An analysis of the blue straggler population in the Sgr dSph globular cluster Arp 2*

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ABSTRACT

We present and discuss new BVI CCD photometry in the field of the globular cluster Arp 2, which is considered a member of the Sagittarius Dwarf Spheroidal Galaxy. The main goal of this investigation is to study of the statistics and spatial distribution of blue straggler stars in the cluster. Blue stragglers are stars observed to be hotter and bluer than other stars with the same luminosity in their environment. As such, they appear to be much younger than the rest of the stellar population. Two main channels have been suggested to produce such stars: (1) collisions between stars in clusters or (2) mass transfer between, or merger of, the components of primordial short-period binaries. The spatial distribution of these stars inside a star cluster, compared with the distribution of stars in different evolutionary stages, can cast light on the most efficient production mechanism at work. In the case of Arp 2, we found that blue straggler stars are significantly more concentrated than main sequence stars, while they show the same degree of concentration as evolved stars (either red giants or horizontal branch stars). Since Arp 2 is not a very concentrated cluster, we suggest that this high central concentration is an indication that blue stragglers are mostly primordial binary stars.

Key words: open clusters and associations: general - open clusters and associations: individual (Arp 2) - binaries: general - blue stragglers - stars: evolution

1 INTRODUCTION

Arp 2 is a globular cluster located at $l = 8.54^\circ$, $b = -20.78^\circ$ ($\alpha = 19^h 28^m 44^s$, $\delta = -30^\circ 21' 14''$, J2000.0). It is commonly believed to have formed inside the Sgr dwarf spheroidal galaxy (Monaco et al. 2005), and then released into the Milky Way through tidal interaction. With a metallicity of [Fe/H]=-1.77 (Mottini et al. 2008), this cluster appears to be 3-4 Gyr younger than the old globulars, but $\sim 1 - 2$ Gyr older than the youngest globulars associated to Sgr (Carraro et al. 2007, Layden & Sarajedini 2000).

The first photometric study of this cluster was performed by Buonanno et al. (1994). The derived color-magnitude diagram (CMD) reveals an intriguing feature, namely that the horizontal branch (HB) is located entirely blue-ward of the RR-Lyrae instability strip, a fact that allowed the authors to assess its age through a differential comparison with 47 Tuc and Ruprecht 106. A secondary, prominent feature, which the authors do not comment on, is a group of stars right above the turn-off (TO), which are probably the blue straggler stars (BSS) population in Arp 2. BSS are a normal stellar population in clusters, since they are present in all of the properly observed Globular Clusters (GC, Ferraro 2006; Ferraro et al. 2009, and reference therein). Current scenarios for these stars in globulars are that either they are binary system with significant mass exchange, or stellar mergers resulting from direct collisions between two or more stars (Davies et al. 2004; Knigge et al. 2009; Perets & Frabrycky 2009).

In all these studies a proper assessment of the membership of BSSs through comparison with Red Giant Branch (RGB) stars is routinely performed (Ferraro et al. 1993). The comparison of their cumulative radial distribution may hint to a possible common origin, specifically to confirm or deny whether they belong to the same parent distribution. Additionally, the radial distribution of BSS in a star cluster is the most effective tool to understand their origin and which is the dominant production channel (Ferraro 2006). BSS are routinely found - with the exception of Omega Cen and NGC 2419 (Dalessandro et al. 2008)- to be centrally concentrated. Their radial profile then smooths down, while in the cluster periphery it shows again an increase of the BSS contribution (Lanzoni et al. 2007, Dalessandro et al. 2008).

In this paper we report on a new photometric data-set of Arp 2 obtained with the goal of analyzing the BSS population in a young, relatively loose GC, that is in an environment significantly different from a typically dense GC. We anticipate here that our
This allows us to cover a field centered on Arp 2 slightly larger than the previous observations by Buonanno et al. (1994). We used multiple exposures of 30 and 1200 secs for the B filter, and 30 and 900 both for V and I filters. As an illustration, an I filter, 900 sec, raw image is shown in Fig. 1. The night was photometric, and we calibrated our photometry against the Landolt (1992) standard field Mark A and PG 2213, observed several times during the night. Arp 2 was observed during an observational run focused on a different science when the principal target was not visible. Data have been reduced in the standard way. Image preparation (trimming, bias and flatfield) was done using the IRAF package, while photometry was extracted by using DAOPHOT and ALLSTAR (Stetson 1987). We obtained a final catalog with 4580 entries having 2000.0 Equatorial coordinates, and B, V and I magnitudes together with associated uncertainties. These latter have been calculated following the prescriptions described in Patat & Carraro (2001).

2 OBSERVATIONS AND DATA REDUCTION

CCD BVI images were acquired with the EFOSC2 camera mounted on the Nasmyth focus of the ESO NTT telescope on the night of August 8, 2008. The CCD is a 1030×1038 array with a scale of 0.24 arcsec, allowing to cover 4.1×4.1 arcmin on the sky.

2.1 Complementary infrared data, astrometry and completeness

Our optical catalogue was cross-correlated with 2MASS, which resulted in a final catalog including BV I and JHKs magnitudes. As a by product, pixel (detector) coordinates were converted to RA and DEC for J2000.0 equinox, thus providing 2MASS-based astrometry.

Finally, completeness corrections were determined by running artificial star experiments on the data. The data-set was divided in two regions, inner (inside 1 arcmin) and outer (beyond 1 arcmin), and completeness was computed for these two different regions, which, due to the nature of the object, are expected to be differently affected by star crowding (Carraro et al. 2007). Basically, we created several artificial images by adding artificial stars to the original frames. These stars were added at random positions, and had the same color and luminosity distribution of the true sample. To avoid generating overcrowding, in each experiment we added up to 30% of the original number of stars. Depending on the frame (short or deep exposures), between 1000-5000 stars were added. In this way we have estimated that the completeness level of our photometry in the outer region is 100% down to $V = 23.00$, and better than 50% down to $V = 23.50$. As for the inner region, we found that the completeness is 100% down to $V = 22.40$, and better than 50% down to $V = 22.80$.

3 STAR COUNTS AND CLUSTER SIZE

We used our photometry to study the cluster stars radial distribution. According to Harris (1996), Arp 2 has a concentration c=0.90, an half-mass radius = 1.91 arcmin, and a core and tidal radius of 1.59 and 12.65 arcmin, respectively. Therefore we expect our photometry to cover just the inner part of the cluster. The radial density profile we constructed is shown in Fig. 2. It has been derived following the method described in Suleznev (1994). This method employs numerical differentiation of the best mean-square polynomial fit for N(r), the number of stars in circles of radius r in the plane of the sky. The center of the cluster was taken at the detector coordinates (512,512) which corresponds to $\alpha = 19^h 28^m 44^s$, $\delta = -30^\circ 21' 14''$ (J2000.0). Vertical bars indicate the profile error-bars derived assuming Poisson statistics. In the same Fig. 2 we fit the profile with a King (1962) model, adopting king parameters (core and tidal radius, and center mass density) from Harris (1996).
blue Stragglers in Arp 2

Figure 3. CMD in the V vs B-V (left panel), and V vs V-I (right panel) for Arp 2. The dashed lines indicate the 100% level of completeness. See Sect. 2.1.

Figure 4. Selection of RGB (red dots), HB (red circle), BSS (cyan circle) and MS (yellow polygon) stars. These latter have been selected in a region of the MS where the completeness is 100%.

compilation. The fit is good within the uncertainties, and therefore we conclude that Arp 2 follows a King-like density profile. It decreases all the way to the edge of the field we covered, slightly beyond the nominal half-mass radius.

4 COLOR MAGNITUDE DIAGRAMS

The resulting color magnitude diagrams (CMDs) are shown in the two panels of Fig. 3. In the left panel, the V versus B-V diagram is shown, while in the right panel we present the V versus V-I. The CMD on the left panel is absolutely identical to the one presented by Buonanno et al. (1994), apart from the slightly different area coverage and the magnitude limit, which in our case is about one magnitude fainter. All the typical features of a globular cluster CMD are present. The MS, RGB, HB -located entirely blue-ward the RR Lyrae instability strip-, and the Asimptotic Giant Branch (AGB). An additional feature which has been overlooked in the past is the plume of blue stars right above the turn off point (TO), which is quite common in globular clusters, and it is composed of candidate blue straggler stars. This plume is the target of our investigation. We look for BSS candidates following the commonly used criteria (Ahumada & Lapasset 1995, 2007; Sandage 1953), which is illustrated in Fig. 4. Together with BSS (blue box), we also indicated the location of HB (red box), RGB (red dots), and a sample of MS stars (yellow box), which we are going to compare. We counted 41 BSS candidates, and 28 HB stars. They are listed in Table 1 and 2, respectively, where we indicate stars’ identification (our numbering, ID), equatorial coordinates for the 2000.0 equinox, magnitude V and color B-V. These can also be useful for future spectroscopic follow-up.

Besides, again following Fig 4, we counted 213 RGB and 517 MS stars, which we do not list here for space reasons. As for MS stars, we stress that they have been extracted in a region of the MS which is not affected by incompleteness.

We stress that the numbers we reported have been computed using the classical definition of BSS locus and assuming that contamination from field stars is negligible, which seems to be the case, since the field of view is very small (0.0044 squared degrees). However, we do not have at our disposal a control field to verify this directly. Therefore, we investigated the amount of contamination by computing synthetic CMDs of stars in the direction of Arp 2 assuming a Galactic model which includes bulge, halo, thin and thick disks (Girardi et al. 2005). We generated several CMDs by varying the random seed and added photometric errors as from Arp 2 photometry. The results are shown in Fig. 5, where the left panel shows the Galaxy CMD in the direction of Arp 2, and the right panel the CMD of Arp 2 as in Fig. 4. In both panel we indicate the boxes used for selecting HB (red) and BSS (blue) stars. A quick glance at this figure is sufficient to conclude that most of the contamination affects the lower MS, and in general contaminating stars are redder than the typical BSS colors. Some contamination is present in the RGB area but, provided the high number of RGB stars in Arp 2, we do not expect their statistics to be significantly affected.

5 ANALYSIS OF THE BLUE STRAGGLER STARS’ POPULATION

To properly assess the probable membership of BSS, it is necessary to measure their radial velocity or their proper motion (Mathieu & Geller 2009; Liu et al. 2008). Since we are relying only on photometry, we will keep considering our BSS as candidates, based on their location in the CMD. To get more insight on their properties and origin, we started by considering their surface distribution, and compared it with the surface distribution of HB stars. This is illustrated in Fig 6, which shows radial density profile of the two populations. Here we plot the number of stars per squared arcmin as computed in concentric bins 10 arcsecs wide. Except for the difference in the inner side of the cluster, the two profiles are identical. We stress that the difference in the very central bin, although real, is exaggerated by the small number statistics (2 BSS and 0 HB stars). In this respect Arp 2 seems more similar to old open clusters, like M 67 (Mathieu & Gheller 2009), than to genuine globulars. The higher concentration of BSS in the cluster internal region with respect to evolved stars we find is not new, and has been found already in several other globulars (Dalealessandro et al. 2008). At odds
with what is found in other globulars, we do not see any outward increase of the BSS population, most probably because we are not sampling the cluster outskirts (see Section 3) in this study.

6 DISCUSSION AND CONCLUSION

To better quantify the relationship between BSS and the other stars we make use of Kolmogorov-Smirnov (KS) statistics, in its one (1D) and two (2D) dimensional flavors. The 2D distributions of BSS with respect to other star samples in different evolutionary phases (HB, RGB or MS stars) were statistically compared with the 2D generalization of 1D KS test described in Press et al. (1997) and Fasano & Franceschini (1987). The same method was employed in Pancino et al. (2003) for comparison of the 2D distributions of RGB stars with different metallicity in the multi-population globular cluster ω Cen.

This test gives the probability $P$ that two distributions are extracted

TABLE 1. BSS candidates. See Fig. 4 for the selection

| ID  | $\alpha$(2000.0) | $\delta$(2000.0) | V   | B-V |
|-----|-----------------|-----------------|-----|-----|
| 140 | 292.1463587     | -30.3394516     | 19.777 | 0.299 |
| 742 | 292.1539322     | -30.3574441     | 21.321 | 0.400 |
| 909 | 292.1560467     | -30.3590792     | 20.831 | 0.482 |
| 1086| 292.1584272     | -30.3590217     | 21.173 | 0.453 |
| 1119| 292.1590122     | -30.3404261     | 20.071 | 0.274 |
| 1463| 292.1627267     | -30.3541401     | 20.191 | 0.437 |
| 1575| 292.1639108     | -30.3676803     | 21.347 | 0.438 |
| 1649| 292.1649792     | -30.3766803     | 21.040 | 0.448 |
| 1942| 292.1681176     | -30.3770277     | 20.871 | 0.340 |
| 2257| 292.1718385     | -30.3565473     | 20.680 | 0.469 |
| 2308| 292.1723293     | -30.3570290     | 20.282 | 0.430 |
| 2324| 292.1727334     | -30.3409102     | 20.315 | 0.432 |
| 2341| 292.1725939     | -30.3404261     | 20.071 | 0.274 |
| 2433| 292.1741541     | -30.3208680     | 20.853 | 0.423 |
| 2531| 292.1743077     | -30.3790334     | 21.371 | 0.431 |
| 2568| 292.1748233     | -30.3722961     | 21.268 | 0.462 |
| 2750| 292.1770090     | -30.3479386     | 21.341 | 0.430 |
| 2826| 292.1779222     | -30.3386991     | 21.040 | 0.403 |
| 2910| 292.1782726     | -30.3795017     | 21.024 | 0.374 |
| 2913| 292.1788245     | -30.3432700     | 20.935 | 0.460 |
| 3146| 292.1810024     | -30.3573719     | 20.947 | 0.396 |
| 3163| 292.1815525     | -30.3322570     | 20.343 | 0.388 |
| 3266| 292.1822050     | -30.3519277     | 21.131 | 0.386 |
| 3351| 292.1829014     | -30.3622331     | 20.172 | 0.281 |
| 3362| 292.1830748     | -30.3598515     | 20.039 | 0.408 |
| 3533| 292.1851738     | -30.3941982     | 20.981 | 0.402 |
| 3633| 292.1858386     | -30.3652012     | 20.082 | 0.414 |
| 3637| 292.1860246     | -30.3541866     | 21.078 | 0.458 |
| 4014| 292.1899276     | -30.3439827     | 20.018 | 0.163 |
| 4140| 292.1907422     | -30.3659683     | 20.510 | 0.458 |
| 4346| 292.1932713     | -30.3685683     | 20.874 | 0.462 |
| 4420| 292.1946120     | -30.3729961     | 21.127 | 0.435 |
| 4635| 292.1967567     | -30.3540156     | 19.512 | 0.203 |
| 4875| 292.1993316     | -30.3591077     | 21.066 | 0.413 |
| 5059| 292.2014691     | -30.3478313     | 22.921 | 0.668 |
| 5174| 292.2029316     | -30.3524965     | 20.789 | 0.421 |
| 5239| 292.2073737     | -30.3534943     | 20.504 | 0.282 |
| 5354| 292.2051005     | -30.3629483     | 21.345 | 0.428 |
| 5611| 292.2091052     | -30.3263457     | 20.941 | 0.382 |
| 5612| 292.2085462     | -30.3696267     | 21.149 | 0.460 |
| 6087| 292.2157226     | -30.3813623     | 20.019 | 0.238 |

Figure 5. Estimate of field star contamination in Arp 2. The left panel shows the Galaxy CMD in Arp 2 direction, and the right panel the CMD of Arp 2 as in Fig. 4.

Figure 6. Radial surface density profile of HB (red triangles) and BSS (blue squares) stars i n the field of Arp 2.

Figure 7. Fractional radial cumulative distribution of BSS and HB stars.
Table 2. HB candidates. See Fig. 4 for the selection

| ID  | α(2000.0) | δ(2000.0) | V   | B-V |
|-----|-----------|-----------|-----|-----|
| 125 | 292.1456946 | -30.3733031 | 17.819 | 0.331 |
| 370 | 292.1493758 | -30.3477929 | 18.091 | 0.260 |
| 1127 | 292.1586924 | -30.3658908 | 17.818 | 0.294 |
| 1549 | 292.1641508 | -30.352455 | 17.735 | 0.456 |
| 1996 | 292.1690971 | -30.3519597 | 18.139 | 0.204 |
| 2040 | 292.1691049 | -30.3828881 | 18.207 | 0.162 |
| 2086 | 292.1701074 | -30.3484238 | 17.966 | 0.253 |
| 2503 | 292.1746582 | -30.3377476 | 18.087 | 0.256 |
| 2608 | 292.1753085 | -30.3659882 | 18.219 | 0.150 |
| 3036 | 292.1802420 | -30.3502122 | 18.000 | 0.336 |
| 3038 | 292.1802864 | -30.3280083 | 18.367 | 0.147 |
| 3129 | 292.1807069 | -30.3656050 | 18.089 | 0.253 |
| 3772 | 292.1815674 | -30.3589202 | 18.038 | 0.271 |
| 3555 | 292.1848119 | -30.3832435 | 18.087 | 0.256 |
| 3682 | 292.1864725 | -30.3582211 | 17.996 | 0.253 |
| 3772 | 292.1871954 | -30.3651926 | 17.886 | 0.341 |
| 3990 | 292.1894482 | -30.3534246 | 17.703 | 0.388 |
| 4040 | 292.1898884 | -30.3533154 | 17.917 | 0.360 |
| 4911 | 292.1998576 | -30.3476994 | 18.097 | 0.258 |
| 4932 | 292.2002557 | -30.3352233 | 17.720 | 0.435 |
| 4940 | 292.1997888 | -30.3748761 | 18.209 | 0.168 |
| 5048 | 292.2011579 | -30.3552338 | 18.054 | 0.277 |
| 5101 | 292.2019892 | -30.3501858 | 18.437 | 0.153 |
| 5165 | 292.2033021 | -30.3208588 | 18.108 | 0.245 |
| 5184 | 292.2029381 | -30.3599449 | 18.018 | 0.243 |
| 5244 | 292.2038283 | -30.3544071 | 18.028 | 0.304 |
| 5646 | 292.2087883 | -30.3863411 | 18.051 | 0.266 |
| 5773 | 292.2115368 | -30.3298674 | 18.037 | 0.287 |

Figure 8. Fractional radial cumulative distribution of BSS and RGB stars from the same parent distribution. Small values of P would show that the two samples are significantly different. Formulas as given in Press et al. (1997) are accurate enough when

\[ N = N_1 \cdot N_2 / (N_1 + N_2) > 20 \]  

and when the indicated probability P is less (more significant than) 0.20 or so. In the above equation N1 and N2 are the two populations under comparison. When P is larger than 0.20, its value may not be accurate, but the implication that the two data sets are not significantly different is certainly correct. We summarize our results in Table 3 and 4, and graphically in the series of Figs. 7 to 9.

Looking at the results listed in the two tables and illustrated in the corresponding figures, we can provide the following considerations.

First, due to the larger number, the statistics (N) improves passing from HB to RGB stars, and from RGB to MS stars.

Second, probabilities P for 2D KS test are smaller than for 1D test in the case of HB and RGB stars. We face the opposite situation as for MS stars. We can explain it by taking into account that 1D distribution is only a function of the distance from the distribution center, while 2D distributions do contain angle information. In the case of HB and RGB stars radial distributions are very close to BSS, while azimuthal distributions have some differences, and this results in larger probabilities in 1D testing. In the case of MS stars radial distribution is very different from BSS distribution, and probability in 1D test is small. Apparently, azimuthal distributions in this case are more similar, which implies larger probability in 2D test.

Third, and more interesting, the tests provide comparable results for HB and RGB stars. This implies that BSS, HB and RGB stars are on the overall distributed in the same way, which in turn means that these populations are not significantly different. We caution however that high probability in KS test is a necessary, but not sufficient condition to prove that these populations have the same parent distribution (see e.g. Press et al., 1997).

At odds with HB and RGB, MS stars show a different distribution.

Figure 9. Fractional radial cumulative distribution of BSS and MS stars

Table 3. Results of the KS statistics in 1D for the BSS.

| Population | N | P  | Reference Figure |
|------------|---|----|------------------|
| HB         | 17 | 0.83 | Fig 7            |
| RGB        | 35 | 0.61 | Fig 8            |
| MS         | 38 | 0.07 | Fig 9            |

Table 4. Results of the KS statistics in 2D for the BSS.

| Population | N | P  |
|------------|---|----|
| HB         | 17 | 0.51 |
| RGB        | 35 | 0.43 |
| MS         | 38 | 0.23 |
bution when compared to BSS. Namely, BSS are significantly more concentrated to the cluster center than normal MS stars. All-together this suggests that most probably BSS are primordial binary systems which, because of their total mass and the relatively loose environment of Arp 2, sank toward the center and survived as binary system.

Our results also imply that present-day RGB and HB stars are, on the overall, more concentrated than actual MS stars. This does not mean that actual HB stars and upper RGB stars are more massive than actual MS stars, which can be the case for RGB stars in earlier stages of evolution. This simply reflects the fact that actual upper RGB and HB stars follow the spatial distribution of their -originally more massive- MS progenitors. The relaxation time for Arp 2 is \( \sim 5 \) Gyr (Harris 1996), specifically much shorter than the cluster age, and therefore mass segregation already occurred in the past, when the progenitors of present-day upper RGB and HB stars were in the MS, and were more massive - and therefore more segregated - than the present-day MS stars.

Our findings confirm very recent results on the BSS distribution and nature in GCs (Ferraro et al. 2009). The suggestions (Knigge et al. 2009) that most BSS in globulars have a binary origin, even in the environment of the densest globulars, is not longer of general validity. In fact, whether BSS are primordial close binaries or merger remnants resulting from direct collision between two stars, depends strongly on the environment. As recently discovered by Ferraro et al. (2009), the existence of double BSS sequences in M30, a famous core collapse globular cluster, confirms that BSS nature depends strongly on the environment, and the dynamical state of the parent cluster. Loose systems, such as open clusters, do indeed show a high primordial binary fraction among their BSS (Mathieu & Gheller 2009), while very dense systems harbour both primordial binaries and merger products, in proportions which vary from cluster to cluster.

In this context, Arp 2 is a relatively low concentration globular, that follows this trend, which will be hopefully confirmed by future spectroscopic observations.

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