The Blue Straggler Population of the Open Clusters Trumpler 5, Trumpler 20, and NGC 2477

M. J. Rain1, G. Carraro1, G. J. A. Ahumada2, S. Villanova3, H. Boffin4, and L. Monaco5

1 Dipartimento di Fisica e Astronomia, Università di Padova, Vicolo Osservatorio 3, I-35122, Padova, Italy
2 Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, X5000BGR, Córdoba, Argentina
3 Departamento de Astronomía, Universidad de Concepción, 160 Casilla, Concepción, Chile
4 ESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany
5 Departamento de Ciencias Físicas, Universidad Andres Bello, Santiago de Chile, Chile

Received 2020 June 28; revised 2020 October 11; accepted 2020 October 13; published 2020 December 22

Abstract

We present a study based on Gaia DR2 of the population of blue straggler stars in the open clusters Trumpler 5, Trumpler 20, and NGC 2477. All candidates were selected according to their position in the color–magnitude diagram, their proper motion components, and their parallax. We also looked for yellow stragglers, i.e., possible evolved blue stragglers. We found that Trumpler 5 hosts a large blue straggler star population, which allowed us to analyze their radial distribution as a probe of the cluster’s dynamical status. The blue straggler star distribution was compared with that of red giant branch stars to evaluate mass segregation. Our results indicate that blue straggler stars are not more centrally concentrated than red giant branch stars in any of the clusters. The radial distribution of blue straggler stars in Trumpler 5 is flat. Additionally, using a multi-epoch radial velocity survey conducted with the high-resolution spectrograph FLAMES/GIRAFFE at the Very Large Telescope, we measured the radial velocities of a sample of stragglers to compare with the mean radial velocity and velocity dispersion of the clusters. Based on the radial velocity variations for different epochs, we roughly classified these stars as possible close or long-period binaries.

Unified Astronomy Thesaurus concepts: Open star clusters (1160); Blue straggler stars (168); Radial velocity (1332); Binary stars (154)

1. Introduction

Blue straggler stars (BSS) belong to the large variety of exotic objects that populate stellar clusters. These stars are located above and blueward of the turnoff (TO) in the color–magnitude diagram (CMD) of globular clusters (GCs; e.g., Sandage 1953; Piotto et al. 2004), dwarf galaxies (e.g., Momany 2015), open clusters (OCs; e.g., Milone & Latham 1994; Ahumada & Lapasset 1995, 2007), and even field populations of the Milky Way (Preston & Sneden 2000; Santucci et al. 2015). Two different mechanisms have been proposed to make a BSS: mass exchange in a binary system, and the collision of two stars induced by stellar interactions in a dense stellar environment. The first scenario suggests that BSS are formed from primordial binaries that evolve mainly in isolation until mass transfer starts, eventually leading to a possible merger (McCrea 1964). The second scenario indicates that BSS are the product of a dynamical merger between single stars or binary systems (Hills & Day 1976; Davies et al. 1994). Nevertheless, these objects are extremely important because they can provide information on the dynamics, the binary population, and the history of the stellar evolution of the cluster they belong to (Bailyn 1995; Ferraro & Lanzoni 2009; Chen & Han 2009; Glebbeek et al. 2010; Wyse et al. 2020). An extensive review of their properties has been compiled and presented in Boffin et al. (2015).

Despite their presence in all stellar environments, there is increasing interest to study the blue straggler population in OCs. A few catalogs of BSS in OCs are currently available, but their main disadvantage is the lack of reliable membership information, as they are based on purely photometric selection criteria (Ahumada & Lapasset 1995, 2007, hereafter AL95 and AL07). While useful, these compilations are not reliable enough to allow the derivation of the statistical properties of BSS because unfortunately, field stars tend to occupy the very same region as the stragglers in the CMD (Carraro et al. 2010). An improvement in the selection of BSS has become possible thanks to the second Gaia Data Release (DR2; Gaia Collaboration et al. 2018), which permits a better discrimination of genuine BSS from field stars using high-quality proper motion and parallaxes information.

Blue straggler stars are strongly affected by dynamical friction, mainly because of their masses—around 1.2–1.7 $M_\odot$, according to observations; therefore, they are perfect test particles to probe the impact of dynamics in different stellar systems. The observed radial distribution of BSS in GCs has been systematically studied. In this context, Ferraro et al. (2012, hereafter F12) grouped GCs in three families based on their BSS radial distributions. Clusters of Family I, or dynamically young GCs, show a flat distribution; in these systems the dynamical friction has not yet caused visible effects, even in the innermost regions. In Family II GCs, the dynamical friction has become more efficient and the mass segregation has started, leading to a bimodal distribution with a peak in the innermost region, followed by a minimum at $r_{\text{min}}$; there is a rise (or maximum) of the BSS density in the outer regions, where the stars are not yet affected by the dynamical friction. Finally, in the Family III class of GCs, the external maximum disappears, and the only noticeable peak in the distribution is the central one, followed by a minimum. A similar work in OCs has been carried out by Vaidya et al. (2020). The authors determined accurate stellar membership and studied the BS radial distribution in seven OCs. Five of them (Melotte 66, NGC 2158, NGC 2506, NGC 188, and NGC 6791) were assigned to Family II. In the remaining two
clusters (Berkeley 39 and NGC 6819), the authors found flat distributions. Recently, individual clusters have also been explored in this context. Bhattacharya et al. (2019) studied the radial distribution of the very old cluster Berkeley 17 (∼10 Gyr, Kaluzny 1994), and placed it in the Family II class of GCs; Rain et al. (2020) found that Collinder 261 (∼9 Gyr, Dias et al. 2014) has a flat BSS distribution, like that of Family I clusters.

While the photometric studies of GCs and OCs are often cited as an introduction to blue stragglers, not many spectroscopic studies have explored this population, especially in OCs. NGC 188 and M67 are the main laboratories for detailed spectroscopic studies of their BSS populations because both have very well identified BSS members (e.g., Peterson et al. 1984; Mathieu & Geller 2009, 2015; Geller & Mathieu 2011, 2012; Milliman et al. 2013). In addition to these two clusters, spectroscopic studies in OCs are available only for individual stars, for example, NGC 6791 (Brogard et al. 2018); NGC 6087, NGC 6530, and Collinder 223 (Aidelman et al. 2018); NGC 2141 (Luo 2015); and Collinder 261 (R20). In a statistical analysis of the distribution of the masses of the secondaries, Geller & Mathieu (2011) found that the companions of the BSS of NGC 188 have mass values of ∼0.5 M⊙, suggesting possible white dwarf (WD) companions. In fact, such WD companions have been detected for seven BSS in NGC 188 using far-ultraviolet Hubble Space Telescope observations (Gosnell et al. 2015). Currently, and thanks to the works of Geller et al. (2009) and Geller & Mathieu (2012), we know that the percentage of binaries among BSS is significantly larger (∼75%) than in the main sequence (MS) of OCs, where it is of about 20%, and also that the orbital period distribution of BSS is quite different from that of MS binaries, with the majority of BSS having orbital periods close to 1000 days, and most of them likely including a WD companion.

In this paper we study the BSS population of three OCs: Trumpler 5, Trumpler 20, and NGC 2477. These clusters cover a wide range of ages, metallicities, and positions in the Milky Way (see Table 1). Trumpler 5 (C0634+094, α = 06h36m29s, δ = +09°28′12″, J2000.0), discovered and cataloged by Trumpler (1930), is an old (∼4 Gyr), metal-poor, massive, and very populous OC. Trumpler 20 (C1236−603, α = 12h39m45s, δ = −60°38′06″, J2000.0) resides in the inner disk and is located beyond the great Carina spiral arm; it is old (∼1.3 Gyr), metal-poor, and not so distant (Platais et al. 2008). Finally, NGC 2477 (C0750−384, α = 07h52m10s, δ = −38°31′48″, J2000.0) is an intermediate-age OC (∼0.7 Gyr) with near-solar metallicity.

The layout of the paper is as follows. In Section 2 we present the data sets. In Section 3 we describe the photometric analysis and the selection criteria of BSS in OCs. We also explore the radial density profile of each cluster and estimate the field contamination. Finally we give the results of our selection in the three clusters. In Section 4 we explain how we reduced the spectra, extracted the radial velocities, and estimated their uncertainties; in this section we also define the criteria for establishing membership and binary status of our targets, and discuss the results of the spectroscopic detections. Section 5 is entirely devoted to exploring the BSS radial distribution of Trumpler 5 and, finally, in Section 6 we summarize this study and conclude.

## 2. Data Sets

### 2.1. Photometric Data

We used Data Release 2 of the European Space Agency mission Gaia (Gaia Collaboration et al. 2016, 2018). For more than one billion stars, this survey provides a five-parameter astrometric solution: position, trigonometric parallax, and proper motion, as well as photometry in three broad-band filters (G, GRIp, and GIp). The Gaia catalog also gives radial velocities for about seven million stars, mostly brighter than G ≈ 13. The astrometric solution, the photometric contents and validation, and the properties and validation of radial velocities are described in Lindegren et al. (2018), Evans et al. (2018), and Katz et al. (2019), respectively.

#### 2.1.1. Differential Reddening

The main effect of differential reddening (DR) in a CMD is a broadness (or dispersion) of the sequences of the cluster; this results from the differential presence of dust along the line of sight and across the field of view, causing different extinction values (Platais et al. 2008). For old OCs (log(age) ≥ 1 Gyr), the effects of DR are most noticeable in the TO and the red giant branch (RGB) morphologies. In this context, the positions of Trumpler 5 and Trumpler 20 in the Galactic disk and their high reddening values (see Table 1) suggest that these two clusters are highly affected by DR. This is noticeable in the left panels of Figure 1, where the elongated red clump and the thick appearance of the main sequence and TO in Trumpler 5 are clear indicators of DR. On a smaller scale, the same effects are observed in the CMD of Trumpler 20. We quantify the effect of DR in the three clusters analyzed in this work, however. The DR correction was performed in two different ways. In the case of Trumpler 5, which is the cluster most affected by this problem, we miss most of its MS due to the cut in G = 18 (see CG18 for more details). On the other hand, its CMD shows a well-defined RC dispersed along the reddening line. First of all, we selected RC stars and

### Table 1

| Cluster   | l   | b   | Distance | E(B−V) | R_e | log(age) | [Fe/H] | V_r  |
|-----------|-----|-----|----------|--------|-----|----------|--------|------|
| Trumpler 5 | 202.86 | +1.05 | 3.19 | 0.62 | 15.4 | 9.60 | −0.40 ± 0.006 | 49.67 ± 0.66 |
| Trumpler 20 | 301.47 | +2.22 | 3.56 | 0.46 | 16.0 | 9.11 | +0.17 ± 0.030 | −40.94 ± 1.20 |
| NGC 2477  | 253.56 | −5.64 | 1.44 | 0.31 | 15.0 | 8.85 | +0.07 ± 0.030 | +98.62 ± 0.46 |

Note. a Apparent radius.

References. (a) Dias et al. (2014), (b) Cantat-Gaudin et al. (2018), (c) Monaco et al. (2014), (d) Mishenina et al. (2015), (e) Carraro et al. (2014b).
determined the reddening law $R_G = A_G/E(G_{BP} - G_{RP})$ by a linear least-squares fit. We obtained $R_G = 1.79 \pm 0.05$. Then we selected an arbitrary point along the RC line as the zero-point for the reddening correction. This point has $G = 13.90$ and $(G_{BP} - G_{RP}) = 1.67$. Then, for each RC star we calculated the distance, both vertical and horizontal, with respect to the reference point. The vertical distance gives the differential $A_G$ absorption at the position of the star, while the horizontal distance gives the differential $E(G_{BP} - G_{RP})$ reddening at the position of the star. After this first step, for each star of the field (both cluster...
and non-cluster members) we selected the three nearest RC stars and calculated the mean differential A_G absorption and the mean differential reddening E(G_BP − G_RP), and finally subtracted this mean value from the star’s (G_BP − G_RP) color and G magnitude.

For Trumpler 20 and NGC 2477, we instead used MS stars for the DR correction because we have much longer and populated main sequences (see Figure 1) for them. We defined a line along the MS, and for each of the selected MS stars, we calculated its distance from this line along the reddening law line. For this reddening law, the line was assumed to be the slope we found for Trumpler 5, i.e., R_G = 1.79. The vertical projection of this distance gives the differential A_G absorption at the position of the star, while the horizontal projection gives the differential reddening E(G_BP − G_RP) at the star’s position. After this first step, for each star of the field (both cluster members and non-members) we selected the 10 nearest MS stars and calculated the mean differential A_G absorption and the mean differential E(G_BP − G_RP), and finally subtracted this mean value from its (G_BP − G_RP) color and G magnitude.

We underline the fact that the number of reference stars used for the reddening correction (3 for Trumpler 5, and 10 for Trumpler 20 and NGC 2477) is a compromise between having a correction that is affected as little as possible by photometric random errors, and the highest possible spatial resolution. Figure 1 shows the uncorrected (left) and corrected (right) CMDs. Figure 2, finally, shows the reddening maps for each cluster.

2.2. Spectroscopic Data

The clusters were observed with the Fibre Large Array Multi Element Spectrograph (FLAMES) attached to the Very Large Telescope of the European Southern Observatory (ESO; Paranal Observatory, Chile), using the combination of the medium-resolution spectrograph GIRAFFE and the fiber link to UVES. NGC 2477 data were collected in two periods, 2011 October to 2012 March, and 2018 January to March. Data for clusters Trumpler 5 and Trumpler 20 were also obtained in two periods, 2012 February to March, and 2018 January to March. These data were gathered under ESO programs 088.D-0045(A) and 0100.D-0052(A).

The UVES fibers were allocated to the cluster’s clump stars, whose membership is very solid, to set the zero-point of the radial velocity. The reduction and analysis of the UVES data are described in Carraro et al. (2014a, 2014b), Monaco et al. (2014), and Mishenina et al. (2015). GIRAFFE was used with setup HR8, which covers the wavelength range 491.7–516.3 nm, with a spectral resolution R = λ/Δλ = 20,000. Integration time ranged between 1500 and 2400 s, depending on the cluster. In total, NGC 2477 was observed in eight epochs, Trumpler 5 in five epochs, and Trumpler 20 in four epochs. Some details of the observations are given in Table 2. For the GIRAFFE data we only performed the sky-subtraction and normalization using the IRAF8 packages sarith and continuum because they had already been reduced in Phase 3.9

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8 http://www.eso.org/sci/facilities/paranal/instruments/flames.html
9 http://archive.eso.org/wdb/wdb/adp/phase3_spectral/form

Figure 2. Reddening maps in R.A. (X) and decl. (Y; expressed in arcmin) obtained for Trumpler 5, Trumpler 20, and NGC 2477 (from top to bottom). The intensity code indicates where differential reddening is stronger (darker) or weaker (lighter).

3. Photometric Analysis

We took advantage of the selection of cluster members already performed by Cantat-Gaudin et al. (2018, hereafter CG18), who used the membership assignment code UPMASK10 (Krone-Martins & Moitinho 2014). UPMASK depends on minimal physical assumptions about the stellar
Table 2
Details of the Spectroscopic Observations for Trumpler 20 (2012 February 11–12 to March 3–4, and 2018 January 30–31 to March 28–29), Trumpler 5 (2018 February 11–12 and 29 to March 28–29), and NGC 2477 (2011 October 28–29 to 2012 March 8–9, and 2018 January 30–31 to March 3–4)

| Epoch | MJD$_{\text{start}}$ (days) | MJD$_{\text{end}}$ (days) | Exposure (s) |
|-------|-----------------------------|-----------------------------|--------------|
| 1     | 55960.306622551             | 55969.3344003785            | 2400.0043    |
| 2     | 55990.200693457             | 55990.2284712834            | 2400.0042    |
| 3     | 58149.29577118              | 58149.3203549282            | 2400.0028    |
| 4     | 58206.118721651             | 58206.146949681             | 2400.0034    |

| Epoch | MJD$_{\text{start}}$ (days) | MJD$_{\text{end}}$ (days) | Exposure (s) |
|-------|-----------------------------|-----------------------------|--------------|
| 1     | 55969.166866965             | 55969.1923299766            | 2400.0042    |
| 2     | 55987.039632022             | 55987.065095023             | 2200.0033    |
| 3     | 58177.077345320             | 58177.102808314             | 2200.0027    |
| 4     | 58180.077972559             | 58180.103435726             | 2200.0177    |
| 5     | 58206.000367976             | 58206.025830970             | 2200.0027    |

| Epoch | MJD$_{\text{start}}$ (days) | MJD$_{\text{end}}$ (days) | Exposure (s) |
|-------|-----------------------------|-----------------------------|--------------|
| 1     | 55863.327186374             | 55863.3445475059            | 1500.0018    |
| 2     | 55863.345536336             | 55863.3628974807            | 1500.0029    |
| 3     | 55995.209882376             | 55995.2183444288            | 1500.0036    |
| 4     | 58179.147028199             | 58179.1643893541            | 1500.0038    |
| 5     | 58181.16996141              | 58181.1873225822            | 1500.0026    |
| 6     | 58122.199733802             | 58122.2170094270            | 1500.0012    |
| 7     | 58135.279591133             | 58135.2969525245            | 1500.0009    |
| 8     | 58149.265756268             | 58149.2831174243            | 1500.0039    |

Note. All dates are Modified Julian Dates (JD−2,400,000.5).

Cluster region and assigns the membership probabilities assuming that member stars are more concentrated than a random distribution (field stars) and that they share properties such as proper motions and parallaxes. CG18 selected data from Gaia DR2 considering as members the stars that are located within a radius twice as large as reported by Dias et al. (2002, hereafter DAML02), with proper motions within 2 mas yr$^{-1}$, and with parallaxes within 0.3 mas of those of the cluster centroid ($\mu_\alpha, \cos \delta, \mu_\delta, \varpi$).

3.1. Cluster Mean Proper Motions and Parallaxes

For consistency, we carried out the same photometric analysis as in our previous paper (R20). To use the membership selection of CG18 with confidence, we calculated the mean proper motions and parallax values for the three clusters. As mentioned in Section 2.1, in Gaia DR2 the radial velocity information is provided for targets with $G < 13$ mag. Here, we identify these objects in all three clusters. First, we selected giant stars with available $V_R$ measurements and calculated a first estimation of the mean $V_R$ value and the corresponding rms for each cluster. Then, only stars within $V_R \pm \sigma$ were selected. The same procedure was performed for each cluster until considerable low values of the rms—of the order of the errors in Gaia radial velocities—and $V_R$ values similar to those reported in Table 1 were reached. We finally had 10, 38, and 79 stars for Trumpler 5, Trumpler 20, and NGC 2477, respectively.

Second, we searched Gaia counterparts of members that were previously identified in the literature with confirmed membership. For Trumpler 5 we used five red clump stars identified as members by Monaco et al. (2014). In the case of Trumpler 20, we used a sample of five bona fide clump stars for which Carraro et al. (2014b) determined the abundance of several elements and their ratios to confirm their membership. Finally, for NGC 2477, we used six giant stars analyzed and identified as members by Bragaglia et al. (2008). We cross-correlated the position on the sky of these stars and the Gaia DR2 catalog, looking for the nearest neighbors within 1". Finally, using both stars from the literature and those selected above, we calculated the mean proper motion and parallax values. The values we found are reported in Table 3. The indicated errors are the standard deviations from the stars.

Our results are in remarkable agreement with the values in the literature (e.g., Cantat-Gaudin et al. 2018; Gao 2018). However, all of them differ considerably from the values reported in DAML02. The most extreme case is that of Trumpler 20, with absolute differences (our work minus DAML02) of 4.87 mas yr$^{-1}$ and 3.89 mas yr$^{-1}$ for $\mu_\alpha$ and $\mu_\delta$, respectively. These differences are unlikely to be caused by systematic errors in Gaia data, and probably arise from significant contamination by field stars and the lack of reliable cluster membership in the DAML02 catalog. For Trumpler 5 and NGC 2477 we found differences of 0.24 mas yr$^{-1}$ and 0.42 mas yr$^{-1}$, and 1.84 mas yr$^{-1}$ and 0.94 mas yr$^{-1}$ for $\mu_\alpha$ and $\mu_\delta$, respectively. The values we estimated were not used in the remaining analysis, but we always employed those of CG18.
3.2. King Profiles and Structural Parameters

For each cluster we determined the stellar density profiles and derived the structural parameters such as the core and tidal radius and concentration parameters (Table 4), using a King profile fitting approach (King 1962). A possible link between cluster dynamical quantities and the BSS population is explored in Section 5.

We constructed the radial density profile of the cluster following Salinas et al. (2012). We first divided all observed cluster members into concentric annuli; then, each annulus was in turn divided into eight subsectors defined by wedges of 45° centered on the cluster. The cluster center values we used are those reported by CG18, obtained using stars with \( P_{\text{memb}} \geq 50\% \). The density in each subsector was measured as the ratio between the number of stars within the subsector and the area of the subsector itself; this allowed us to obtain a mean stellar surface density and its uncertainty at the mid-point of each shell. The resulting profile was fit with an isotropic single-mass King (1962) model,

\[
n(r) = k \left( \frac{1}{1 + (r/r_c)^2} - \frac{1}{1 + (r/r_t)^2} \right)^2 + b,\]

where \( r_c \) is the core radius, \( r_t \) is the tidal radius, \( k \) is a scaling constant, and \( b \) is the background level. This last parameter was fixed by the nonlinear least-squares method fit to the total (cluster + background) density profile—i.e., we approximated the model by a linear one and the parameters were estimated by successive iterations; the fitting gave us \( k, r_c, r_t, \) and \( b \) for each cluster. After obtaining the cluster parameters, we found another cluster center using the new value of \( r_c \). With this new center, a new calculation of the radial profile was performed, resulting in a new \( r_c \). The procedure was repeated until the position of the cluster center and the value of \( r_c \) stopped changing.

The final density profile for each cluster is shown in Figure 3. The open circles represent the observed density profile, while the black circles mark the background-subtracted profile, obtained as the difference between the observed profile and the background level. The structural parameters are given in Table 4, where \( c = \log(r_t/r_c) \) is the concentration parameter. The derived parameters for Trumpler 20 and NGC 2477 are in good agreement with those measured by Donati et al. (2014) and Eigenbrod et al. (2004), respectively.

### Table 4

| Cluster | \( N_c \) (arcmin) | \( r_c^a \) (arcmin) | \( r_t^b \) (arcmin) | \( R \) (arcmin) | \( c^c \) | \( t_{\text{relax}} \) (Myr) | \( N_{\text{relax}} \) | Age (Gyr) |
|---------|-------------------|---------------------|---------------------|-----------------|--------|---------------------|------------------|----------|
| Trumpler 5 | 1908 | 4.57 ± 1.07 | 48.97 ± 15.80 | 15 | 1.02 ± 0.02 | 124 | 31.45 | 3.9 |
| Trumpler 20 | 850 | 4.07 ± 1.01 | 36.30 ± 9.27 | 13 | 0.95 ± 0.02 | 115 | 10.41 | 1.2 |
| NGC 2477 | 1367 | 6.21 ± 1.59 | 16.90 ± 6.33 | 12 | 0.43 ± 0.10 | 130 | 5.38 | 0.7 |

Notes.

- \(^a\) Core radius.
- \(^b\) Tidal radius.
- \(^c\) Concentration parameter.
to define the red limit for NGC 2477 and Trumper 20 because AL07 did not report it for the first cluster and did not include the second cluster in their catalog.

Notes.

a Blue/yellow stragglers over the entire extension of Cantat-Gaudin et al. (2018).

b Blue/yellow stragglers within the cluster radius $R$ calculated in Section 3.4.

c Blue/yellow stragglers within the cluster radius $R$ and with $P_{\text{memb}} \geq 50\%$.

Stars redder than this limit are considered possible yellow straggler stars (YSS).

Finally, recalling that the mass-transfer theory for the BSS (McCrea 1964) sets an upper limit of 2.5 mag above the TO, we regard stars above it as potential massive blue stragglers, as AL07 did.

### 3.4. Field Contamination

In the CMDs of OCs, the different evolutionary status of the stars and their corresponding sequences—i.e., main sequence, binary sequence, turnoff point, subgiant and giant branch, and, in the case of the older clusters, the red clump—are usually well defined and provide essential information on the physical properties of the stars that define them. These sequences are deformed by differential reddening (Section 2.1.1) and field contamination; these effects are particularly noticeable in clusters located toward the Galactic center. In this context, the decontamination of field stars is very important in the study of OCs. Given the proximity to the Galactic plane of Trumper 5 and Trumper 20, and because we identified our BSS and YSS within a radius twice as large as the apparent radius reported in DAML02, we expected field contamination from young stars that—as described in Carraro et al. (2008)—would occupy similar positions in the CMD as our straggler candidates. Our method for assessing membership using proper motions and parallaxes from Gaia DR2 decreases but does not remove all the contamination by such field young stars. To do so, and following Vaidya et al. (2020), we limited each cluster’s radius to that at which there are more cluster stars than field stars. We estimated the cluster size as the radius $R$ where the cluster density profile separates appreciably from that of the background (see Figure 3); the radii obtained in this way are listed in Table 4. The rate of false positives was estimated by counting stars located inside an annular region—selected outside the tidal radius—with the same area as that of the cluster. All the selected sources are within $\mu_\alpha \sin \delta \pm \sigma$, $\mu_\delta \pm \sigma$, and $\varpi \pm \sigma$.

We found 13 and 2 interlopers for Trumper 5 and Trumper 20, respectively. No contamination by field stars was observed in the case of NGC 2477.

### 3.5. Final detections

The most extensive published catalog of BSS in OCs so far is AL07. They looked for BSS candidates in the CMDs of galactic OCs taking advantage of the Open Cluster Database WEBDA\(^{11}\) (Mermilliod & Paunzen 2003) and the Lund Catalogue of Open Cluster Parameters (Lyngå, 1983, ed. 1987), with limited membership information. The AL07

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\(^{11}\) https://webda.physics.muni.cz/
catalog lists 1887 BSS candidates in 427 clusters. The present work instead uses the powerful astrometric solution of Gaia DR2 to identify cluster members, as described in Section 3. First, the stragglers were identified over the entire extension of each cluster, as given by CG18. Then, each BS population was limited to the radius R estimated in Section 3.4. Finally, for the three clusters we left out all stars with a membership probability ($P_{\text{memb}}$) below 50%. This operative and conservative cutoff has been defined in the literature as the probability of containing the most likely members (Cantat-Gaudin et al. 2018; Carrera et al. 2019; Yontan et al. 2019; Banks et al. 2020). Using the above-mentioned restrictions, we thus defined bona fide nonspurious BSS populations. Our results for each cluster are presented in Table 5.

Trumpler 5 hosts the largest population of BSS of our sample (see the upper panels of Figure 1); two stars are located above the upper limit of 2.5 mag defined for massive stragglers (Section 3.3). In the case of Trumpler 20, all stars visible in the CMD are within $\sim$1 mas yr$^{-1}$, and only one massive straggler candidate was identified. Finally, NGC 2477 does not harbor many BSS, and no massive stragglers are visible in its CMD.

Additionally, we compared our BSS candidates with those of AL07 in Trumpler 5 and NGC 2477 only because Trumpler 20 was not included in AL07. To do so, we searched the Gaia counterparts of the AL07 candidates. For Trumpler 5, there are only seven BSS in common, and the rest are non-members. This is not surprising, given the position of this cluster at a low galactic latitude. It is therefore expected to suffer from significant field contamination, which was not accounted for in AL07. In the case of NGC 2477, all BSS identified in AL07 are indeed members, but they are all concentrated around the cluster TO; only three of them are in our list of BSS candidates.

4. Spectroscopic Analysis

This is the first high-resolution spectroscopic analysis of the BSS population in the OCs Trumpler 5, Trumpler 20, and NGC 2477. Unfortunately, not all the candidates were observed with FLAMES because when the observational time was allocated, we used the BSS list of V20 to select the targets. This list is very different from that found in this work using Gaia information.

The spectroscopic analysis was carried out on 7 out of the 40 blue stragglers in our list for Trumpler 5—plus one star with $P_{\text{memb}} \leq 50\%$, on one out of our 8 blue stragglers for Trumpler 20—and two stars not identified as BS in this study, given their low $P_{\text{memb}}$, and in 3 out of the 5 blue stragglers in NGC 2477.

4.1. Radial and Rotational Velocities

The radial velocities were calculated with the cross-correlation task IRAF fxcor (Tony & Davis 1979). Each spectrum was cross-correlated with synthetic templates obtained with the SPECTRUM code$^{12}$ (Gray & Corbally 1994). The synthetic spectrum was computed with a molecular data file stdatom.dat Grevesse & Sauval (1998), a linelist luke.lst, suitable for mid-B- to K-type stars, and a model atmosphere calculated with the code ATLAS9 (Castelli & Kurucz 2003).

One of the most interesting observational features of BSS is the projected rotational velocity of $v \sin i$. From the theoretical point of view, BSS driven from the proposed formation mechanisms (i.e., mass transfer and collisions) are expected to rotate fast. In practice, however, from observations in stellar clusters, BSS have been identified as low and fast rotators (e.g., Lovisi et al. 2010, 2013). In this sense, a braking mechanism has been suggested to occur and slow down the stars (Sills et al. 2005). Given this complex scenario, the selection of a proper template for each star was mandatory given the different rotational velocities of the targets. The model atmospheres were calculated with parameters for F-type MS, or slightly evolved stars ($T_{\text{eff}} = 7500$ K and log g = 4.0), adopting solar metallicity. The microturbulence was set as $\xi = 0.0$ km s$^{-1}$ for all templates. Spectra were convolved with a Gaussian to model the instrumental resolution of the spectrograph, and rotational broadening was applied. Spectra were modeled assuming a $v \sin i$ value varying from 10 to 300 km s$^{-1}$, with a step of 10 km s$^{-1}$. For each target, synthetic spectra were then renormalized to maintain the continuum level at 1 and to match the core depth of the observed spectral lines. In this way, it was particularly easy to estimate the rotational velocity of the stars: we just compared the width of the observed and synthetic spectral lines by eye. The error of this procedure critically depends on the signal-to-noise ratio of the spectra. However, it was never above $\pm 10$ km s$^{-1}$.

The radial velocities measurements for the blue population are reported in Tables 6, 8, and 7 for Trumpler 5, Trumpler 20, and NGC 2477, respectively.

4.2. Errors

We considered the errors returned by fxcor as conservative estimates of the true uncertainties of the radial velocity. For each star we have four to eight radial velocity measurements and fxcor error estimates. We followed the same procedure as R20, i.e., we first computed the fxcor error for each star, and we calculated the radial velocity difference divided by the root square of 2 for each pair of measurements; then we built the distribution histogram and fit a Gaussian. We considered the standard deviation $\sigma$ of the Gaussian as the true radial velocity error. We plot the histogram together with the Gaussian fit and the true error in Figure 4.

Additionally, we calculated the mean fxcor error for each rotational rate, estimated as we described above in Section 4.1. Stars rotating with velocities ranging between approximately 30 and 50 km s$^{-1}$ have errors of about 2–4 km s$^{-1}$, and stars rotating with velocities of 80–150 km s$^{-1}$ have uncertainties of about 10 km s$^{-1}$; finally, the typical uncertainties for the fast-rotator stars ($v \sin i > 150$ km s$^{-1}$) are about 15 km s$^{-1}$. Similar uncertainty values were found by Mucciarelli et al. (2014) in their BSS sample. Therefore we decided to adopt the fxcor error as a conservative estimate for the radial velocity uncertainty.

4.3. Membership and Evolutionary Status

By means of the comparison between the radial velocities we measured for our BSS candidates and the mean radial velocity of the clusters, we can now try to assess possible membership. In what follows, we assume that BSS are the result of collisions or that they are binary systems, with either relatively short periods (a few days or less), or long ones (about 1000 days).

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$^{12}$ http://www.appstate.edu/~grayro/spectrum/spectrum.html
Given the example of NGC 188, we expect most BSS to be rather long-period binaries (Geller & Mathieu 2011; Davies 2015; Ivanova 2015). We adopted the mean velocity obtained in previous studies of clump stars as the mean velocity of each cluster.

For each cluster, we have between four and eight radial velocities, obtained at epochs separated by days, months, and years (Table 2). To assess membership, the radial velocities of the stars can be compared with the mean radial velocity of the cluster, taking into account the error bars—as derived in Section 4.1—and the possibility of binarity.

In this work we adopted the same criteria as in R20. A statistical analysis of the mass distribution of the secondary components of BSS in binaries with orbital periods near 1000 days shows that the masses of the companions peak between 0.5 and 0.6 $M_\odot$ (Geller & Mathieu 2011). Such masses suggest white dwarf (WD) secondaries, whose presence would indicate mass transfer as the dominant formation mechanism in BSS. Using the TO mass values of our clusters (1.12–1.5 $M_\odot$) and assuming the mass ratio $q$ of the systems to be 0.5, the separation between the stars should be larger than $\sim 3.5 R_\odot$ for the system not to fill its Roche lobe. The minimum orbital period should be of about 0.5 day, with a corresponding maximum orbital velocity of about 100 km s$^{-1}$. Stars with radial velocities changing between epochs up to 100 km s$^{-1}$ from the cluster mean could therefore still be considered as members, provided they are close binaries. On the other hand, if we consider post-mass-transfer long-period binaries ($P \sim 1000$ days), we would expect a maximum radial velocity of 10–13 km s$^{-1}$. Of course, it is possible to have a binary system in between the two cases.

These considerations led us to define the following rather conservative approach to confirm membership of BSS in our clusters. If the individual radial velocities are, given their error bars, compatible with the cluster mean $V_R$, and do not change significantly over the four epochs, the star is taken as a possible single-star member, i.e., the outcome of a collision or a merger. Of course, it could also be a binary with a long period—longer than $\sim 1000$ days. These stars are classified “M.” If a star's velocity is compatible with the cluster mean $V_R$, but the velocity errors are too large (e.g., larger than one-third of the radial velocity value) to discriminate between long-period or close binaries, we indicate it as “M?,” (ii) On the other hand, if the individual radial velocities are, given their error bars, within 100 km s$^{-1}$ with respect to the cluster mean $V_R$, then (a) if the velocities differ by more than 20 km s$^{-1}$ from $V_R$ and change

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### Table 6

|                  | Tr5-BS1          | Tr5-BS2          | Tr5-BS3          | Tr5-BS4          | Tr5-BS5          | Tr5-BS6          | Tr5-BS7          |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| $RV_1$           | $+22.72 \pm 11.12$ | $+46.03 \pm 3.65$ | $+31.25 \pm 10.41$ | $+31.71 \pm 13.75$ | $+03.87 \pm 7.93$ | $+26.92 \pm 12.25$ | $+43.33 \pm 12.77$ |
| $RV_2$           | $+24.87 \pm 6.68$  | $+165.46 \pm 6.18$ | $+67.26 \pm 13.90$ | $+26.34 \pm 14.31$ | $-09.56 \pm 14.74$ | $+15.73 \pm 11.25$ | $+49.34 \pm 8.01$  |
| $RV_3$           | $+21.41 \pm 11.10$ | $-13.43 \pm 3.16$  | $+25.84 \pm 12.41$ | $+33.09 \pm 15.33$ | $-16.44 \pm 6.38$  | $+13.40 \pm 12.77$ | $+09.99 \pm 6.29$  |
| $RV_4$           | $+12.03 \pm 11.96$ | $-22.52 \pm 3.69$  | $-57.84 \pm 18.19$ | $+33.23 \pm 13.56$ | $-13.80 \pm 12.75$ | $+00.58 \pm 14.49$ | $+23.49 \pm 5.44$  |
| $RV_5$           | $+17.80 \pm 7.70$  | $-17.48 \pm 3.10$  | $-7.62 \pm 16.13$  | $+24.28 \pm 15.29$ | $-14.77 \pm 12.95$ | $+10.75 \pm 14.70$ | $+04.03 \pm 4.14$  |

Class: a NM: non-member, M: member, CB: close binary system, LP: long-period binary.

### Table 7

|                  | NGC2477-BS1     | NGC2477-BS2     | NGC2477-BS3     |
|------------------|----------------|----------------|----------------|
| $RV_1$           | $+07.78 \pm 1.63$ | $+11.83 \pm 2.64$ | $+06.51 \pm 1.98$ |
| $RV_2$           | $+07.79 \pm 1.85$ | $+11.80 \pm 2.80$ | $+06.27 \pm 2.21$ |
| $RV_3$           | $+08.67 \pm 1.61$ | $+13.01 \pm 2.30$ | $+07.49 \pm 1.85$ |
| $RV_4$           | $+08.26 \pm 1.70$ | $+11.68 \pm 2.00$ | $+06.18 \pm 2.10$ |
| $RV_5$           | $+08.30 \pm 1.57$ | $+11.32 \pm 2.14$ | $+06.76 \pm 1.87$ |
| $RV_6$           | $+08.53 \pm 1.55$ | $+10.92 \pm 1.98$ | $+05.84 \pm 1.89$ |
| $RV_7$           | $+08.50 \pm 1.79$ | $+11.63 \pm 1.87$ | $+06.12 \pm 1.97$ |
| $RV_8$           | $+08.06 \pm 1.65$ | $+10.16 \pm 2.27$ | $+06.96 \pm 1.88$ |

Class: a M: member.

### Figure 4

Histogram of the differences—divided by the root square of 2—between pairs of radial velocity measurements for the same star. The best-fitting Gaussian to the distribution is plotted, and its standard deviation $\sigma$ is indicated.
significantly between two epochs, we can consider the star as a candidate close binary member of the cluster, “M, CB.” When this happens but the error bars are too large, we tag the star as “M, CB?” However, note that when the period is close to the difference in time between the epochs, we should not expect much change in radial velocity. (b) If the velocities are within 20 km s$^{-1}$ from $V_R$ and do not change by more than a few km s$^{-1}$ between epochs (depending on the possible period, which is constrained by the difference with $V_R$), we possibly have a long-period (above 100 days) binary, and it is classified as “M, LP.” When this is true but error bars are too large, the classification instead is “M, LP?”.

The membership status of the binaries (CB and LP) can only be secured once we have determined the full orbital solution and thus derived the systemic velocity. If none of the above apply, we label the star a non-member, “NM.”

4.4. Spectroscopic Detections

Several explanations have been proposed for the blue straggler phenomenon, although none is completely satisfactory (see Section 1). The binarity hypothesis is the most accepted one, mainly because it can in principle account for most of the observations. Mathieu & Geller (2009) have shown that the percentage of binaries among BSS is significantly larger than in the cluster main sequence (MS). Previous studies in OCs have revealed that the BSS population in OCs mostly contains long-period binaries (Geller et al. 2009); these have periods ranging from a few years to decades or even centuries, and it is very difficult to detect them spectroscopically and photometrically. On the other hand, R20 found a significant number of BSS in Collinder 261 that are possible close binaries.

Following the description of Section 4.3 and based on their radial velocity variations, we attempted to roughly assess the binary nature of the sample studied here, that is, to decide whether they may be close long-period binaries, or single stars without radial velocity variations. All the probable binaries would need additional spectroscopic follow-up to be properly characterized given the small number of observations.

4.4.1. Trumpler 5

This object contains a larger number of stars than many old OCs in the Galaxy. Although it is located relatively close to the Sun ($\sim$3 kpc), given its location in a highly and differentially reddened region, not many photometric and spectroscopic studies have been carried out of their members, and none of its blue straggler population.

Out of our 40 BSS candidates, only 7 were observed with FLAMES, for which five epochs of spectra were available (see Table 6). Among these stars, we found four close binaries. We classified stars Tr5-BS2 (80%), Tr5-BS3 (90%), Tr5-BS6 (100%), and Tr5-BS7 (100%) as members and possible close binaries (M, CB). On the other hand, we found three possible interlopers: Tr5-BS1 (80%), Tr5-BS4 (100%), and Tr5-BS5 (100%), which are not members according to our criteria and measured radial velocities. The high probability of membership ($P_{mb}$) that these three receive from CG18 shows that a good astrometric solution—such as that of Gaia DR2—is not enough for a correct identification of a bona fide blue straggler, but that spectroscopic data are also needed. We found that almost all stars in Trumpler 5 observed with FLAMES are fast rotators (including the interlopers), except for Tr5-BS2. The theoretical expectations for rotation velocities of BSS are not well defined, but all current scenarios can plausibly spin them up. These stars are similar to those found by Mucciarelli et al. (2014), with the fastest rotate up to $\sim$200 km s$^{-1}$.

4.4.2. NGC 2477

This cluster is moderately old and slightly metal-poor. It is also known to be one of the clusters with the largest number of member stars in the southern sky (Gao 2018). For the five BSS we identified in the CMD (bottom panels of Figure 1), we obtained eight epochs of radial velocities for only three stars (see Table 7). These stars are NGC2477-BS1 (100%), NGC2477-BS2 (90%), and NGC2477-BS3 (80%). Despite the high binary frequency ($\sim$36%) found by Eigenbrod et al. (2004), our radial velocity measurements indicate that these three stars are single nonvariable members—although they could also be long-period binaries or binaries seen face-on. When we consider their projected rotational rates, BSS do not seem to rotate unusually fast, similarly to what Smith & Hesser (1983) found. In the work previously mentioned, NGC2477-BS2 (90%) or HART 7302 is classified as a G3IV-V dwarf and is considered to be a probable interloper according to its position in the CMD, allegedly close to the cluster TO. However, in our CMD this object appears to be clearly separated from the TO, and given their proper motion, parallax, and radial velocity values, this star may be considered a member. Smith & Hesser (1983) give a rotational velocity of 50 km s$^{-1}$ for this star, very close to the 45 km s$^{-1}$ we found.

4.4.3. Trumpler 20

Given its position in the inner disk (where not many old OCs reside), age, proximity, and mass, Trumpler 20 is particularly interesting. The blue straggler population of this cluster has been identified in a handful of photometric studies (AL95, V20, Carraro et al. 2010), but not with spectroscopy. Unfortunately, only one star out of the eight BSS with $P_{mb}$ $\geq$ 50% was observed with FLAMES. Star Tr20-BS1 (100%) is a possible close binary according to our criteria. Two stars with probabilities below 50% were also observed, namely Tr20-BS2 (10%) and Tr20-BS3 (30%), which were identified as one possible close binary (member) and a non-member (possible long-period binary), respectively. For this cluster, we measured radial velocities in four epochs for the three stars (see Table 8).

5. Radial Density Profiles

The radial distribution is a powerful tool to estimate the dynamical age of star clusters and has been studied extensively (e.g., F12 and Beccari et al. 2013). In this context, and given their relatively high masses and luminosities, BSS are the perfect objects for analyzing dynamical friction and the mass segregation, in view of their direct relation with the cluster dynamics.

An analysis of the stellar radial distribution can only be carried out in Trumpler 5, given its significant number of blue stragglers. To analyze the behavior of BSS relative to that of normal stars and to better understand the dynamical state of the cluster, we studied the BSS radial distribution and compared it to that of a reference population that is assumed to trace the normal cluster stars. A bright, natural reference population in the optical is the RGB; given the accurate astrometric solutions for stars in the RGB, we measured the radial velocities of the BSS and compared them to their corresponding radial velocities of the RGB.
of Gaia, these stars can be very reliably identified. Sources with $G < G_{\text{TO}} - 0.5$ (in the dereddened CMD) and $P_{\text{memb}} \geq 50\%$ were selected as RGB stars. We thus identified 142 RGB stars in Trumpler 5.

5.1. Cumulative Radial Distribution and Population Ratios

The cumulative spatial distributions on the y-axis as a function of $r/r_c$ is shown in the left panels of Figure 5. The solid black line indicates the normalized cumulative distribution of the BSS candidates in comparison with the sample of RGB stars (dashed red line). For Trumpler 5 the BSS do not appear more centrally concentrated than the reference population. Our finding disagrees with what is observed in other clusters, whose BSS show a high concentration in the cluster internal region relative to the evolved stars (Geller et al. 2008; Bhattacharya et al. 2019; Vaidya et al. 2020, R20).

To find whether the radial distributions of BSS and RGB stars are extracted from the same parent distribution, thus indicating the absence of segregation, we used the $k$-sample Anderson–Darling test (Scholz & Stephens 1987, hereafter A-D test). The A-D test indicates a difference of $99.9\%$ between the distributions of BSS and RGB stars, i.e., both populations do not originate from the same distribution.

Additionally, a further indicator of segregation is the number of BSS normalized to the number of a reference population. We divided the field of view into concentric annuli, such that each annulus has at least one BSS. The right panel of Figure 5 shows the number of BSS candidates with respect to that of RGB stars in each annulus as a function of $r/r_c$. The ratio was corrected assuming that the field contamination we found in Section 3.4 is homogeneous. In the case of Trumpler 5—and considering the errors—the distribution does not become flat, indicating that BS and RGB stars are more or less equally distributed in the central part of the cluster and in its outskirts.

When we compare this distribution with those described by F12 for GCs, it appears to be somewhat similar to that of Family I clusters. In this family, the radial distribution of the stragglers is fully consistent with that of the reference population, and dynamical friction has not yet played a major role, even in the core.

Following V20, we decided to test the possible location of $r_{\text{min}}/r_c$ in the radial distribution in this cluster. To do so, we first estimated the central relaxation time $t_{\text{relax},c} \sim \tau_{\text{cross}} N_5/6 \log N_5$, for the three clusters—for the sake of completeness, $\tau_{\text{cross}} \sim D/\sigma_5$ is the crossing time, $N_5$ is the total number of stars (within the radius of each cluster and with $P_{\text{memb}} \geq 50\%$), and $\sigma_5$ is the velocity dispersion (Binney & Tremaine 2008). In the calculations we employed the standard deviations of the projected proper motions of each cluster, as well as the core radius we derived from the King profiles (Section 3.2). Second, using the values of $t_{\text{relax},c}$ and the evolutionary age of each cluster, we estimated the parameter $N_{\text{relax}} = \text{age}/t_{\text{relax},c}$. These three parameters and the number of stars are reported in Table 4. Finally, using the value of $N_{\text{relax}}$, we estimated $r_{\text{min}}/r_c$ using Equation (1) from V20, but only for Trumpler 5. The dynamical state of this cluster is discussed in more detail in the conclusions (Section 6).

6. Summary and Conclusions

We have studied the blue and yellow straggler population of the OCs NGC 2477, Trumpler 5, and Trumpler 20 using the selection of cluster members published by Cantat-Gaudin et al. (2018) and updated by Cantat-Gaudin & Anders (2020). They performed a membership selection based on the latest Gaia release (Gaia DR2) of the astrometric solution. Additionally, we complemented our results with spectroscopic data from FLAMES/GIRAFFE and defined a rough classification of their binary nature based on their radial velocity variability. The accuracy and precision of Gaia DR2 enables the discovery of astrometric binaries, which are, however, significantly affected...
by the measurements and data processing. The Gaia single-body five-parameter astrometric solution is fit to the binary under the assumption that the binary moves like a single-point mass, which leads to considerable biases. In this sense, we are aware that the CG18 astrometric selection of members likely leaves out some binaries. Long-period binaries will be affected by an excess of proper motions, and systems with periods of about 1 yr will have an effect on their parallax values (under- or over-estimated).
overestimation, Penoyre et al. 2020). On the other hand, in close binary systems the proper motions will be affected by the orbital velocity.

Using red clump stars and members with radial velocity measurements \((G < 13)\) in Gaia, we calculated the cluster mean proper motions and parallax; we found large differences with the values reported by DAML02, and Trumpler 20 was the worst case, with differences of \(\sim 4-5\) mas yr\(^{-1}\). We believe that these differences are not caused by systematic errors in Gaia, but by the lack of reliable cluster membership and the presence of field contamination.

Before the selection of the straggler candidates, we corrected every CMD for the effect of differential reddening and estimated the field contamination caused by young stars. The most affected cluster in both aspects is Trumpler 5, followed by Trumpler 20. This is expected because their positions are low in the Galactic plane. In NGC 2477 the effect of both extinction and contamination is negligible. Of the three clusters, Trumpler 5 hosts the largest sample of blue straggler candidates. We found 40 blue stragglers and three yellow stragglers among the cluster members (Table 9). In the case of Trumpler 20, we identified only eight BS candidates (Table 10), and in NGC 2477, five BSS and four YSS candidates were visible in the CMD (Table 11). All YS candidates are listed in Table 12, and the final results for the three clusters are shown in Figure 1. We found large inconsistencies in the AL07 blue straggler candidates, especially in Trumpler 5, where only \(\sim 6\) % of the BSS listed in AL07 are members. In the case of NGC 2477, all AL07 BSS are members, but they are all concentrated around the TO. Evidently, the quality of Gaia data contributes to improving the construction of better bona fide lists of blue straggler candidates.

Following Bhattacharya et al. (2019), R20, and V20, we used our candidates as test particles to probe the dynamical state of Trumpler 5. Our goal was to explore the bimodal distribution of BSS in OCs, which is poorly understood, unlike its GC counterpart. First, we compared BSS candidates with a reference population (RGB stars)—expected to follow the cluster light distribution—selected within the dereddened \(G < G_{TO} - 0.5\) mag range; exploring the normalized cumulative radial distributions, we found that BSS are not more centrally concentrated than RGB stars (left panels of Figure 5) in Trumpler 5. Second, we plotted the ratio of BSS to RGB stars \(N_{\text{BSS}}/N_{\text{RGB}}\) (see right panel of Figure 5); to do so, we split the field of view into concentric annuli, each containing at least one BS. Before the comparison, we performed an A-D test to confirm that both populations were not extracted from the same parent distribution. The test gave a 99.9% probability that RGB stars are not drawn from the same distribution as BSS. Based on his flat radial distribution, Trumpler 5 can be classified as a Family I-type cluster. Additionally, we calculated the predicted \(r_{\text{min}}\) using the correlation (Equation (1)) of V20 and the corresponding values of \(N_{\text{relax}}\) (Table 4), and obtained a value of 2.29 \(r_e\). The distribution of Trumpler 5 is flat up to 15\(r_e\), with no clear signs of a minimum in the BSS radial distribution at the predicted \(r_{\text{min}}\). The case of Trumpler 5 is similar to both Berkeley 39 and NGC 6819 (see V20), whose estimated values of \(N_{\text{relax}}\) suggest that they are dynamically evolved, but that their radial distributions are flat. In Section 4 we presented the first high-resolution spectroscopic study of the BSS population of Trumpler 5, adopting more solid membership criteria than the simple photometric ones. For this cluster we obtained four epochs of radial velocities; based on their variations, we separated these stars into candidate members, probable close binaries, and long-period binaries. Unfortunately, these data

### Table 11

| Gaia DR2 Source Id. | \(G_{\text{corr}}\) (mag) | \((G_{\text{BP}} - G_{\text{RP}})_{\text{corr}}\) (mag) | \(\mu_\alpha \cos \delta\) (mas yr\(^{-1}\)) | \(\Delta \mu_\alpha \cos \delta\) (mas yr\(^{-1}\)) | \(\mu_\delta\) (mas yr\(^{-1}\)) | \(\Delta \mu_\delta\) (mas yr\(^{-1}\)) | \(\varpi\) (mas) | \(\Delta \varpi\) (mas) | \(P_{\text{mem}}\) M |
|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| 5538883317769763072 | 12.364 | 0.437 | -2.493 | 0.041 | 0.813 | 0.046 | 0.739 | 0.0252 | 0.9 | N |
| 5538871193083003264 | 11.561 | 0.454 | -2.329 | 0.055 | 0.85 | 0.057 | 0.696 | 0.0324 | 0.8 | N |
| 5538867622016153088 | 12.371 | 0.529 | -2.277 | 0.047 | 0.339 | 0.06 | 0.6589 | 0.0293 | 1.0 | N |
| 5538493682642912256 | 11.357 | 0.388 | -2.316 | 0.045 | 0.447 | 0.06 | 0.6468 | 0.0313 | 1.0 | N |
| 5538494885233812864 | 11.732 | 0.384 | -2.406 | 0.045 | 1.063 | 0.048 | 0.6434 | 0.0254 | 0.9 | N |

### Table 12

| Gaia DR2 Source Id. | \(G_{\text{corr}}\) (mag) | \((G_{\text{BP}} - G_{\text{RP}})_{\text{corr}}\) (mag) | \(\mu_\alpha \cos \delta\) (mas yr\(^{-1}\)) | \(\Delta \mu_\alpha \cos \delta\) (mas yr\(^{-1}\)) | \(\mu_\delta\) (mas yr\(^{-1}\)) | \(\Delta \mu_\delta\) (mas yr\(^{-1}\)) | \(\varpi\) (mas) | \(\Delta \varpi\) (mas) | \(P_{\text{mem}}\) |
|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| NGC 2477 | 10.851 | 0.98 | -2.318 | 0.04 | 0.982 | 0.05 | 0.6276 | 0.0261 | 0.8 |
| 553886634450937952 | 10.564 | 1.245 | -2.54 | 0.051 | 0.938 | 0.062 | 0.6881 | 0.0315 | 1.0 |
| 5538494679707370572 | 11.153 | 1.375 | -2.404 | 0.043 | 0.835 | 0.057 | 0.6368 | 0.027 | 0.7 |
| 5538493579557251072 | 10.714 | 1.318 | -2.53 | 0.045 | 0.665 | 0.062 | 0.6548 | 0.0313 | 0.9 |
| Trumpler 5 | 14.85 | 1.30 | -0.691 | 0.072 | 0.022 | 0.066 | 0.2245 | 0.0404 | 0.8 |
| 3326780722869330304 | 14.621 | 1.362 | -0.179 | 0.088 | 0.528 | 0.075 | 0.0678 | 0.0465 | 0.5 |
| 3326823603382996608 | 14.387 | 1.398 | -0.873 | 0.069 | 0.291 | 0.067 | 0.117 | 0.0371 | 1.0 |
| 3326783746526306176 | 14.519 | 1.375 | -0.58 | 0.063 | 0.294 | 0.058 | 0.2805 | 0.0342 | 1.0 |
| 3326809997366180608 | 14.795 | 1.353 | -0.501 | 0.073 | 0.333 | 0.062 | 0.3609 | 0.0462 | 1.0 |
| 3326852328563919744 | 14.532 | 1.279 | -0.591 | 0.065 | 0.44 | 0.058 | 0.2445 | 0.0354 | 1.0 |
only cover 7 out of the 40 possible BSS found in our analysis with Gaia. Our spectroscopic results are reported in Table 6. Radial velocities for four epochs are available for seven stars, among which we identified four as probable contact binaries and three as non-members. All the stars are fast rotators, with the exception of star Tr20-BS2. We conclude that Trumpler 5 hosts 37 blue straggler candidates within r/r, ∼ 3/28.

Our spectroscopic results for Trumpler 20 are reported in Table 8. Radial velocities for five epochs are available for three stars. Only one of these stars was safely classified as a BSS candidate (within the radius R and with P_{ memb} ≥ 50%); this star is a possible close binary system. The remaining two stars with probabilities below 50% are Tr20-BS2 (10%) and Tr20-BS3 (30%), identified as one possible close binary (member) and a non-member, respectively. Given our conservative criteria, it is expected that we would miss some genuine stragglers, and star Tr20-BS2 is an example. Although we did not attempt to estimate the number of uncounted BSS, we are confident that it is small because our choice of members with P_{ memb} ≥ 50% captures the majority of the cluster members, as has also been found by other authors. Having said that, we found that Trumpler 20 hosts nine BSS.

In the case of NGC 2477, our results are shown in Table 7. Radial velocities for eight epochs are available for three stars, and only one of them has probabilities high enough to be a BSS candidate.

We estimated the field contamination in all three cluster areas within their radius R (Table 1 and Section 3.4) and found 13 and 2 interlopers for Trumpler 5 and Trumpler 20, respectively, and none for NGC 2477. This means that we have ∼25% of field contamination in the case of Trumpler 5 and ∼13% for Trumpler 20. Although this work shows an improvement over the photometric selection of AL07, the contamination in both clusters is quite high and consistent with the results from our spectroscopic follow-up, where 3 of 7 observed stars were classified as non-members in Trumpler 5. This shows once again that such a spectroscopic follow-up is rather essential to a proper understanding of these exotic populations in OCs.

This study and other recent ones such as R20, Bhattacharya et al. (2019), or AL07 indicate that there is an increasing interest for BSS in Galactic clusters. In addition, evidence emerges that a proper membership assessment is mandatory before any statistical analysis of the BSS population in OCs is performed. We hope to be able to extend this membership assessment to many more clusters in the near future.

We are grateful to the anonymous referee for helpful comments that significantly helped improve the paper.

M.J.R. is supported by CONICY PFCCHA through Programa de Becas de Doctorado en el extranjero- Becas Chile/2018-72190617.

S.V. gratefully acknowledges the support provided by Fondecyt reg. n. 1170518.

J.A. wishes to thank ESO for stays in the Santiago Headquarters in 2010 January, 2011 November, and 2015 October, where part of this work was originally developed.

This work is based on data obtained through ESO programs 088.D-0045(A) and 0100.D-0052(A).

Software: IRAF (Tody 1986, 1993), UPMASK (Krone-Martins & Moitinho 2014), Topcat (Taylor 2005), SPECTRUM (Gray & Corbally 1994), ATLAS9 (Castelli & Kurucz 2003).

ORCID iDs
M. J. Rain https://orcid.org/0000-0003-4009-8316
G. Carraro https://orcid.org/0000-0002-0155-9434
J. A. Ahumada https://orcid.org/0000-0002-7091-5025
S. Villanova https://orcid.org/0000-0001-6205-1493
H. Boffin https://orcid.org/0000-0002-9486-4840
L. Monaco https://orcid.org/0000-0002-3148-9836

References
Ahumada, J., & Lapasset, E. 1995, A&AS, 109, 375
Ahumada, J. A., & Lapasset, E. 2007, A&A, 463, 789
Aidelman, Y., Cidale, L. S., Zorec, J., & Paneli, J. A. 2018, A&A, 610, A30
Bailyn, C. D. 1995, ARA&A, 33, 133
Banks, T., Yontan, T., Bilir, S., & Canbury, R. 2020, JApA, 41, 6
Beccari, G., Dalessandro, E., Lanzoni, B., et al. 2013, ApJ, 776, 60
Bhattacharya, S., Vaidya, K., Chen, W. P., & Beccari, G. 2019, A&A, 624, A26
Binney, J., & Tremaine, S. 2008, Galactic Dynamics: Second Edition (Princeton, NJ: Princeton Univ. Press)
Boffin, H. M. J., Carraro, G., & Beccari, G. 2015, Ecology of Blue Straggler Stars (Astrophysics and Space Science Library Vol. 413) (Berlin: SPinger)
Bragaglia, A., Sestito, P., Villanova, S., et al. 2008, A&A, 480, 79
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Brogard, K., Christiansen, S. M., Grundahl, F., et al. 2018, MNRAS, 481, 5062
Cantat-Gaudin, T., & Anders, F. 2020, A&A, 633, A99
Cantat-Gaudin, T., Jordi, C., Vallenari, A., et al. 2018, A&A, 618, A93
Carraro, G., Costa, E., & Ahumada, J. A. 2010, A3, 140, 954
Carraro, G., de Silva, G., Monaco, L., Milone, A. P., & Mateluna, R. 2014a, A&A, 566, A39
Carraro, G., Vázquez, R. A., & Moitinho, A. 2008, A&A, 482, 777
Carraro, G., Villanova, S., Monaco, L., et al. 2014b, A&A, 562, A39
Carrera, R., Bragaglia, A., Cantat-Gaudin, T., et al. 2019, A&A, 623, A80
Castelli, F., & Kurucz, R. L. 2003, in IAU Symp. 210, Modelling of Stellar Atmospheres, ed. N. Piskunov, W. W. Weiss, & D. F. Gray (San Fransisco, CA: ASP), A20
Chen, X., & Han, Z. 2009, MNRAS, 395, 1822
Davies, M. B. 2015, ASSL, 413, 203
Davies, M. B., Benz, W., & Hills, J. G. 1994, ApJ, 424, 870
Dias, W. S., Alessi, B. S., Moitinho, A., & Lépine, J. R. D. 2002, A&A, 389, 871
Dias, W. S., Alessi, B. S., Moitinho, A., & Lepine, J. R. D. 2014, A&A, 564, A79
Donati, P., Cantat Gaudin, T., Bragaglia, A., et al. 2014, A&A, 561, A94
Davies, M. B., Benz, W., & Hills, J. G. 1994, ApJ, 424, 870
Dias, W. S., Alessi, B. S., Moitinho, A., & Lépine, J. R. D. 2002, A&A, 389, 871
Gao, X.-h 2018, PASP, 130, 12401
Geller, A. M., & Mathieu, R. D. 2011, Natuer, 478, 356
Geller, A. M., & Mathieu, R. D. 2012, AJ, 144, 54
Geller, A. M., Mathieu, R. D., Harris, H. C., & McClure, R. D. 2008, AJ, 135, 2264
Geller, A. M., Mathieu, R. D., Harris, H. C., & McClure, R. D. 2019, AJ, 137, 3743
Glebbeek, E., Sills, A., & Leigh, N. 2010, MNRAS, 408, 1267
Gosnell, N. M., Mathieu, R. D., Geller, A. M., et al. 2015, ApJ, 814, 163
Gray, R. O., & Corbelli, C. J. 1994, AJ, 107, 742
Grevesse, N., & Sauval, A. J. 1998, SSRv, 85, 161
Hills, J. G., & Day, C. A. 1976, ApL, 17, 87
Hurley, J., & Tout, C. A. 1998, MNRAS, 300, 977
Ivanova, N. 2015, ASSL, 413, 179
Jordi, C., Gebran, M., Carrasco, J. M., et al. 2010, A&A, 523, A48
Kaluzny, J. 1994, AcA, 44, 247
Katz, D., Sartoretti, P., Cropper, M., et al. 2019, A&A, 622, A205
King, I. 1962, AJ, 67, 471
Krone-Martins, A., & Moitinho, A. 2014, A&A, 561, A57
Lindegren, L., Hernández, J., Bombrun, A., et al. 2018, A&A, 616, A2
Rain et al. The Astronomical Journal, 161:37 (15pp), 2021 January
