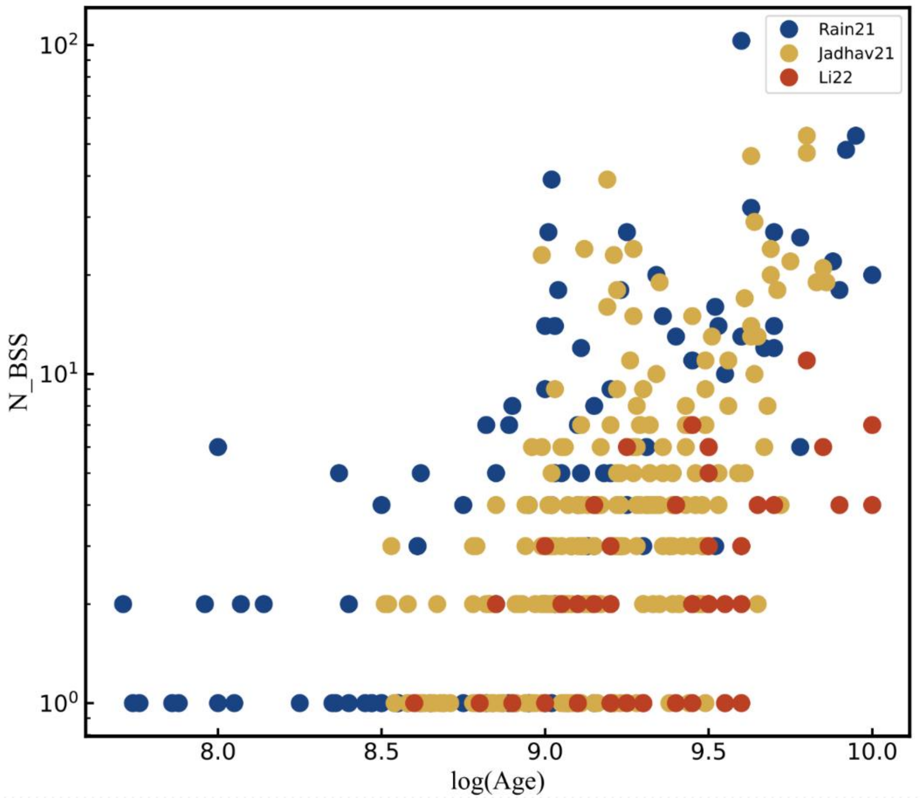


Fig. 3. Relationship of the number of blue stragglers in different works on the age of clusters. Red dots represent the BS+pBS sample in this work, yellow dots represent the BSS+pBS sample in Jadhav21, blue dots represent the BSS in Rain21.

- the age range of open clusters with blue stragglers in this work is consistent with that of Jadhav21;
- the relationship between the number of blue stragglers and the cluster age is also similar to that of Jadahav21, the older open clusters show a trend of having more blue stragglers.

3. Results

- The properties of the 50 open clusters are listed in Table 1, and the properties of BSS, YSS, and all other member stars are listed in Table 2.
  - — The clusters that have a clear main sequence pattern in the CMD are defined as Class 1 objects (FLAG = 1), and are shown in Fig. 1 as an example.
  - — The clusters with a dispersed form of main sequence are ranked as Class 2 objects (FLAG = 2), as shown in Fig. 2.

Table 1. List of all clusters with newly identified BSS.

idx	RA	Dec	pmRA	pmDE	Plx	$N_{\rm mem}$	$N_{\rm BS}$	$N_{\rm pBS}$	log(t)	DM	$E(G\text{-RP})$	Z	name	FLAG
–	(deg)	(deg)	(mas yr^{-1})	(mas yr^{-1})	(mas)	–	–	–	–	(mag)	(mag)	(dex)	–	–
1	29.40	37.76	9.69	−11.97	2.28	467	1	0	9.30	8.1	0.0	0.015	NGC_752	1
2	45.51	47.96	0.53	−1.26	0.34	73	1	0	9.40	11.9	0.1	0.019	CWNU_365	1
3	51.16	54.91	0.29	−1.08	0.42	172	1	1	9.50	12.9	0.43	0.019	CWNU_483	2
4	56.32	50.74	0.81	−1.24	0.35	150	1	0	9.40	13.0	0.37	0.019	CWNU_17	2
5	88.63	31.18	0.76	−3.38	0.57	94	2	0	8.85	11.4	0.16	0.011	CWNU_197	1
6	101.97	−7.14	−0.10	1.78	0.43	75	1	0	9.20	12.5	0.14	0.019	CWNU_251	1
7	111.58	−18.44	−2.08	1.93	0.24	206	1	5	9.2	13.2	0.25	0.015	FSR_1253	2
8	111.76	−37.52	−1.21	2.73	0.09	254	2	2	9.40	15.5	0.2	0.007	DC_3	2
9	112.13	−20.11	−2.28	2.53	0.29	235	1	0	8.80	13.1	0.2	0.019	LP_198	1
10	122.84	−31.95	−2.64	3.19	0.21	323	2	0	9.05	13.2	0.14	0.019	LP_386	1
11	146.49	−52.49	−1.64	−0.43	0.97	213	1	0	9.60	10.5	0.14	0.03	LP_2236	1
12	153.20	−60.90	−6.37	3.11	0.50	281	1	0	8.60	11.5	0.07	0.017	LP_2059	1
13	156.26	−72.55	−6.89	1.45	0.53	463	4	3	9.45	11.5	0.07	0.011	UBC_274	1
14	170.24	−59.30	−5.25	1.81	0.35	302	2	0	9.20	12.5	0.11	0.019	UBC_271	1
15	191.00	−58.08	−2.21	−1.26	0.52	258	1	0	9.10	11.9	0.19	0.03	UBC_288	2
16	233.85	−57.67	−3.61	−5.75	0.40	177	1	0	9.90	12.2	0.43	0.019	UFMG34	2
17	236.04	−55.26	−6.06	−4.39	0.36	167	5	2	10.0	13.2	0.72	0.015	UFMG42	2
18	236.57	−56.81	−1.68	−3.23	0.38	378	1	2	9.10	12.1	0.33	0.019	UBC_306	2
19	237.58	−55.96	−4.41	−3.09	0.37	892	1	1	9.60	12.1	0.52	0.015	UBC_308	2
20	241.49	−52.68	−1.70	−2.69	0.30	453	2	1	9.60	12.5	0.57	0.019	UFMG38	2

- Table 2 describes the catalog of BS, pBS, YSS, and all the other member stars.

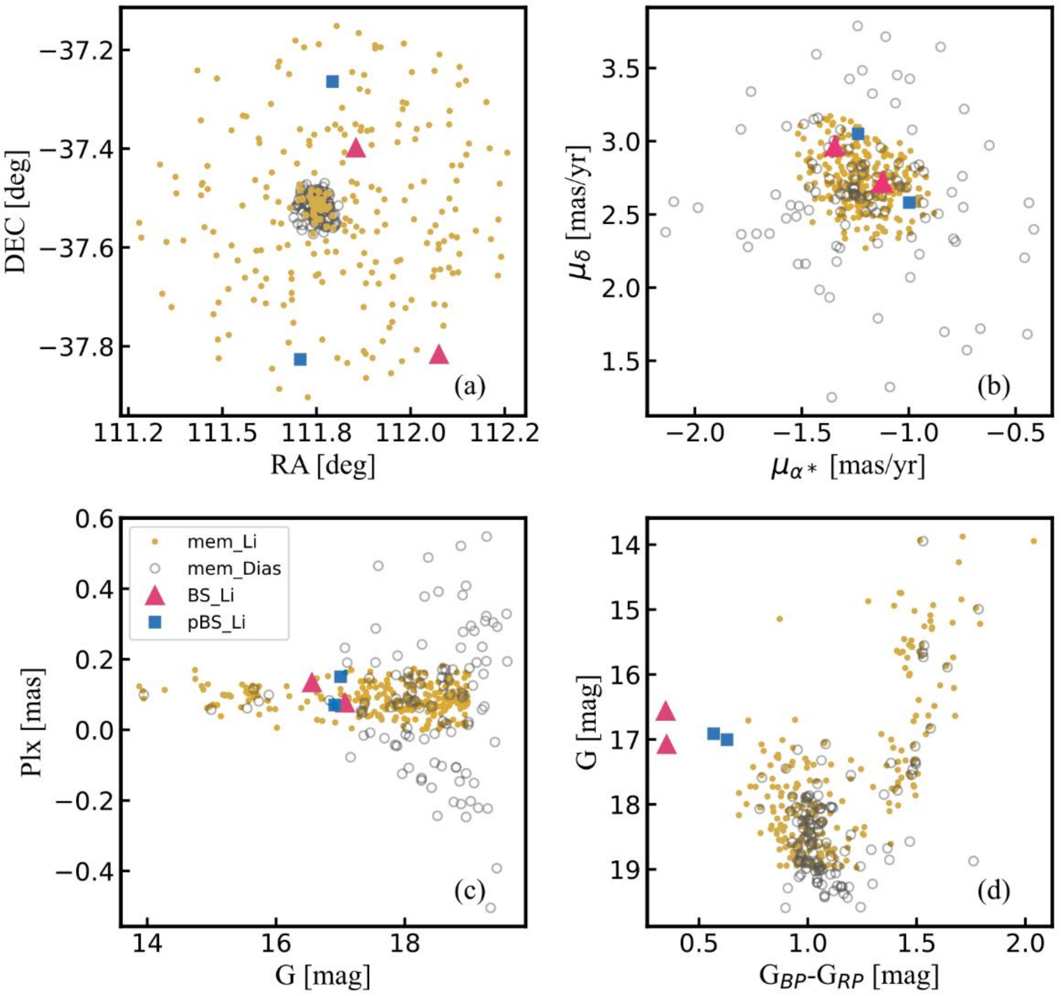
Table 2. Description of the catalog of BSS, pBSSs, and all the other member stars.

Column	Format	Unit	Description
ID_DR3	Long	–	Unique source designate in *Gaia* DR3
Cluster	String	–	The name of the corresponding cluster
P_{m}	Float	–	The membership probability of stars
f_strg	String	–	Flag indicating that the star is a genuine blue straggler (BS), a possible blue straggler candidate (pBS), a yellow straggler (YSS), or not a straggler (N)
RA	Float	deg	Right ascension at Ep = 2016.0
Dec	Float	deg	Declination at Ep = 2016.0
μ_{α^*}	Float	mas yr^{-1}	Proper motion in right ascension direction
μ_{α^*}_err	Float	mas yr^{-1}	Standard error of μ_{α^*}
μ_δ	Float	mas yr^{-1}	Proper motion in declination direction
μ_δ_err	Float	mas yr^{-1}	Standard error of μ_δ
ϖ	Float	mas	Parallax
ϖ_err	Float	mas	Standard error of parallax
*G*_mag	Float	mag	*G* band mean magnitude
BP_mag	Float	mag	Integrated BP band mean magnitude
RP_mag	Float	mag	Integrated RP band mean magnitude
Gmag_cor	Float	mag	*G* band magnitude after differential reddening correction
(*G*-RP)_cor	Float	mag	(*G*-RP) magnitude after differential reddening correction

Notes. This table contains 17 columns, including the astrometric and photometric parameters of cluster members in *Gaia* DR3 (Col. 1, Cols. 5–15), the corresponding cluster name (Col. 2), the membership probability of these stars in this work (Col. 3), the results of identification of stragglers (Col. 4), and the magnitudes after differential reddening correction (Cols. 16 and 17).

4. Discussion

- DC 3 was first identified as an open cluster by *Drake (2005*), and later listed in the major open cluster catalogs *(e.g., Kharchenko et al. 2013; Dias et al. 2021).*
  - — For DC 3, we obtained 254 member stars with Pm > 0.5, and identified two BSS and three pBSS that were not reported in previous studies.
- *Dias et al. (2021)* also provided the membership estimation for DC 3 using Gaia DR2 data.
- Compared with the *Dias et al. (2021)* sample, our cluster members are distributed in a much larger area, while appearing to be more compact in the parallax distribution and proper motion space as well.
- The BSS candidates we identified are found outside the confined cluster region inspected by *Dias et al. (2021).*



- Panels a–d of Fig. 4 show the comparison between our estimated cluster members and that from Dias et al. (2021).

a: spatial distribution for the cluster members and identified blue straggler candidates.
b: proper motion distribution of cluster members and identified blue straggler candidates.
c: parallax distribution for cluster members and identified blue straggler candidates.
d: CMD of DC 3.

4. Discussion

Table 3. Parameters of DC 3.

Param	Unit	$Value_{K13}$	$Value_{D21}$	$Value_{L23}$	Num_{L23}
RV	km s^{-1}	–	–	103.89 ± 18.60	15
V_t	km s^{-1}	107.81	109.61	121.17 ± 8.07	254
[Fe/H]	dex	–	−0.146 ± 0.049	−0.455	–
Dist	kpc	4.32	7.93	8.59	–
log*t*	–	9.26	9.47	9.40	–

Notes. RV and Vt are the radials and tangential velocities of the cluster respectively.
[Fe/H], Dist, and logt are the isochrone fitting results for metallicity, photometric distance, and age of DC 3, respectively.
In this work, RV and Vt are calculated by the average radial and tangential velocity of the cluster members with Pm > 0.5.

- Compared with K13 and D21, we obtained the radial velocity data of 15 member stars for the first time
- the metallicity of the cluster we fitted is more metal poor than that of D21.

4. Discussion

- It is worth noting that for the first time we have found a blue straggler on the tidal tail of NGC 752.
- NGC 752 is a close open cluster at a distance of about 440 pc *(Kharchenko et al. 2013; Castro-Ginard et al. 2020; Dias et al. 2021).*

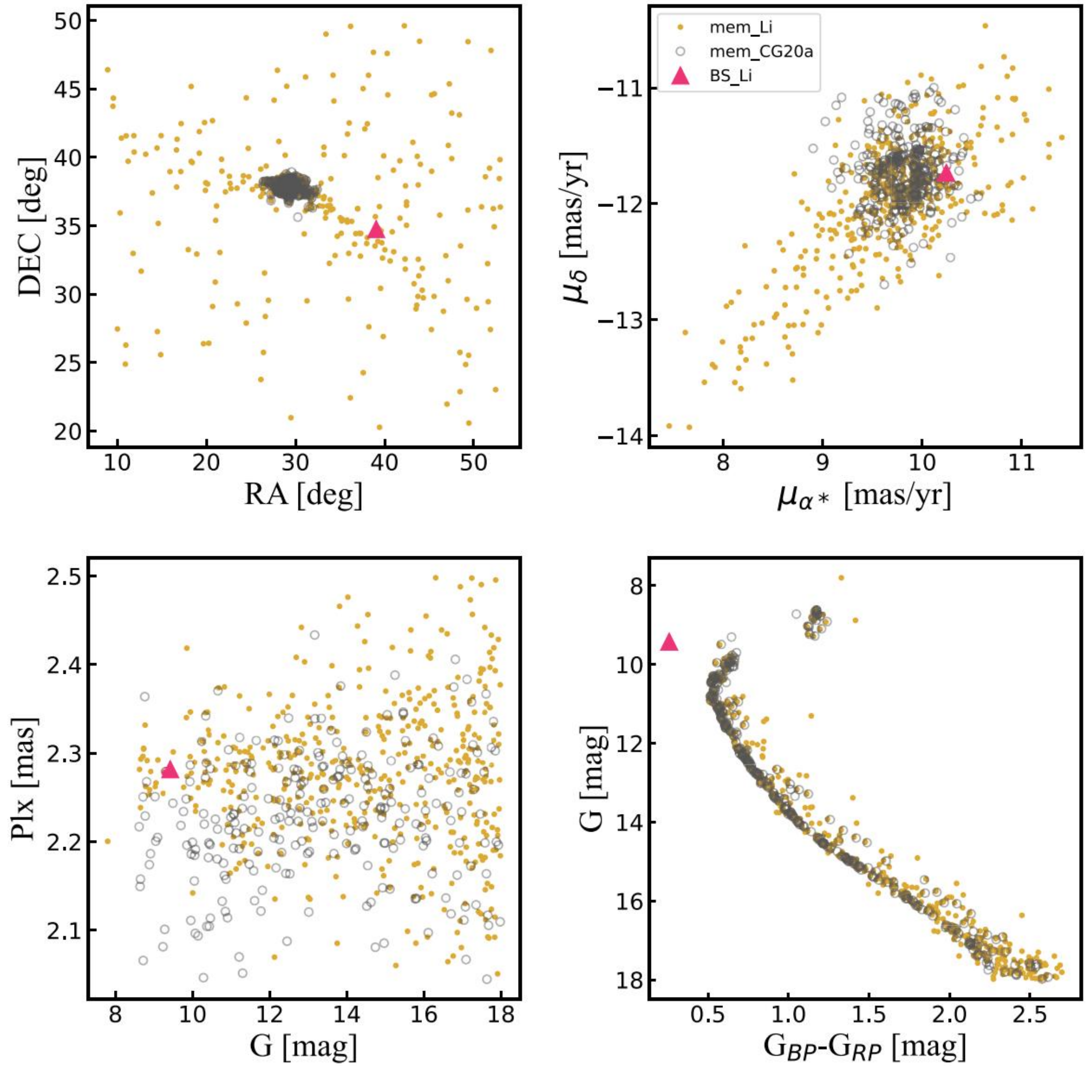


Fig. 5. Parameters of NGC 752.
Yellow dots are the cluster members re-determined in this work, and a magenta triangle represents the BS of NGC 752 we identified.
The member stars provided by *Cantat-Gaudin & Anders (2020)* are shown as gray circles.
All these stars have a member probability over 50%.

- As shown in the figure, there is a blue straggler on the tidal tail of NGC 752, which has never been reported.
- A detailed study of this blue straggler will be presented in our next work (Li et al., in prep.).

5. Summary

- We searched for blue stragglers from over 1000 open clusters, either newly found open clusters based on Gaia data or those beyond the sample clusters picked out by Rain21 and Jadhav21.
- In order to identify blue straggler stars more reliably and accurately, we used five dimension parameters (position, proper motion, and parallax) provided by Gaia DR3 to calculate the membership probabilities of stars with pyUPMASK, and selected stars with Pm > 0.5 for the subsequent analysis.
- Then we re-evaluated the properties of the clusters by isochrone fitting, and picked out the blue stragglers in a specific region of the clusters' CMD.
- In view of the different reliabilities, the blue stragglers we identified were divided into two different classes (BS and pBS) based on their relative positions to MSTO.
- As a result, we identified 138 blue straggler candidates from 50 open clusters, including 81 BSS and 57 pBSSs, which had not been reported before. In addition, 14 YSS in seven clusters of our sample were also recognized.